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Risk analysis

Risk Analysis Karawanken Tunnel – an extended application of the Austrian Risk Model TuRisMo

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ABSTRACT: The risk analysis study for Karawanken tunnels is a very illustrative example for a modern integrated, risk-based approach to tunnel safety, applied to an existing tunnel with specific characteristics which requires upgrading to fulfil the minimum requirements as per EC-Directive 2004/54/EC and the Austrian Tunnel Safety Law, respectively. On the one hand the risk assessment supports the decision making process for long-term upgrading alternatives from a safety point of view, on the other hand it aims to identify and evaluate additional safety measures to mitigate risk in a short and medium term perspective.

The paper presents selected results of the risk assessment study and demonstrates an advanced application of the Austrian Tunnel Risk Model TuRisMo, implementing new tunnel specific sub-models for smoke propagation and evacuation simulation. Thus even complex tunnels like Karawanken tunnel can be assessed individually.

Keywords: Road Tunnel Safety, Risk Analysis, Tunnel Risk Model, QRA

1 Scope and basis of the study

Tunnel Karawanken is an old bidirectional tunnel at the Austrian – Slovenian border. The 7,8 km long tunnel was designed in the 1980's and opened to traffic in 1991. This tunnel has many specific characteristics respectively deviations from modern safety standards, the most relevant being:

- an unconventional ventilation system, combining a transversal ventilation with a longitudinal ventilation in the middle of the tunnel
- a varying tunnel cross section
- missing emergency exits
- a low average traffic load, but very high traffic peaks in summer

In a long term perspective an extensive upgrading of the tunnel will be necessary to fulfil the minimum safety requirements according to EC-Directive 2004/54/EC and Austrian and Slovenian national legislative regulations. On the basis of separate studies, different upgrading alternatives had been elaborated which were to be evaluated from a safety point of view. However, as all upgrading alternatives include constructive measures, their implementation will take time; therefore the risk of the existing tunnel should be evaluated as well as a basis for intermediate safety measures.

2 Methodical approach

2.1 Objectives

The objectives of the risk assessment study for the Karawanken tunnel were twofold:

- risk based evaluation of different upgrading alternatives:
  The results of the risk assessment study should provide additional inputs to the decision making process for the definition of the upgrading concept from the safety point of.
- evaluation of safety level of existing tunnel:
  The deficiencies of the Karawanken tunnel with respect to prescriptive safety requirements should be evaluated by a quantitative risk-based approach. On the basis of a risk analysis options for short and medium-term safety measures should be identified and evaluated.

2.2 Tunnel risk model

For the risk assessment study the Austrian tunnel risk model TuRisMo was applied. TuRisMo is the standard method for risk analysis in Austria and was also used for a comprehensive risk analysis study for motorway tunnels in Slovenia. TuRisMo is an integrated, system-based risk model which implements almost all relevant influence parameters for tunnel safety in a quantitative way. The risk model was developed under the authority of the Austrian Ministry for traffic, innovation and technology together with a group of experts of different technical disciplines and published in the framework of the Austrian Guidelines for Road, Rail and Traffic RVS (RVS 09.03.11 [5]) in 2008.

The risk model allows a systematic and quantitative risk assessment taking all relevant scenarios of incidents in a road tunnel into account:

- Light vehicle fire / HGV fire (with/without dangerous goods) / bus fire
- Light vehicle accident / HGV accident (with/without dangerous goods) / Bus accident
- Light vehicle accident with fire – as consequence / HGV accident with fire (with/without dangerous goods) – as consequence / bus accident with fire – as consequence

The risk analysis model examines the risk of tunnel users (fatalities and injuries). As reference value, the societal risk (expected value EV, statistically expected fatalities per year) of the tunnel is calculated. The share in risk of mechanical damage, fire effects and hazardous goods effects is displayed separately.

