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EXPERTS IN FLUID ENGINEERING

Methodologies for accurate risk modeling in the context of integrated quantitative risk analysis

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ABSTRACT

In this paper the basic methodologies implemented in the new Austrian Risk Model for motorway tunnels are presented. The fundamental structure is based on the variation of the most important influencing factors using distribution density functions of recorded data allowing highly accurate risk assessment of road tunnels. The statistical methodologies presented in this paper are aimed to increase the depth of the analysis without overly increasing the computational demands in order to assess all kinds of special characteristics of a tunnel.

1 BACKGROUND AND OBJECTIVES

1.1 Motivation and objectives of the study

Since the implementation of the EC-Directive 2004/54/EC (1) and its corresponding Austrian federal law on tunnel safety (2), big efforts have been made in the refurbishment of existing road tunnels in the Austrian motorway network in order to fulfil the required safety standards. However, due to the fact of structural limitations in the refurbishment of existing tunnels, deviations in single paragraphs cannot be avoided. In this case these deviations can be accepted if the additional risk is compensated by additional safety measures. The equality of compensating safety measures needs to be proven by the means of quantitative risk analysis.
As the complexity of tasks increased the existing risk assessment methodology TuRisMo (3) showed to be insufficient. This was the starting point for the development of a high accuracy integrated risk assessment tool as an update the existing methodology which is published in the new guideline RVS 09.03.11 (4) and a background report (5) that documents the applied methodologies.

The objectives for the new risk model were:

- The possibility to cover a large number of cases in order to allow for a variation of important influencing factors such as traffic volume, traffic asymmetry (in case of bidirectional tunnels) and accident location

- The coverage of consecutive events – i.e. rear-end collisions at the end of the queue behind a traffic disruption, which may contribute considerably to fire risk in long unidirectional tunnels
- The implementation of a multi-scale (one dimensional combined with three dimensional) flow model. The longitudinal flow conditions (initial velocity and unsteady flow development after the traffic disruption and fire start) are simulated in a realistic way in a one dimensional CFD model. This gives the boundary conditions for the three dimensional simulations
- A statistically correct representation of the assessed ventilation system and all its components (jet fans, exhaust dampers, sensors, etc.) as well as the ventilation program and ventilation strategies for different sectors
- The use of an accumulative intoxication model for assessment of self-rescue limits
- The possibility to assess additional safety measures which work in the reduction of people in the endangered zone. These can be improved incident detection systems to reduce the time until tunnel closure as well as means to make the closure be respected faster (i.e. barriers in addition to red lights which usually are not respected immediately)
- Comparability with a reference tunnel which fulfils all requirements according to (2) – e.g. a $1200\,m$ long tunnel should be simulated with an average distance between emergency exits of $500\,m$. This means in reference tunnels the statistical density of emergency exits shall be used while in real tunnels the accurate position of emergency exits is used (i.e. the $1200m$ long tunnel would have 1.4 emergency exits which cannot be built in reality)

The model should allow assessing different types of safety relevant deviations from the design guideline and different ventilation systems. These can be point extraction, transversal ventilation and longitudinal ventilation by jet fans or momentum injection. Different geometric parameters such as cross section and longitudinal gradient should be included in the analysis as well. Furthermore the large number of cases to be assessed required a fully integrated approach with possibility of quality control on all levels of the simulation process.

2 REQUIREMENTS FOR THE INTEGRATED RISK MODEL

Based on the objectives for the new risk model the requirements for the basic structure of the Integrated Risk Model were defined and the submodels for the correct implementation of the influencing factors in each step were selected.

Each of the submodels represents one specific aspect of the risk analysis. In order to perform a comparable and accurate analysis the risk model is based on the following sub models:

- **Grid Setup**
  Grid Setup represents the selection of the assessed scenarios in the overall workflow. For each variation parameter a pre-defined number of cases are selected based on the underlying distribution density of the parameter. For the traffic density this distribution density is the distribution of hourly traffic over a sufficiently long observation period.
- **One dimensional CFD simulation**
  These simulations determine the initial velocity (longitudinal velocity at the time of the initial traffic interruption) and the unsteady development of the longitudinal

velocity after the interruption. This gives the boundary conditions for the following three dimensional CFD simulations.

