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Numerical and Statistical Methods in Quantitative Risk Analysis of Road Tunnels

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Abstract

This paper covers the topic of tunnel risk assessment in general. It shows that by application of appropriate statistical and numerical models it is not only possible to demonstrate that the required safety level can be reached but also to compare the risk level of different designs in a relative approach. In the first section the background of tunnel risk assessment is presented to give a basic understanding of the issue followed by a description of requirements and applicable methods for the calculation of expected risk values. Finally the application of the methodology in the upgrading process of Učka tunnel is presented.

Keywords: quantitative risk analysis, tunnel risk, fire risk, consequence analysis, fire evacuation, traffic statistics, accident evaluation, expected risk, scenario analysis.

1 Introduction

Fires in underground facilities have come to public attention after a number of severe incidents (i.e. Mont Blanc tunnel fire, Tauerntunnel fire). Rapid fire development and the enclosed environment lead to poor conditions for the evacuation of people as well as for fire fighting.
Based on an EU directive on the minimal safety requirements in tunnels in the Trans European road network published in 2004 [1] various risk assessment methodologies were developed in the members of the European Union. The Austrian risk assessment model is called TuRisMo - TUnnel RISk MOdel and published in the design guideline RVS 09.03.11 [2]. It does not only cover methodologies for the assessment of fire risk but also includes an approach for the calculation of the risk coming from mechanical accidents.
In this paper the latest developments for an extended application of the methodology are present. After a short introduction into quantitative risk analysis and calculation

of expected risk values the requirements for data and simulation procedures will be analysed. Then the used methods will be explained and the application as support of the design decision for the upgrading process of an existing tunnel will be demonstrated.

2 Analysis

2.1 Preparation

In order to calculate the expected risk of a tunnel (statistically expected casualties per year) it is required to determine the potential outcome of a wide range of scenarios and scenario developments. These scenarios can either be traffic situations such as congested traffic instead of fluent traffic for example. On the other hand there are a number of factors that can greatly influence the development of a scenario such as cross section, longitudinal gradient of the tunel, etc.
Therefore these scenarios and scenario developments have to be integrated in a statistical model combining the likelihood of a certain event with the outcome of this particular event. This happens within an event tree analysis as shown in Figure 1.

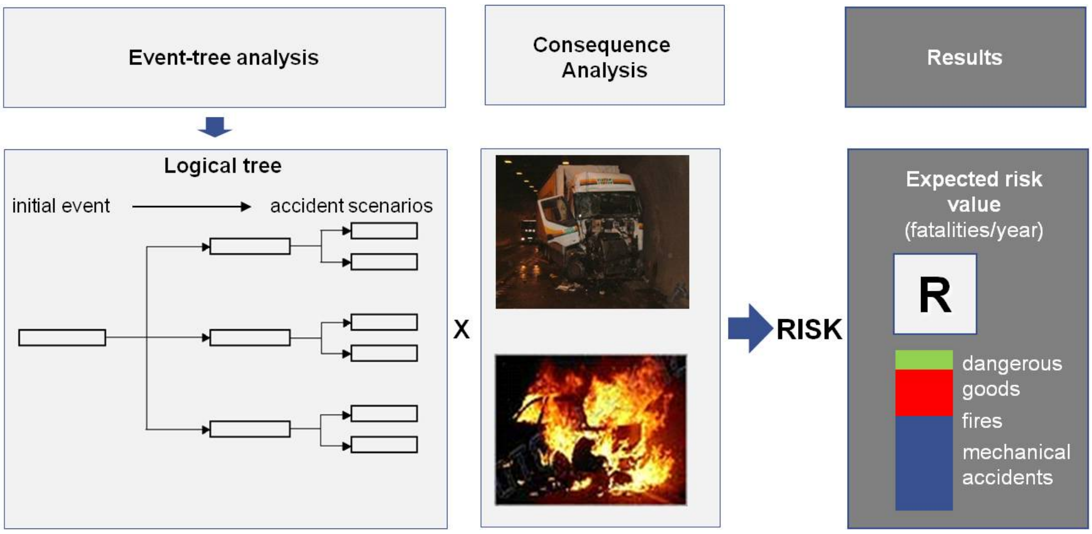

Figure 1: Calculation of expected risk values in an event tree

This means that the focus on one 'worst case' scenario or the calculation of a certain percentile of cases that define the design criteria is not a valid approach in this case especially not if different designs are assessed.
On the other hand specific consequence analysis for fires are time and resource consuming so that it is impossible to run simulations on every combination of influencing factors. Therefore the first step needs to be the selection of a number of scenarios that cover the entire range of possible scenario developments in a representative way.

This number needs to be large enough in order to assure all relevant cases are covered but small enough to keep the entire risk analysis process manageable on computational level.