The method consists of the following two basic elements:

- a quantitative frequency analysis (event tree analysis) – to compute the frequencies of a set of damage scenarios
- a quantitative consequence analysis – assess the consequences of these damage scenarios by applying statistical approaches (mechanical accidents) or a combination of various sub models (fires)

The basic structure of the tunnel risk analysis is presented in the following picture:

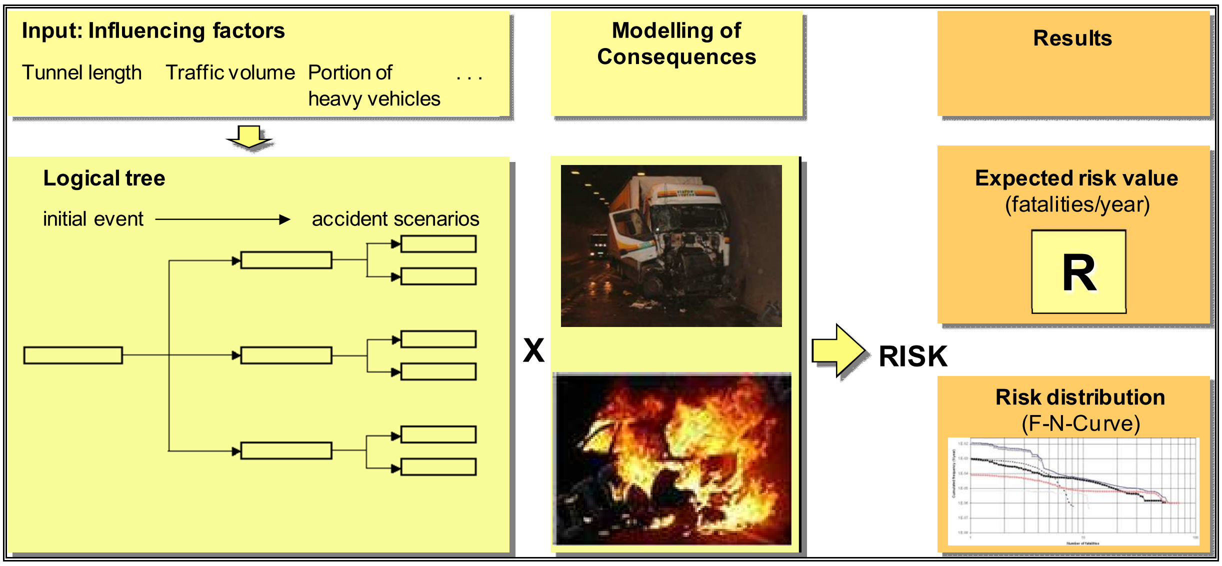

Figure 1: Basic structure of the risk analysis

For the application in the Karawanken tunnel the risk model had to be modified and extended, because the varieties of this tunnel are beyond the limits for the application of the standard model (see chapter 2.4).

2.3 *Approach for risk evaluation*

Risk evaluation is done by a relative comparison with a so called “reference tunnel”. This principle of risk evaluation directly relies on the EC Directive with its safety-related minimum requirements for road tunnels: a tunnel that fulfils all requirements and conditions laid down in the EC Directive is considered as sufficiently safe. Therefore a tunnel similar to the tunnel to be investigated, which in all aspects is fully in line with the requirements and definitions of the EC Directive are defined as reference tunnel. The risk assessment is performed for both, the reference tunnel as well as the real tunnel. If the risk of the real tunnel exceeds the risk of the reference tunnel additional safety measures have to be applied to reduce the risk of the real tunnel below the risk of the reference tunnel.

In addition to this relative approach the absolute risk values were classified according to the classification scheme of the Austrian guideline RVS 09.02.31 [6] which can be used as a bench mark generally applicable to evaluate absolute risk level of a tunnel:

Expected risk value in tunnel		
Lower limit	**Upper limit**	**Danger classes**
-	$2 . 10^{-2}$	I
$> 2 . 10^{-2}$	$1 . 10^{-1}$	II
$> 1 . 10^{-1}$	$5 . 10^{-1}$	III
$> 5 . 10^{-1}$	-	IV

Table 1: Classification scheme for absolute risk values for tunnels on motorways – according to Austrian guideline RVS 09.02.31 [6]

The effects of additional safety measures on the risk are taken into account in the tunnel risk analysis in accordance with their effect mechanisms. With the risk model, in most cases the effectiveness of additional safety measures can be assessed in a quantitative way (reduction of the expected risk value).