- **Three dimensional CFD simulation**
  Based on the velocity development determined in the one dimensional CFD simulations the smoke propagation in the three dimensional environment are simulated covering aspects as backlayering and smoke stratification according to the local geometry (cross section and inclination). This gives concentrations of flue gases which are the input parameter for the following evacuation simulations.
- **Evacuation simulation**
  In the evacuation simulation the distance a certain person can cover under the circumstances (gas concentrations) determined in the three dimensional CFD simulation are computed. This needs to be performed for a certain number of agent types with different walking speed and incapacitation limits.
- **Mapping process**
  In the mapping process the maximum evacuation distances determined in the evacuation simulation are projected onto the tunnel and the given locations of emergency exits. This gives the mortality rate for each meter of the tunnel. Multiplication of this mortality rate with the exposure (i.e. statistically expected density of people in the tunnel) results in the number of fatalities for the assessed scenario.
- **Data collection**
  In the data collection step the fatalities computed for each of the different scenarios are multiplied with the basic probability of the scenarios and summed up. The resulting number represents the statistically expected number of fatalities.

In the following chapter the requirements for each of the sub models of the Integrated Risk Model are defined:

2.1 Grid Setup

In contrast to a classic Monte Carlo simulation where the set of parameters for one specific random test is generated as a random draw of a distribution density the selection of scenarios in this model is based on a regular pattern in the density distribution. This means that two tunnels with the same traffic characteristics (normally the assessed tunnel and the applicable reference tunnel) will get precisely the same parameters for the corresponding scenarios. The reason for this slightly different approach from classic Monte Carlo is the fact that in order to achieve full comparability between the two tunnels in the total risk values full comparability of each scenario with the corresponding scenario of the reference tunnel is needed.

2.2 One dimensional CFD simulation

The purpose of the one dimensional CFD simulation is the precise calculation of the initial conditions (steady conditions at the time of the first traffic disruption) and the unsteady development thereafter to be used as boundary conditions in the following three dimensional CFD simulations. This level includes all parameters that cannot be implemented in a three dimensional model in an accurate way (or only with extreme effort, i.e. moving mesh etc.) such as the piston effect generated by moving vehicles or the flow resistance on tunnel walls and internals (laybys, traffic signs, etc.). Another effect which has to be taken into account in the one dimensional model is the ventilation system in its integral functionality. This means all components have to be switched during the simulation process in a logical (statistically correct) waymeaning that the resulting flow velocity developments should be idealized average developments. Too high oscillation of the longitudinal velocity can again lead to incomparable results between the same scenario in the real tunnel and the reference tunnel.

2.3 Three dimensional CFD simulation

The three dimensional CFD simulations are used to examine local effects such as smoke stratification and turbulent smoke propagation on the downstream side of the fire as well as the assessment of possible backlayering effects on the upstream side. The requirements here are the possibility to define time-dependent functions for all different types of ventilation equipment and fire source terms for different types of toxic gases. The implementation of the function of firefighting equipment in the CFD model is necessary if deluge or water mist systems shall be assessed.

2.4 Evacuation simulation

The most important requirement for the simulation of the self-rescue process is the use of an accumulation based intoxication model. Limit based models (i.e. evacuation fails if a certain threshold for visibility or temperature is reached) have shown to be inaccurate in case of extraction systems. The reason for this is that a person might be able to survive a few seconds in conditions that are much worse than according to the selected threshold as long as the time of exposure is limited but the limit based self-rescue model concludes that egress fails. Another requirement for evacuation simulation is the possibility to define a number of different agents with a variation of evacuation specific parameters such as walking speed and intoxication limits.

2.5 Mapping process

In the mapping process there are two main tasks to be performed. The first task is the determination of the representative distribution of emergency exits for a person starting at a location x relative to the fire. More precisely the distribution of possible distances to be covered has to be computed. In combination with the distances people during egress can cover this gives the probability of death for a person at a given location. The second task is the calculation of a representative density of people in the tunnel. While the first task defines the zones with endangerment the second task gives the exposure. Multiplication of exposure and endangerment then results in the risk for the specific scenario.

2.6 Data collection

Naturally the results (fatalities) of all the scenarios have to be collected and summed up weighted by their probability. The results are specific risk value (number of fatalities) for the assessed tunnel as well as for the reference tunnel. These are computed for each fire size and for each assumed case of system failure and emergency exit configuration. The final step of calculating the overall risk values for the tunnel can be done in a spreadsheet using event trees.