2.2 Requirements

The overall risk of a tunnel can be separated in three main categories of basic incidents:

1. **Mechanical risk** - representing the risk of accidents in the tunnel that do not involve fire
2. **Fire Risk** - representing the risk of tunnel fires
3. **Dangerous goods risk** - representing the risk coming from lories carrying hazardous materials in the tunnel

While the mechanical risk can be assessed appropriately by statistic analysis of a statistically representative number of accidents over the past years the situation is entirely different when coming to tunnel fires or exposure of dangerous goods where (un)fortunately only a very limited number of incidents is documented with extremely varying outcome.
In this paper the approach for the calculation of mechanical risk and fire risk will be outlined starting with requirements for the calculation of statistic values, covering the implementation and finally showing the application in a specific tunnel upgrading project.
The risk of transport of dangerous goods in the tunnel however will not be covered within this paper.

2.2.1 Mechanical risk

For the calculation of the expected risk values of the mechanical share of risk the basic frequency of incidents in tunnels of the road network as well as the severity of incidents are required.
Furthermore different classes of mechanical events regarding the involvement of different types of vehicles and different types of collisions need to be assessed.
Regarding the involvement of different types of collisions the following scenarios are possible:

1. **Single accident** - only one vehicle is involved, i.e. crash in the tunnel wall
2. **Rear end collision** - a vehicle crashes into another from behind when travelling the same direction
3. **Front end collision** - a vehicle crashes into another from the front when travelling in opposite direction

Regarding the involvement of different types of vehicles the following scenarios are possible:

1. **Personal cars only** - in this incident class no involvement of heavy good vehicles (HGV) is assumed
2. **HGV(s) involved** - this means that one vehicle in case of single accidents or a minimum of one involved vehicles is a HGV
3. **Bus involved** - means that one of the involved vehicles is a bus or coach

Frequencies for these types of events can be derived from accident records over a long period covering a large number of tunnels in order to compensate special characteristics of individual tunnels.
In addition to accidents breakdowns of vehicles in tunnels that can lead to accidents (rear end collisions) have to be assessed as well.

2.2.2 Fire risk

While the data basis for statistic evaluation of mechanical accidents in road tunnels is relatively good (as accidents occur regularly in tunnels as well as in the open) the situation is completely different with fire scenarios. (Un)fortunately there has only been a small number of fire incidents in tunnel environments which showed a great range of different scenario developments and number of fatalities so that statistic methods cannot be applied.
Instead physical models need to be used in combination with numerical simulations based on the results of scaled fire lab tests and large scale fire tests which are either carried out in the commissioning process (<5MW corresponding a personal car on fire) or in test tunnels where high fire loads (up to 200MW corresponding the involvement of dangerous goods) can be investigated.
In the following paragraphs the strengths and limitations of the different approaches will be analyzed in order to derive general requirements for the calculation of casualty numbers for fire incidents.

2.2.2.1 Small scale model tests

Small model tests are pretty rare and connected with very complex physical and mathematical background of dimensional analysis. Some general aerodynamic analysis can be done successfully (e.g. pressure losses due to various traffic conditions), but fire testing which include real temperature gradients and fields can lead to very complex analysis with doubtful conclusions. During the design process of Sveti Rok tunnel (Croatia) estimation of critical air velocity was carried out during the isothermal model testing of ventilation system in hydrodynamic laboratories of *Brodarski Institute* in Zagreb. At that time (1998) Sveti Rok with length of 5670 m was the longest tunnel in Croatia. The critical velocity is the characteristic parameter for efficiency evaluation of longitudinal road tunnel ventilation in conditions of fire incident. During the mentioned model testing special attention was paid to the analysis of smoke distribution in the vicinity of the simulated fire source in correlation to the various heat release rates. Analysis is done on the basis of the smoke visualisation by means of helium - paraffin vapour mixture. The experimental results of the critical air velocity estimation were matched very well with the results of the ventilation systems fire tests performed in real tunnels.

2.2.2.2 On-site large scale fire tests

Fire tests in real conditions are limited because of possible damages of sophisticated tunnel equipment if on-site tests are performed on real tunnels in operation. Only controlled pool-fire tests are prescribed in some national regulations (e.g. Austrian guidelines RVS 09.02.31 [3]) in the phase of final approval of ventilation and fire detection systems. In that case fire heat release rate is limited to approximately 3,5 MW and generated by the mixture of gasoline, diesel and water. Apart from the tunnels which are part of real motorway networks, there were some complex fire tests in road tunnels, carried out with much higher heat release rates. In those cases, tunnels were testing polygons, specially customized for the testing purposes, like Memorial tunnel fire tests (1993 – 1995, USA) or large scale fire tests in Runehamar tunnel (2003, Norway). Both mentioned large scale tests, like many others in road tunnels, were focused on specifics goals and cannot be used for other purposes.