Thus, it is possible

- to compare different measures or combination of measures with respect to their efficiency (in terms of risk reduction),
- to compare different upgrading alternatives for the tunnel, with respect to their effects on risk (to give input to the decision making from the safety point of view).
- to verify that risk-enhancing influences can be compensated by additional safety measures and that the required safety standard can be achieved,

2.4 Modification of TuRisMo for the application in the Karawanken tunnel

In the guideline RVS 09.03.11 [5] pre-processed data for the application of the risk model is presented which refers to a representative set of typical model tunnels. As a prerequisite for the use of some data of this guideline (specifically the accident consequence data of fires) a tunnel must fulfil specific preconditions.

The Karawanken tunnel does not fulfil these preconditions, mainly due to the varying tunnel cross section and the combined ventilation system. Furthermore, in the current state the ventilation performance in the tunnel sections with transverse ventilation does not comply with the demands defined in this guideline. Therefore the simulations carried out in the course of the development of the risk model are not valid for the Karawanken Tunnel.

Nevertheless the risk model can be applied for the Karawanken Tunnel, but it has to be modified in such a way that it takes the specific conditions of Karawanken Tunnel into account. Hence the standard damage values for fire scenarios of RVS 09.03.11 [5] are replaced by values specifically calculated for Karawanken Tunnel. For that purpose the following simulations were carried out specifically for Karawanken Tunnel:

- a 3D CFD modelling of smoke propagation in the tunnel (model FDS – Fire Dynamic Simulator) for different fire scenarios / at various locations in the tunnel in order to determine the propagation of flue gases along the tunnel in dependence of time
- A specific evacuation simulation (model buildingEXODUS [7]) in order to investigate the effects of smoke on people during the self rescue process and to calculate new specific damage values for fire scenarios
- The damage values specifically calculated for Karawanken Tunnel were implemented in the TuRisMo event trees to calculate the overall risk value for The Karawanken Tunnel.

For all relevant simulation parameters (like alarm time, activation of ventilation, reaction time of people etc.) the same parameters as defined in TuRisMo are applied.

2.4.1 Simulation of smoke propagation

Fire Dynamics Simulator (FDS) is a computational fluid dynamics (CFD) model of fire-driven fluid flow. The software solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow, with an emphasis on smoke and heat transport from fires. Besides giving a three dimensional prognosis on smoke propagation based on given boundary conditions and convectional flux it also offers a powerful function for behaviour of different gas species and their vertical distribution. This allows calculating the concentrations of toxic gases at a given height (1.6 m above ground – corresponding to head level of people walking in the tunnel) in dependence of time. The results of smoke propagation simulation are transferred into the evacuation model.

2.4.2 *Simulation of egress of people*

The evacuation of people in the tunnel in case of fire is calculated with the simulation software “buildingEXODUS v4.0” [7]. This is a valuable tool for a dynamic simulation of evacuation processes. It focuses on the computation and simulation of large streams of people in pre-defined geometric structures.

In order to calculate the evacuation time, the program covers the people-people, the people-structure and the people-environment interaction. For this computation, every person is seen as an individual, whose behaviour and movement is determined by heuristic rules. The respective rules are allocated to 5 different sub models (occupant, behaviour, movement, toxicity, hazard).

As, in case of a fire, smoke spreads inside the tunnel, the visibility is impaired as is the escape capability of the people heading to the emergency exits. The spreading of smoke leads to orientation and breathing problems. In the evacuation simulation these problems are considered by reducing the walking speed of the people seeking to escape the hazard scenario. As soon as people are enclosed in smoke they inhale toxic fumes which reduce their capabilities for self rescue and may after some time degrade their chance to escape.