3 IMPLEMENTATION OF THE SUB MODELS USED IN THE ANALYSIS

In this section the used sub models will be presented in detail. To give a better idea of the concept behind each presented sub model application examples will be included at the

end of the paper but the focus will be on the theoretical methodologies and statistical modeling.
The basic aim of the entire structure of the risk model has to be to minimize the computational demands and at the same time maximize the accuracy of the analysis.
Furthermore two different levels of accuracy in covering the distribution density functions have been implemented to allow better coverage by a fine pattern in computationally not overly demanding sub models as mapping and a more coarse pattern in case of the highly demanding three dimensional CFD simulations.

3.1 Grid Setup

The total number of simulations required for a risk analysis of a tunnel project depends on various aspects and can be basically divided into two different levels:

1. Independent scenarios such as positive and negative direction in unidirectional tunnels, different fire sizes or system failure. The results of these scenarios will be summed up in the last step of data collection and weighted according to their basic probability.
2. A sufficiently large number of sub scenarios for each of the independent scenarios in order to calculate representative risk values taking into account the large variance of parameters observed over a year of operation.
   The most important parameters to be subject of a variation are the incident location, traffic and in case of bidirectional traffic the degree of asymmetry of traffic. Other parameters that can be varied are the time of closure (basically affecting the total number of vehicles in the queue and the likelihood of consecutive events) and meteorological influences.
   If consecutive events (a rear-end collision at the end of the queue after a primary accident without ignition) shall be assessed the time delay between the first incident and the secondary event has to be varied as well. Here it needs to be stated that particularly in the case of unidirectional tunnels these secondary events are the key factors for an accurate risk analysis. This is becausein case of fire ignition at the location of the primary accident (top end of the queue) and a properly designed ventilation system there are no people in the endangered zone (downstream side of the fire).

While the scenario setup in case of point one is rather obvious the selection of representative sub scenarios requires in depth analysis of given data for the tunnel project to be assessed. The procedure of scenario selection will be briefly presented in the following paragraphs. For more detailed information on this procedure, please refer to the author’s previous publication (6).

Besides the location of the primary accident (which is again a quite obvious variation parameter) the most important parameter to be varied is the traffic volume which is the main influencing factor for the initial flow conditions in the tunnel. Except for the initial conditions it also influences the transition phase from undisturbed traffic at the beginning of the event to completely stopped traffic in the tunnel and also the total amount of drag in the tunnel that needs to be compensated by the tunnel’s ventilation system.
Ideally the process starts with the analysis of recorded data of a permanent traffic counting station in the vicinity of the tunnel. This does not mean it has to be exactly at the tunnel’s portals or in the tunnel itself. It can be some kilometers away from the tunnel but should definitely show the same traffic characteristics. This means the morning peaks at the position of the counting station shall match the (expected) morning peaks in the tunnel etc. In case the total traffic volume does not match (which is particularly the case

for risk analysis for a defined year ahead) the distribution can easily be adapted. If no recorded data is available then characteristic traffic curves (day curves, week curves and year curve) can be used in order to rebuild the distribution density of hourly traffic volume.
This distribution density function for hourly traffic volume is the key for the selection of representative sub scenarios in the parameter variation of traffic. The use of AADT is not a valid approach if realistic flow conditions shall be assessed. The only use of AADT in this submodel is the adaption of given traffic data to the absolute traffic values.
Once this distribution density is set up the area can be divided into a number of equally large segments and in the center of each segment the simulation scenario is located. The probability of each sub scenario is then defined by the total quantity of vehicles-hours in these segments (not equal to the segment size as this only gives the frequency of hours within the specific range of hourly traffic and not the frequency of events). The reason for scenario selection based on the frequency of occurrence and not the frequency of events is due to the fact that the initial velocity does not increase in linear sense and therefore the variation of conditions is higher in the left side of the distribution density function. Another valid approach would be evenly distributed simulation cases in the distribution density but this would require a larger number of scenarios.
In case of bidirectional tunnels the asymmetry of traffic in another crucial factor for the initial velocity as well as for the development in the transition phase from flowing traffic to stopped traffic, particularly in combination with the location of the primary incident. While the flow velocity can increase in one situation it can be reduced or even reversed in another. Therefore the asymmetry of traffic has to be assessed carefully, which results in a number of asymmetry cases for each traffic case. The selection of asymmetry cases is performed the same way as the selection of traffic cases based on recorded data or characteristic curves. Please note that each of the traffic cases has one independent distribution density function of asymmetry.
If wind shall be taken into account it is important to perform a coupling of traffic volume and wind. The reason therefore is that in most location wind effects are both seasonal and daytime dependent (winter storms and valley wind systems). The coupling factors in this case are month and daytime. If possible wind data from more than one year shall be used to prevent singular events (such as heavy weather phenomena at a given day) affecting the results of the risk analysis. Only in cases where the weather phenomena do not depend on season and daytime weather can be seen as an independent variation parameter.
As with wind and weather phenomena the detection time can either be an independent variation parameter or be a function of the hourly traffic volume. This is the case if one or more components of the detection system work based on the length of the formed congestion (induction loops detecting congested traffic) or similar systems like vehicle counters. In the latter case the coupling shall be performed in a similar way as with traffic asymmetry.
As a general statement regarding the selection of sub scenarios for a representative coverage of the entity of possible sets of parameters it has to be mentioned that the total number of sub scenarios for each of the independent basic scenarios is the product the of case numbers in each variation parameter. So if one chooses to cover 3 traffic volumes with 3 asymmetry cases each, 3 wind cases and 3 delay times (or detection times) the total number of cases is 81 for each fire size and failure case which can cause big computational demands on the level of three dimensional CFD simulations.