2.2.2.3 Numerical modeling

Taking account all the advantages and disadvantages of previous approaches, numerical modeling became a very useful tool for tunnel fires analysis in the last decade. Repeatable calculations with numerous possibilities of fire scenarios and unlimited combinations of input data put the numerical modeling in the first plan as the engineering method for the prediction fire development and smoke propagation. When numerical modeling is mentioned in tunnel fire engineering we generally talk about CFD (*Computational Fluid Dynamics*) or “field models”. These models, based on very complex Navier-Stokes partial differential equations, inherently simplified in solver module, offer the most accurate prediction of fluid flow in road tunnels (e.g. smoke stratification, backlayering, etc.). There are many commercial CFD software which can be used for tunnel fire analysis, like FLUENT, SOLVENT, FDS, etc. Some of them are general purposes CFDs which can be used for tunnel fire simulation and analysis after some modifications (like FLUENT). Some of them are so called “fire-driven” CFDs like FDS (*Fire Dynamic Simulator*) and some of them are specially customized for tunnel geometry like SOLVENT.
The downturn of numerical simulations is the considerable amount of computational resources as simulations have to be performed for a large domain in relatively high resolution. This is why the selection of representative scenarios for application in the statistic model is a key issue in the analysis of fire risk.

2.3 Proceeding

In this chapter the proceeding for the calculation of frequencies and severities of incidents are presented in detail covering the statistic methods for the calculation of likelihood and severity of mechanical incidents as well as the frequency of fires.

Furthermore the different factors which have influence on the scenario development and therefore casualty numbers will be listed and a procedure for the selection of representative scenarios will be demonstrated for the calculation of statistically expected fire risk.

3.2.1 Mechanical risk

As outlined in the chapter 'requirements' at first the basic frequency of accidents in tunnels of the higher road network needs to be determined. This can be done by the evaluation of accident records.

The data used in the Austrian methodology [2][4] of risk analysis is based on an evaluation of 447 accidents with injury or death of passengers in road tunnels of the Austrian motorway network. The date indicates a dependency of incident rates of the tunnel length and average annual daily traffic. Furthermore a specific frequency for each type of accident could be determined.

3.2.1.1 Basic incident frequency

Based on the accident records the following frequencies of accidents with injury or death (AID) could be determined based on the average annual daily traffic (AADT):

Bidirectional tunnels:

$$f_{AID} = \frac{1}{0.077} * (3.217 * 10^{-14} * AADT^3 - 2.209 * 10^{-5} * AADT^2 + 5.021 * 10^{-5} * AADT) \quad (1)$$

Unidirectional tunnels:

$$f_{AID} = \frac{1}{0.112} * (7.934 * 10^{-2} * \ln(AADT) - 0.6935) \quad (2)$$

Furthermore a decrease of the basic incident rate by increasing length has been found for unidirectional (twin bore) tunnels:

$$f_{CORR} = f_{AID} * \frac{1}{0.112} * (0.1081 * L^{-0.3543}) \quad (3)$$

For bidirectional tunnels no corresponding effect could be found.

3.2.1.2 Frequencies for different types of incidents

The distribution of accidents to the types of mechanical incidents as outlined in 'requirements' are shown in table 1 for unidirectional and bidirectional tunnels. It should be mentioned that the numbers represent the share of a certain type of accident of the overall accidents with injury or death in contrast to the total number of accidents.

	Bidirectional tunnel	Unidirectional tunnel
Single accident	17.34 %	39.78 %
Rear end collision	49.71 %	58.76 %
Front end collision	32.95 %	1.46 %

Table 1: Share of different types of accidents

3.2.1.3 Involvement of different types of vehicles

As for the different types of accidents the specific shares of involved types of vehicles could be determined by evaluation of the accident records. The results shown in table 2 below are valid for unidirectional tunnels as well as for bidirectional tunnels.

	Single accident	Rear end collision	Front end collision
Personal car only	90.60 %	63.56 %	37.70 %
HGV involved	9.30 %	34.42 %	59.02 %
Bus involved	0.1 %	2.02 %	3.28 %

Table 2: Share of involvement of different types of vehicles

As these results are valid for a composition of vehicles containing 76.5 % personal cars, 20.0 % HGVs and 3.5 % busses the numbers have to be corrected for the actual composition of vehicles in a given tunnel S_{Pers}, S_{HGV} and S_{Bus}. The correction factors are shown in table 2. Is has to be noted that the normalisation is disrespected on purpose in this branching of the event tree. This is taking into account that incident rates increase with the share of HGVs.