2.4.3 *Implementation of simulation results in TuRisMo*

Based on these effects as well as the results of the smoke propagation simulation the model calculates a model value for each single fire scenario which is taken as representative for the number of victims. These specific damage values are implemented in the event tree of the risk model, thus replacing the standard damage values for fires defined in RVS 09.03.11 [5].

To calculate representative model values as a basis for the risk analysis, the simulations need to be repeated several times with following variations:

- Random variation of allocation of individual occupants to vehicles; (5 repetitions of simulations with constant position of fire, vehicles, cross passage) to average the influence of occupants distribution
- Systematic shifting of location of fire relative to an emergency exit (in steps of app. 100 m) , to average the influence of favourable/unfavourable situations; this requires up to five different simulations (e.g. for a cross passage distance of 500m)

This process was repeated for each fire scenario (different fire sizes) and each fire location in the Karawanken Tunnel. The results were taken as representative for a specific tunnel section.

3 Demonstration of the application of the modified risk model in the Karawanken tunnel

3.1 Smoke propagation simulation

The most relevant aspect of the specific application of TuRisMo to the Karawanken tunnel is the modelling of the unconventional ventilation system of this tunnel. The ventilation system in Karawanken Tunnel is basically divided into three zones:

- A cross ventilated section of 3.332 m from the tunnel portal, one each on Austrian and Slovenian side
- A longitudinally ventilated section of 1.200 m length in the middle of the tunnel

The change in the ventilation system causes a change in the tunnel cross section, too, because in the transversally ventilated tunnel section an intermediate ceiling is provided.

Furthermore, the existing transversal ventilation does not comply with important specifications of the Austrian ventilation design guideline RVS 09.02.31 [6]. Due to insufficient exhaust capacity and not yet perfectly sealed leaks in the exhaust air duct the ventilation suffers inefficiency in the inner parts of the cross ventilated sections. Therefore the four scenarios simulated for the existing structure were placed as shown in the figure below in order to get specific information about smoke propagation mechanisms for representative tunnel sections.

- Fire location 1.025 m from northern tunnel portal
  This position represents the cross ventilated section with good ventilation efficiency. The fire is placed between the two closest flaps which both have to be activated.
- Fire location 3.000 m from northern tunnel portal
  This position was selected to represent unfavourable conditions in the cross-ventilated tunnel section. It is located in a section with low intermediate ceiling and virtually no exhaust volume left.
- Fire location 3.925 m from northern tunnel portal
  This is exactly the middle of the tunnel located in the longitudinally ventilated section and has been chosen to be representative for the whole section.
- Fire location 4.550 m from northern tunnel portal
  This forth scenario is put in the second cross ventilated section situated right after the beginning of the intermediate ceiling.

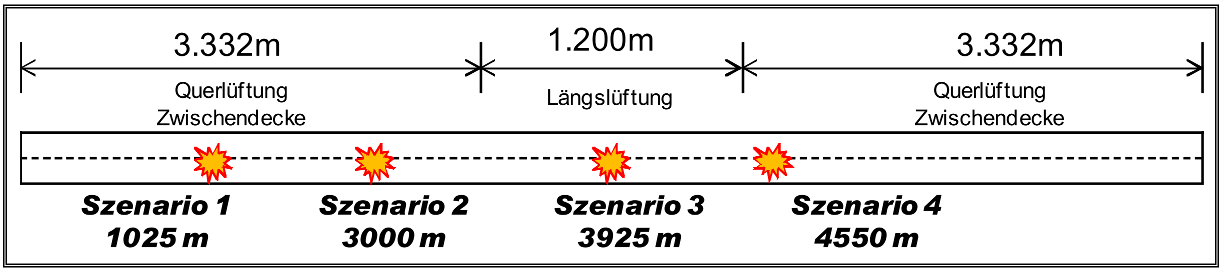

Figure 2: location of scenarios investigated - Karawanken Tunnel, current state

As an example, the results of smoke propagation simulations for scenario 2 are presented in form of time series. Each line shows the longitudinal cut of the studied tunnel section at a given time. The data shown is the linear extinction coefficient which is directly linked to the visibility. It can be assumed that under normal light conditions an extinction coefficient of 0.65 corresponds to a visibility of approximately 5 m. This is the limit where efficient and coordinated evacuation tends to get impossible. In figure 3 this limit is represented by a yellow zone. In the red zone movement is heavily impaired.