3.2 One dimensional CFD simulation

As the topic of one dimensional flow simulation is well understood and widely applied in ventilation design only a brief overview of requirements will be presented in this section.

The main difference between the requirements for ventilation design and risk analysis is the fact that for the latter an unsteady solver has to be used. This is becausethe aim is to calculate the development of the longitudinal airflow in the tunnel based on the development of the influencing factors. On the other hand, in ventilation design for most purposes a steady solver is sufficient.

In this aspect ‘statistically correct’ assumptions have to be implemented for the switching of the components of the ventilation system. This means that all high frequency effects in the resulting longitudinal velocity (oscillations due to switching of fans) have to be eliminated in order to achieve an in fact unrealistically good match of the desired target velocity (in reality there will always be oscillations). If this was not the case there would be areas in the vicinity of the fire location where the lethality rate is overestimated and other areas where the lethality is underestimated resulting in unpredictable instability of the results and therefore leading to incomparable risk values. One advantage in the theoretical study which allows for this ‘perfect’ ventilation program is the fact that in contrast to a real tunnel environment the ‘measurement’ of the longitudinal velocity is not disturbed by local effects.

On the other hand system specific restrictions such as a time delay in between the activation of single jet fans (unless frequency controlled) has to be taken into account as this is a systematic effect in all cases (restricted by power supply).

By this approach the limits of the ventilation system can be assessed, which is particularly important if fire loads higher than the design limits shall be included in the risk analysis, without the downturn of fuzzy effects which can occur in case of overly correct modeling. In other words the *statistically expected position* of a volume element (over slightly different switch times, jet fan positions etc. in fire scenarios at slightly different locations) has to be computed.

3.3 Three dimensional CFD simulation

With the three dimensional CFD model there are two important aspects that need to be mentioned in this paper while the standard application of the used simulation program FDS (Fire Dynamic Simulator) (7)will be left aside. These aspects are:

1. The application of boundary conditions derived from the one dimensional flow simulation and the required length of the simulation domain
2. A modified way to define the fire growth in order to achieve realistic smoke stratification during the fire growth phase particularly at low longitudinal velocities
3. The statistically correct positioning of components of the ventilation system and statistically expected vehicle arrangement (vehicles in queue behind the fire location)

3.3.1 Application of boundary conditions and domain length

The application of boundary conditions derived from the one dimensional CFD simulations as well as the total domain length is based on the fact that FDS uses an incompressible formulation of the Navier Stokes equations. This means that no matter how long the defined domain of the three dimensional CFD environment is a change of velocity at the domain boundary will have an immediate effect onto the entire domain. Virtually the speed of sound in an incompressible system is infinite. The consequence is that the user may define the domain length based on other considerations than inertia and wave propagation (which does not exist in incompressible systems apart from numerical instabilities).