	Single accident	Rear end collision and Front end collision
Personal car only	$\frac{S_{Pers}}{76.5}$	$\frac{S_{Pers}^2}{76.5^2}$
HGV involved	$\frac{S_{HGV}}{20.0}$	$\frac{S_{HGV}^2 + 2 * S_{Pers} * S_{HGV}}{20.0^2 + 2 * 76.5 * 20.0}$
Bus involved	$\frac{S_{Bus}}{3.5}$	$\frac{S_{Bus}^2 + 2 * S_{Pers} * S_{Bus} + 2 * S_{HGV} * S_{Bus}}{20.0^2 + 2 * 76.5 * 3.5 + 2 * 20.0 * 3.5}$

Table 3: Correction factors for given composition of vehicles

3.2.1.4 Severity of incidents

In addition to the frequencies described in the previous points the severity of the different types of incidents is needed in order to calculate the mechanical share of

the expected risk. The numbers given in table 4 and table 5 show the average fatalities per accident with injury or death. Table 4 contains the numbers for bidirectional tunnels and table 5 the numbers for unidirectional tunnels.
These numbers are valid for speed limits of 80 km/h in bidirectional traffic and 100 km/h in unidirectional traffic. In case of deviating speed limits in the tunnel the numbers have to be adapted based on kinetic energy models.

	Single accident	Rear end collision	Front end collision
Personal car only	0.138	0.019	0.250
HGV involved	0.083	0. 419	0.429
Bus involved	0.100	0.100	0.750

Table 4: Severity of accidents in bidirectional tunnels

	Single accident	Rear end collision	Front end collision
Personal car only	0.175	0.010	0.250
HGV involved	0.083	0.093	0.429
Bus involved	0.100	0.100	0.750

Table 5: Severity of accidents in unidirectional tunnels

3.2.2 Fire risk

Depending on the traffic volume and the tunnel's characteristics different environmental conditions (airflow in the tunnel) can be found in the tunnel having a great influence on the resulting risk in case of a fire incident. In addition to the conditions at the beginning of the incident (initial conditions) the development of the longitudinal airflow is important when performing simulations of smoke propagation in the tunnel [5].

3.2.2.1 Calculation of longitudinal airflow

The longitudinal airflow in a tunnel is influenced by a number of different characteristics and times a certain action is taken. Some of these characteristics can be implemented in a three dimensional simulation environment (i.e. cross section, gradient, etc) but others cannot be taken into account unless the mesh resolution is increased to an unmanageable level. Examples for those are the aerodynamic parameters of vehicles or the drag at the tunnel walls.
To overcome this situation the numerical model is separated into an one dimensional global model and a three dimensional local model. The global model contains all tunnel characteristics which have an influence on the resulting initial airflow and the development after the incident happens. An overview of influencing factors is shown in figure 2. Constants such as the aerodynamic parameters of vehicles or the drag on the tunnel walls are selected based on national guidelines.

3.2.2.2 Calculation of smoke propagation

After calculation of the development of the longitudinal velocity is calculated as described above the results are applied in terms of boundary conditions in the three dimensional simulation environment. Care has to be taken that the mesh boundaries are far enough away from the fire location that the smoke stratification which can be obtained in the three dimensional environment is not influenced by the boundary conditions (where the flow field is equally distributed over the entire cross section). The simulation environment used in the risk analysis is Fire Dynamic Simulator (FDS) developed by the National Institute of Standards and Technology. It is based on a finite differences code and is capable of dealing with different species of gas and thermal gradients.