Figure 3 represents a 1.000 m long tunnel section with fire and exhaust positions as indicated above. The situation in scenario 2 is that at the beginning the smoke is carried on by initial air movement and then sucked back after ventilation is activated. The main problem here is that the exhausts at the end of the transversally ventilated section do not provide sufficient exhausted volume so that the airflow will be reversed and the smoke is pushed back against the initial upwind direction and fills up the whole tunnel cross section up to 600 m on the left side of the fire location after first filling up 350 m on the right side.

Hence in a time period of 15 minutes an approximately 1 km long tunnel section is filled with smoke; furthermore the direction of smoke propagation is changing after approximately 5 minutes. As the tunnel has no emergency exits this might cause serious problems to people trying to evacuate, as a long tunnel section remains filled with smoke over a long period of time.

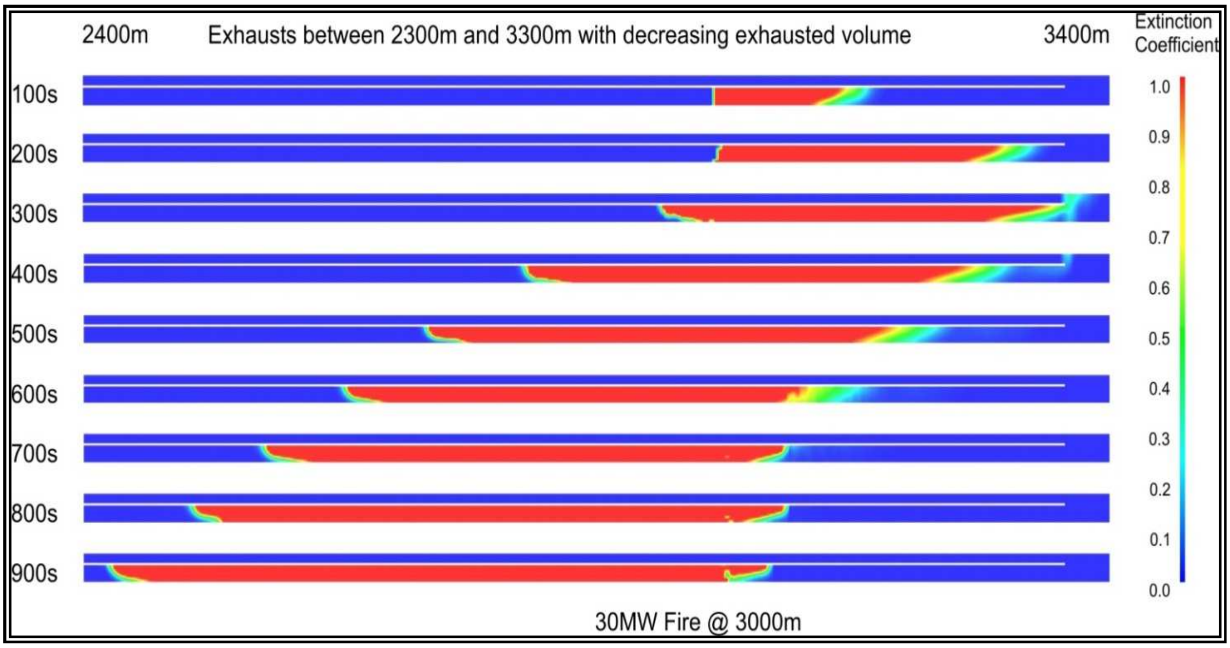

Figure 3: smoke propagation in tunnel – scenario 2

3.2 *Effects on risk*

The results of the smoke propagation simulations (concentrations of toxic fumes in dependence of tunnel location and time) were transferred to the evacuation model, thus investigating the effects on people trying to escape.