On the upstream side of the tunnel the selected domain length is based on two considerations:

1. The accumulation of toxic gases during the evacuation process of a person shall be calculated over the entire evacuation path. This means that either at least one maximal distance of emergency exits needs to be covered unless the smoke does not reach that far on the upstream side.
2. The boundary conditions can only be applied in a distance to the fire which is not affected by backlayering effects any more. This is due to the fact that application of boundary conditions is homogenous over the entire vertical range meaning effectively the destruction of smoke stratification and smoke being 'sent back into the domain' evenly distributed over the entire cross section.

These two criteria are more or less equivalent but in application it is rather difficult to estimate the length of the affected range upstream of the fire. A good estimate is given by the integral over the difference between critical velocity and observed velocity (from the one dimensional simulation) over time. Another quite pragmatic approach which also allows for direct comparison of slice files (longitudinal cuts through the domain) is used in the described project:

- One time the maximal distance between emergency exits (or a minimum of $500m$) on the upstream side and three times the same distance on the downstream side in unidirectional tunnels
- Two times this distance on the upstream side as well as on the downstream side in bidirectional tunnels

This means that the total domain length can be longer than the assessed tunnel itself. The reason for this fact will be described later in the description of the mapping process. Naturally on no side of the fire the domain length needs to be longer than the tunnel.

3.3.2 Modified fire definition for realistic fire growth

When defining a fire in FDS there are different options but the preferable way is to define a fire with given source terms for different gas species with individual ramps (time dependent functions) is the use of $VENT$ objects. While the global effects (mass terms in the domain and total heat release) are correct defining one single $VENT$ for a fire during the growth phase this leads to locally faulty results.

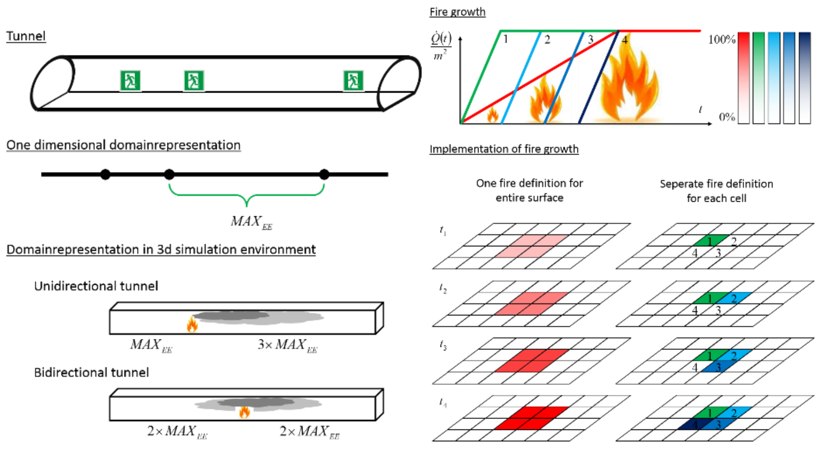

Figure 1. Domain representation (left) and fire growth (right) in 3D environment

The reason for this is that in the initial phase a rather small heat release is spread over a quite large area meaning that the plume formed by the buoyancy is incorrect preventing the smoke (soot and toxic gases) to rise to the ceiling.
This effect occurs particularly with low longitudinal velocities which are found in bidirectional tunnels.This unphysical effect can be rectified by defining a number of separate small $VENT$ objects with time delayed individual fire ramps. This is emulating the option of circular fire growth which is an option in FDS but lacks the flexibility of $VENT$ objects. The separate fire cells are ignited in form of a spiral. The application of this approach is shown in Figure 1.

3.3.3 Statistically correct positioning of components of the ventilation system and statistically expected vehicle arrangement

While basic influencing parameters such as traffic volume and asymmetry, location etc. can be varied in order to achieve representative results in the risk analysis process other local phenomena have to be arranged in the statistically correct way in order to get the average situation in a single scenario. The most important phenomena are the positioning of the components of the ventilation system and vehicle arrangement but can also include large single traffic signs (overhead direction indicators) or regularly arranged signs.
In case of components of the ventilation system the two big classes are components with a defined position such as jet fans or large punctual exhausts in contrast to regularly arranged dampers of a transversal ventilation system with intermediate ceiling. While the first class is positioned according to its position in the global coordinate system (i.e. the item is in the same distance to the fire location in FDS as in the assessed scenario) in the second class the fire is always positioned exactly between two dampers. This means that the statistical variation in class one is covered by the variation of locations in the simulation grid whereas in class two the first activated damper is always in the statistically expected location versus the fire. These considerations on statistically correct positioning are illustrated in Figure 2. The same considerations can be applied for the different types of road signs.
The main question concerning traffic is the statistical arrangement of vehicles near the fire. The effect of vehicles are turbulences caused by the obstruction in the tunnel and in this aspect the difference between a car and a truck is huge. Therefore the arrangement or the different types of vehicles has to be according to the statistically expected situation based on the share of HGVs for the simulated traffic case. The statistically expected arrangement for 9.1% of HGV and no passing of HGVs is shown in Figure 2.