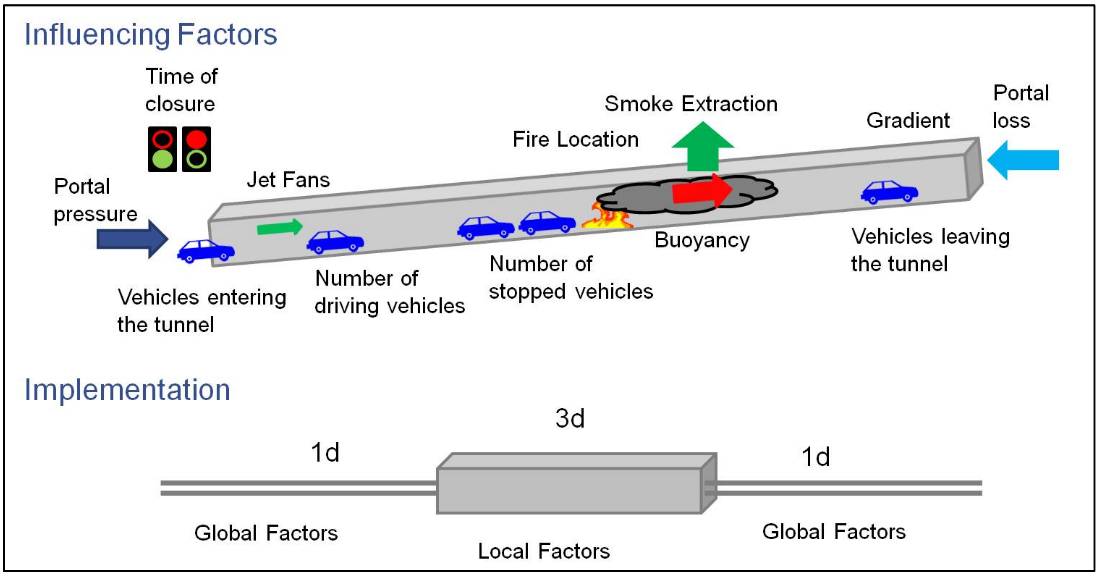

Figure 2: Influencing factors for calculation of airflow in tunnel

The results of the three dimensional simulation of smoke propagation are the concentrations of different species of flue gases and visibility parameters as well as the temperature depending on the location in the tunnel and the time after the initial event. These are used in a latter step to compute casualty numbers by means of evacuation simulation tools.

3.2.2.3 Simulation of evacuation of people

For the simulation of the self rescue process of people in the tunnel a one dimensional evacuation tool is used based on the theory of David Purser [6][7][8][9] on the toxicity gases. It is an accumulation based toxicity model which means that a short but high concentration of gases does not necessarily lead to failure of self rescue in contrast to limit based models where this could be the case. This is an important issue when comparing different ventilation systems (longitudinal ventilation vs. transversal ventilation) where the duration of exposure can be limited. The following hazards that occur in a fire incident in a tunnel can be taken into account in the evacuation simulation.

Intoxication by carbon monoxide:

$$FICO = \frac{3.317 \times 10^{-5} \times CO(t)^{1.036} \times RMV}{PID} \quad (4)$$

Intoxication by hydrogen cyanide:

$$FICN = \frac{e^{\frac{HCN(t)}{43}}}{220} \quad (5)$$

Intoxication by carbon dioxide:

$$FICO_2 = \frac{1}{e^{6.1623 - 0.5189 \times CO_2(t)}} \quad (6)$$

Effects of hypoxia (lack of oxygen):

$$FIO_2 = \frac{1}{e^{8.13 - 0.54 \times (20.9 - O_2(t))}} \quad (7)$$

Increased respiratory volume by increased concentration of carbon dioxide:

$$VCO_2 = e^{\frac{CO_2(t)}{2}} \quad (5)$$

The overall intoxication at a given time is obtained by integration over the total time of exposition:

$$FIN = \int_{t_{\exp}} \left(FICO + FICN + FICO_2\right) \times VCO_2 + FIO_2 \, dt \quad (8)$$

In addition to the effects of toxic gases the effects of radiant and convectional heat is taken into account:

Convective heat:

$$FIH_C = 2.0 * 10^{-8} \times T(t)^{3.4} \quad (9)$$

Radiant heat

$$FIH_R = \frac{60 \times q(t)^{1.33}}{D_r} \quad (10)$$

The total effect of heat at a given time is obtained by integration over the total time of exposition:

$$FIH = \int_{t_{\exp}} \left(FIH_c + FIH_R\right) dt \quad (11)$$

Furthermore the impairment of flue gases, heat and poor visibility have negative influence on the agents' egress velocity [10]:

Effects of intoxication on agents' mobility:

$$M_I = \begin{cases} 1, FIN \in [0; 0.9[\\ 0.9, FIN \in [0.9; 0.95] \\ 0.8, FIN \in]0.95; 1] \end{cases} \quad (12)$$

Effects of poor visibility on agents' mobility:

$$M_S = 1.105 - 0.488 \times K - 0.161 \times K^2 \quad (13)$$

Total influence of intoxication and poor visibility on agents' mobility:

$$V = V_I \times M_I \times M_S \quad (14)$$

If one of the impairing effects - total intoxication or heat - reaches the threshold of 1 the agent is incapacitated and the egress cannot be completed without assistance.
For the calculation of representative results different types of agents (people in evacuation models) have to be defined. These include differences in walking speeds of male and female as well as reduced walking speed of elderly people. In the simulation a total of 18 different agents is assessed and the results averaged according to the population.
The entire evacuation simulation is re-run by moving the fire location (and therefore the concentrations of gases) along the tunnel axis while holding the location of the emergency exits constant. This is done in order to achieve average results as the fire rate is distributed equally over the tunnel length.