For each of the 4 scenarios and each of the fire sizes investigated (5 MW and 30 MW – according to RVS 09.03.11) specific model values were calculated, to estimate fire damage values representative for the respective scenario and in a further step for the whole tunnel. These values were implemented in the event tree to calculate risk values for the whole tunnel.

This procedure was repeated for the reference tunnel thus providing the basis for a relative risk evaluation approach. As reference tunnel a tunnel with transversal ventilation (in line with requirements of RVS 09.02.31 [6]) and emergency exits every 500 m was chosen and the simulations were repeated for this tunnel on the basis of the same traffic model.

Based on the results of the smoke propagation simulations and on the results of the evacuation simulations the following risk values were calculated for the current state of the Karawanken tunnel and the reference tunnel in step 1 (traffic data 2015):

	Total Risk EV	Mechanical	Fire	Dangerous goods
Karawanken Tunnel Reference Tunnel	0,2878	0,1611	0,1247	0,0020
		56,0 %	43,3 %	0,7 %
Karawanken Tunnel Current state (average traffic)	0,3626	0,1719	0,1883	0,0024
		47,4 %	51,9 %	0,7 %

Table 2: Risk of Karawanken tunnel and reference tunnel – current state (traffic data 2015)

The calculations refer to a traffic of 8.392 veh. / day with 17 % HGV (AADT – traffic forecast for year 2015). Hence there is a clear need for additional risk mitigation measures.

The study on “current state” of the tunnel is focussing on short and medium term measures, applicable to improve safety until the long term upgrading measures can be realized. The study on “upgrading alternatives” is addressing structural measures including improvement of the ventilation system.

This paper is focussing on parameter and measures influencing smoke propagation and consequently fire risk in Karawanken tunnel.

3.3 *Evaluation of risk mitigation measures – parameters influencing fire risk*

In the study a wide range of possible risk mitigation measures were investigated to identify and evaluate all options for risk reduction in a short, medium and long term perspective. This paper is focussing on measures influencing smoke propagation and consequently fire risk in Karawanken tunnel. The results of the investigation of the following measures are presented.

- Effects of a proper function of the existing – transversal ventilation system
- Effects of longitudinal air velocity on fire risk
- Effects of a faster activation of the ventilation in a fire scenario

3.3.1 *Effects of a proper function of the existing – transversal ventilation system*

As explained before, in parts of the transversally ventilated tunnel section the exhaust capacity of the ventilation is insufficient (see figure 3). To demonstrate the effect of a proper function, smoke propagation in a tunnel section with full exhaust capacity is shown in figure 4.