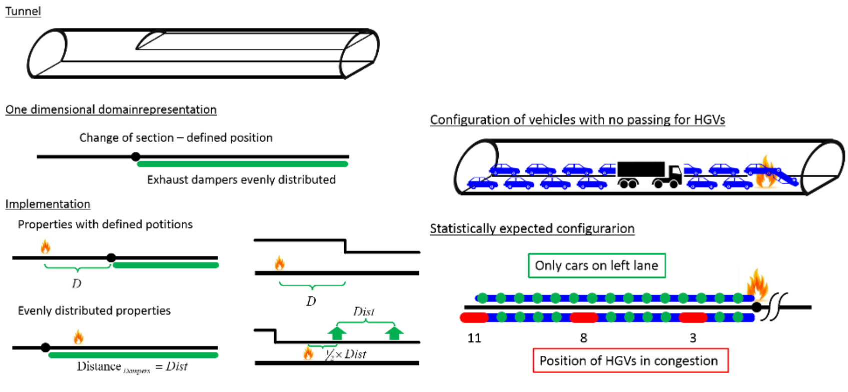

Figure 2. Ventilation (left) and vehicle arrangement (right) in 3D environment

3.4 Evacuation simulation

The model used for toxic accumulation and the effects on walking speed is derived from the commercial software 'BuildingExodus' (8) which was used to calculate the specific risk values in the original version of TuRisMo. The main reason besides consistency in the risk model was the fact that the underlying theory by D. A. Purser (9) - (13) represents the best available piece of research on toxic effects on human. It covers the effects of carbon monoxide, cyanide and oxygen deprivation as well as the indirect effect of carbon dioxide (hyperventilation and therefore faster accumulation of toxic gases). The effects of accumulated intoxication and reduced local visibility on the walking speed were implemented in accordance with BuildingExodus. However, the simulation pattern was reduced to a one dimensional domain as there are normally no local bottleneck effects at doors or at the sidewalk due to the relatively low initial person density in a road tunnel (in contrast to rail tunnels where exactly these effects have a large influence on the time of exposure).

On the level of evacuation simulation neither location nor number of emergency exits is taken into account. The only question to be answered here is how far a person can get when starting at a location x in reference to the fire location. If the person reaches the domain boundary, then they will survive in any case.If the accumulated intoxication leads to incapacitation before the domain boundary the distance where the incapacitation is reached is stored in order to be used in the mapping process. This procedure is applied for both evacuation directions and a number of different types of agents (age and gender) according to RVS 09.03.11 (4) in order to get a representative coverage of the tunnel users.

3.5 Mapping Process& data collection

The mapping process is the core element in the new risk analysis model and allows for an accurate assessment of all measures working on detection and closure of the tunnel without increasing the number of time consuming simulations in the previous steps. The main idea is that the resulting risk in a tunnel is the intersection of zones with endangerment and zones with presence of people. Zones with endangerment without people do not cause any risk as well as zones with people without endangerment.

The reason for the name 'mapping' can be explained briefly: it is a projection of final vehicle arrangements and configurations of emergency exits onto the results of the evacuation simulation. This allows for a much more precise assessment of parameters influencing the detection and closure of the tunnel, as the numerical effort in calculation of the final configuration of traffic is negligible compared to three dimensional CFD simulations. This means that a much larger number of cases can be taken into account on this level. This covers traffic volume, traffic asymmetry, accident location and detection time of the primary traffic disruption in conjunction with the time needed until the closure of the tunnel is respected. The basic assumption is that these cases of the fine grid can be projected onto the scenarios (support points) of the coarse grid of the CFD simulations which give the maximal evacuation range depending on the agents' origin. If for example the coarse grid has support points (simulated scenarios) for $500\ vehicles/h$ and $1000\ vehicles/h$, a scenario in the fine grid with $700\ vehicles/h$ will be projected onto $scenario$ 1 with 60% of the basic probability and with 40% onto $scenario$ 2. This corresponds in fact to a linear interpolation of fatalities per incident in case of uniform distribution of people in the tunnel and is called impact factor $\mathcal{J}_P$ for the given parameter. But as the distribution of people is not uniform (short sections with congestion formed behind the accident location and traffic lights in the tunnel), a linear interpolation would give faulty results. By subsequently applying this projection algorithm for all parameters which were subject to a variation in the grid setup (and therefore have independent CFD scenarios) the nonlinearity on the exposure level can be bypassed. The total impact factor $\mathcal{I}_{Scenario}$ is then the product of the independent impact factors by