3.2.2.4 Selection of representative scenario locations

Depending on the tunnel characteristics a certain number of different scenario locations has to be simulated in order to calculate representative results for an average tunnel fire. This can be because of punctual exhausts, changes in the cross section or a change in the gradient.
One important factor however is true for every tunnel. This is the fact that depending on the incident location in the tunnel the traffic influence (piston effect of moving vehicles) is different as well as the number of vehicles queuing behind the fire location (length of congestion corresponds to number of people in endangered zone). This is why at least two incident locations should be taken into account on CFD and evacuation level when performing a risk analysis for unidirectional tunnels. In case of bidirectional tunnels the influence is even higher; an asymmetry (fire location out of tunnel's midpoint) can lead to a reverse of airflow or significant increase of velocities.

3.2.2.6 Selection of representative traffic scenarios

In a first step the traffic data for the tunnel needs to be analyzed. This data can either come from an automatic counter in close proximity of a tunnel project, measurements in an existing tunnel or the prediction based on specific time variation curves for day, week and year. For further use as basis for the selection of representative scenarios the data is converted into a histogram.
If the aim is to perform 3 sets of three dimensional simulations of smoke propagation the normalized area under the graph needs to be divided by 3 and the scenario to be simulated has to be the center of the section. These three scenarios will be used as representative for low traffic, medium traffic and high traffic.
Additionally a histogram of the incident rate is generated by multiplying the histogram of hourly traffic load by the traffic volume. Other parameters such as the share of HGVs or share of busses can be taken into account the same way if the data is available. Examples for these histograms and averaged values used for the representative scenarios are shown in figure 3.