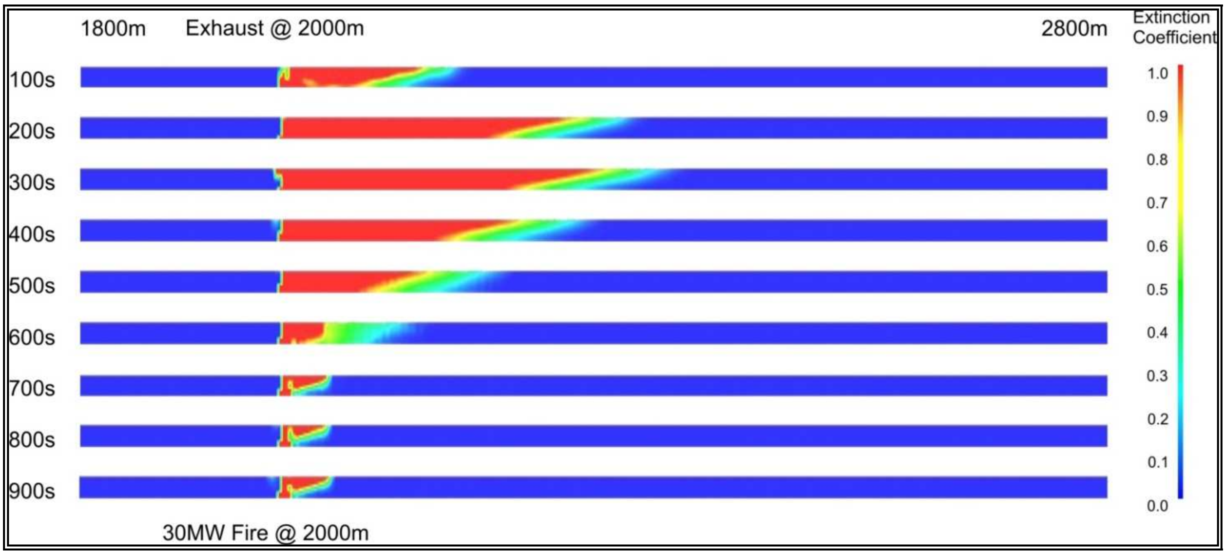

Figure 4: Smoke propagation in tunnel section with full exhaust capacity (initial velocity of 1,5 m/s)

It can clearly be seen that after full activation of the ventilation smoke is sucked back after approximately 5 minutes and almost fully exhausted after approximately 10 minutes. However, this influence is only relevant for a limited part of the transversally ventilated tunnel sections and therefore the influence on risk is not as big as the figure may indicate. A respective improvement of the ventilation in the existing tunnel (without changing the system) would reduce overall risk by 8 % and fire risk by 16 %.

3.3.2 *Effects of longitudinal air velocity on fire risk*

In figure 5 the same situation is shown with an increased longitudinal air velocity of 2,5 m/s in the initial phase (instead of 1,5 m/s – as assumed for standard situations). It can be seen in figure 5, that smoke propagates farther along the tunnel (than in figure 4) and it takes 13 – 15 minutes until it is sucked back.

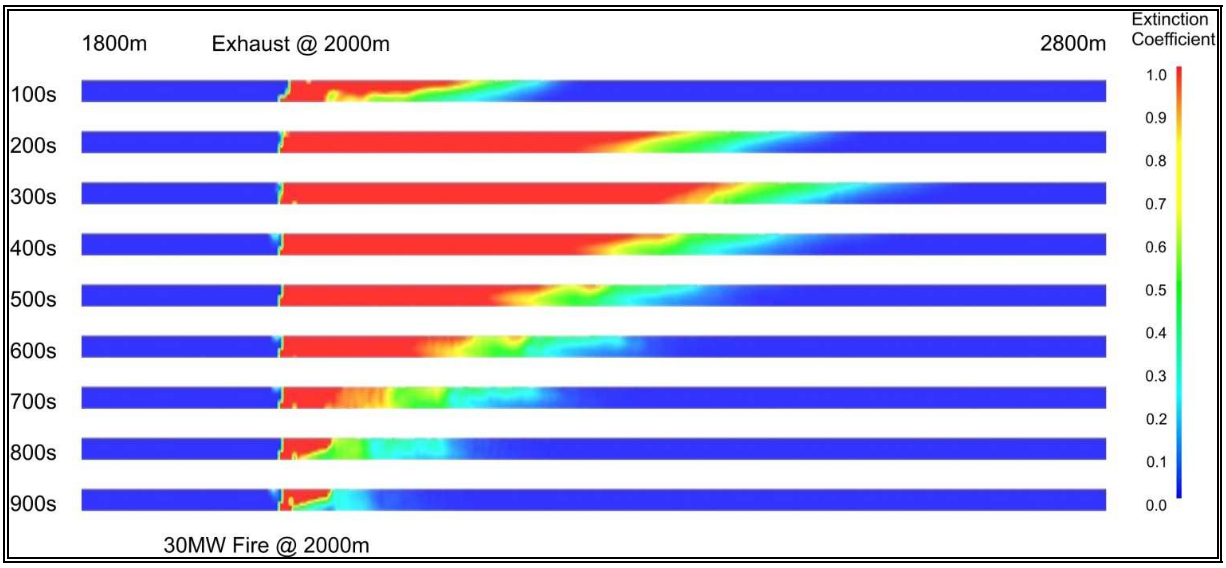

Figure 5: Smoke propagation in tunnel section with full exhaust capacity (initial velocity increased to 2,5 m/s)

Hence it can be concluded, that the prevailing longitudinal air velocity at the beginning of a fire is an important parameter for fire risk in a bidirectional tunnel like Karawanken.