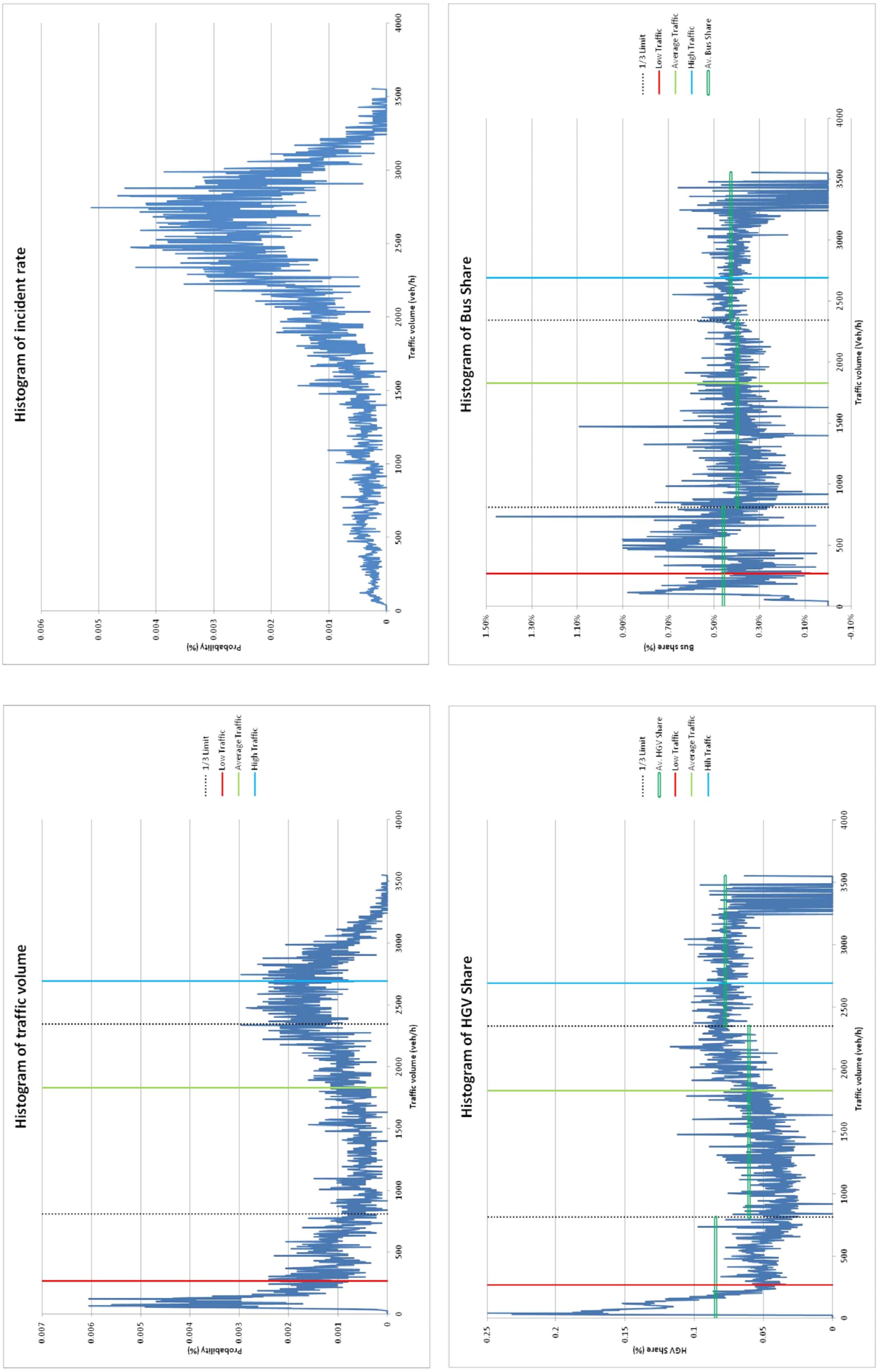

Figure 3: Histograms of traffic volume, incident rate, HGV share and Bus share

In case of bidirectional traffic the distribution of traffic onto the two directions has to be assessed the same way as the traffic load. For each of the basic traffic scenarios at least 3 sub scenarios should be simulated for symmetric and asymmetric traffic.

3.2.2.6 Averaging process for representative casualty numbers

Even though the process of averaging in order to achieve has been mentioned already in each section the entire process is summarized in the following two figures. Figure 4 shows how the casualty numbers of the representative traffic scenarios are interpolated and averaged weighted with the frequency of fire incidents for the specific traffic volume. Figure 5 shows the process of obtaining the average casualty numbers for the representative traffic scenarios.
The numbers finally obtained correspond to the numbers given in table 4 and table 5 for the severity of mechanical incidents.

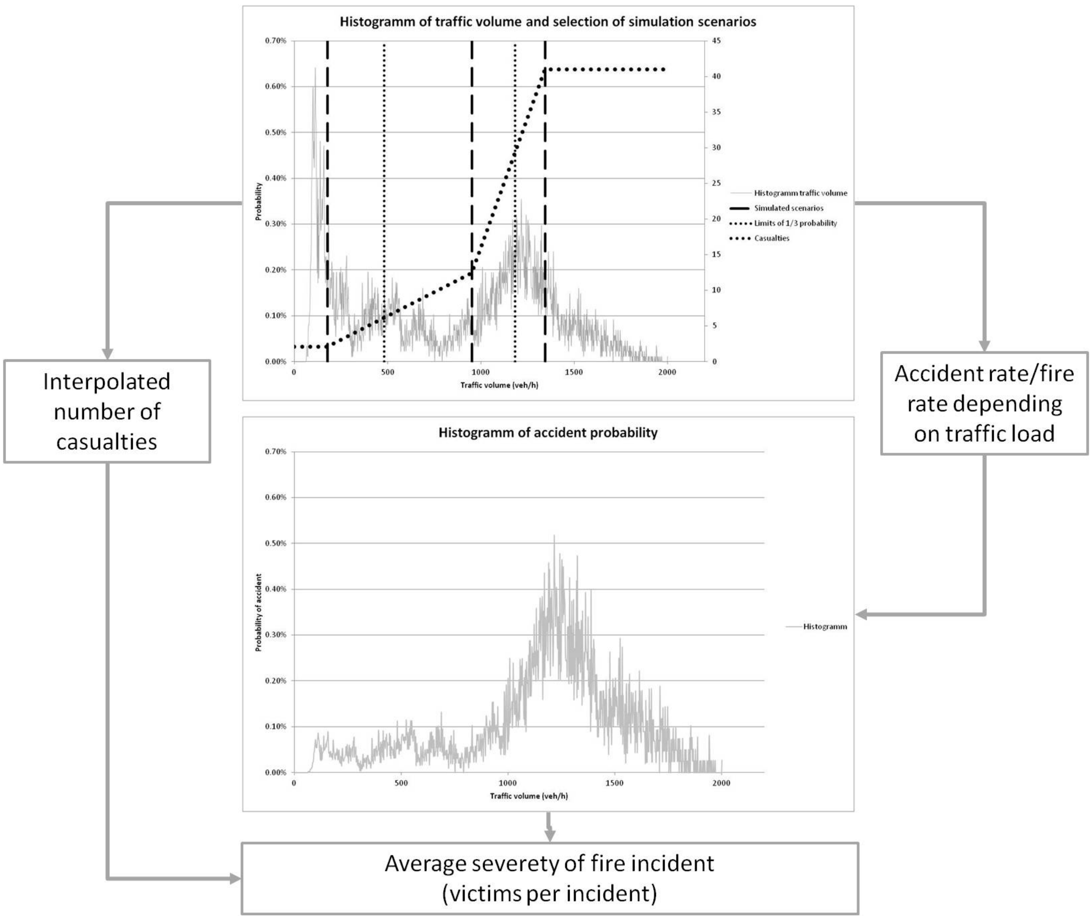

Figure 4: Procedure of calculating average casualties for a given traffic distribution

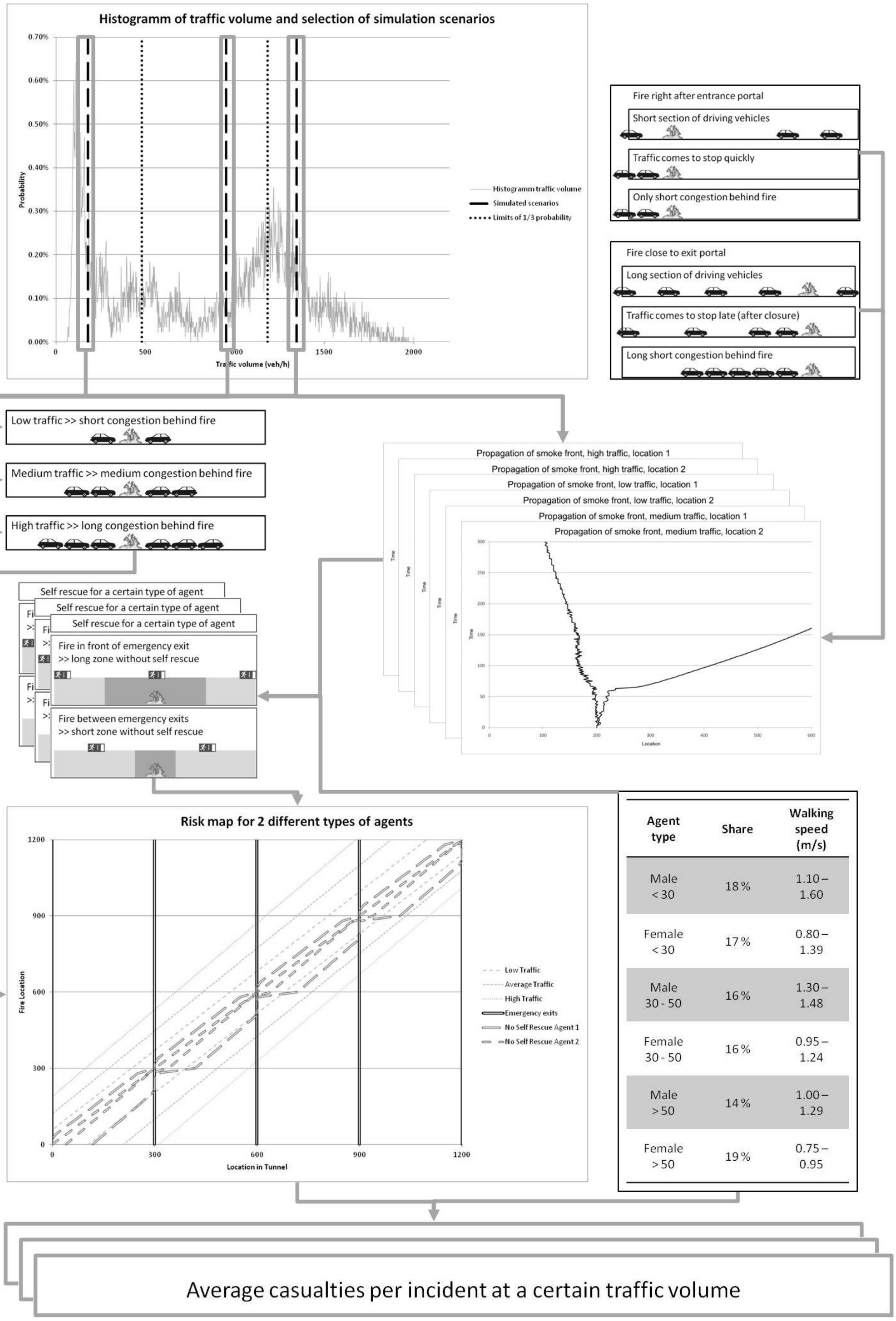

Figure 5: Procedure of calculating average casualties representative traffic scenarios

3 Application for risk analysis of Učka Tunnel

3.1 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. A risk assessment study performed in 2011 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.

3.2 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. 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 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:

1. **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
2. **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

3.3 The results

3.3.1 Consequence values for fires

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

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

Table 5: Average casualty numbers (fatalities per incident) for longitudinal ventilation (LV) and 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:

1. 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.
2. 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.

Fire Size	5MW	30MW	100MW
Direction Istria	0,2	0,8	12,4
Direction Kvarner	0,4	0,8	13,3

Table 5: Average casualty numbers (fatalities per incident) with additional safety measures

3.3.3 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.

These results can be commented as follows:

1. The fire risk in the new Učka Tunnel is very low (approximately 2,0 – 2,5 %);
2. 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.
3. 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.
4. 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.
5. 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.

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