3.3.3 *Effects of a faster activation of the ventilation in a fire scenario*

According to RVS 09.02.31 a detection time of 150 s and additional 180 s until ventilation being fully effective is admissible. In Karawanken tunnel measures for a faster and more efficient start of the emergency ventilation in case of a fire were developed, successfully tested and put into practice. These improvements are taken into account by reducing the overall ventilation response time to 30 seconds after fire detection in the smoke propagation model (achievable improvement on the basis of tests).

The effects are shown in figure 6 – the smoke filled tunnel section can be reduced efficiently and the smoke can be fully exhausted after approximately 6 – 7 minutes only.

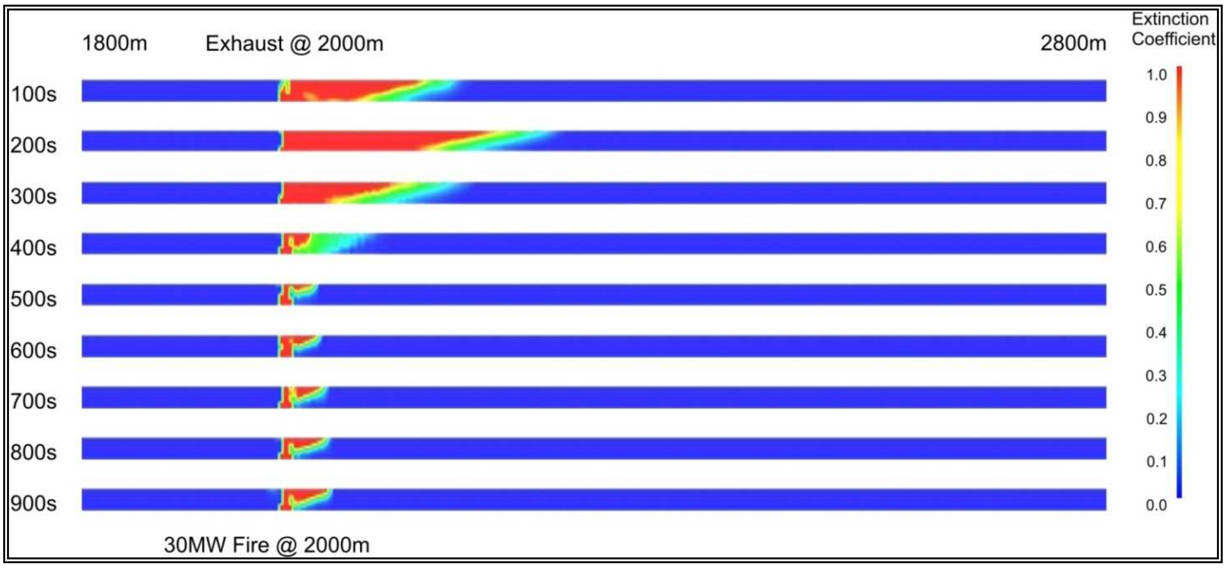

Figure 6 Smoke propagation in tunnel – section with full exhaust capacity – reduced ventilation response time

This measure would reduce overall risk by 12 % and fire risk by 23 %.

4 Conclusions

The risk analysis study for Karawanken tunnel is an illustrative example for a modern integrated, risk-based approach to tunnel safety for an existing tunnel and also demonstrates the potential of the Austrian Tunnel Risk Model TuRisMo.

- In its standard version the risk model can easily be applied for existing and new tunnels, for the assessment of the safety level of a tunnel or support for safety-relevant design decision or for the evaluation of additional risk mitigation measures.
- For advanced applications, which are beyond the application limits of the standardized model published in RVS 09.03.11 it can be extended implementing new tunnel specific sub-models for smoke propagation and evacuation simulation. Thus even complex tunnels (like tunnels with varying cross sections) complex ventilation systems (like combined longitudinal and transversal ventilation systems or local smoke extractions) or tunnels with parameters beyond usual values (like steep gradients) can be assessed individually.

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