$$\mathcal{I}_{Scenario} = \prod_{Parameter} \mathcal{I}_p$$

This projection algorithm is used in two levels:
First it is required in order to calculate the occurrence probability of having people in a position in relation to the fire location with the fire location as free dimension in order to calculate the representative distribution of emergency exits which then give the zones with endangerment.
Second it is used in order to calculate the final density of people at a position in relation to the fire giving the exposure. In this case the fire location dimension collapses. In fact this distribution density is the sum over the possible fire locations. In cases where only the expected risk values are of interest the first function can be reused but if FN curves shall be derived in addition to expected risk values the process has to be rerun.

The question now is: what does this mean in reality and how do the resulting equations of the functions look like?

To start with the representative distribution of emergency exits one has to begin with the definition of the local probability density of fire locations. The algorithm does not only take into account fires starting at the location of the primary accident (which would start at $\tau = 0$) but also the possibility of fires occurring due to rear end collisions at the end of the queue (distance $\bar{x}$ to the front end of the queue) with $\tau(\bar{x}) > 0$ and an impact $\mathcal{I}_{\text{Delay}}$ on the delayed fire scenarios of the CFD simulations. With a final vehicle configuration in a tunnel with N_{Lanes} lanes consisting of n sections $[\mathbb{l}_i, \mathbb{r}_i]$ for given location, traffic and delay of closure the probability of a fire at the location $\hat{\text{x}}$ follows to

$$\mathcal{B}_{\text{Scenario}}(\hat{\text{x}}) = \sum_{r=1}^{n} \int_{\mathbb{l}_r}^{\mathbb{r}_r} N_{Lanes}(\bar{x}) \cdot \mathcal{I}_{\text{Delay}}\big(\tau(\bar{x})\big) \cdot \delta(\hat{x} - \bar{x}) d\bar{x}$$

This means each point of every jam section can be the location of the fire caused by a rear end collision but not all are projected onto the current scenario of the coarse grid. Summing over all variation scenarios of the fine grid one gets

$$\mathcal{B}(\hat{\text{x}}) = \sum_{Scenarios} \mathcal{P}_{\text{Scenario}} \cdot \tilde{\mathcal{I}}_{\text{Scenario}} \cdot \sum_{r=1}^{n} \int_{\mathbb{l}_r}^{\mathbb{r}_r} N_{Lanes}(\bar{x}) \cdot \mathcal{I}_{\text{Delay}}\big(\tau(\bar{x})\big) \cdot \delta(\hat{x} - \bar{x}) d\bar{x}$$

with the total impact function $\tilde{\mathcal{I}}_{\text{Scenario}} = \mathcal{I}_{\text{Traffic}} \cdot \mathcal{I}_{\text{Asymmetry}} \cdot \mathcal{I}_{\text{Location}}$ reduced by the delay time and the basic probability $\mathcal{P}_{\text{Scenario}}$ of the scenario.
Based on this basic probability density for fire locations concerning the CFD case in question the density function of people at a location versus the fire can be derived to

$$\Upsilon_{\text{Scenario}}(x,\hat{x}) = \sum_{r,s=1}^{n} \sum \int_{\mathbb{l}_r}^{\mathbb{r}_r} \varrho_{Jam} \cdot N_{Lanes}(\hat{x}) \cdot \mathcal{J}_{\text{Delay}}\big(\tau(\hat{x})\big) \cdot \delta(\hat{x}-\bar{x})$$

$$\cdot \int_{Domain} \varrho_{Jam} \cdot \eta_{Lanes}(x) \cdot \delta(x-\bar{\bar{x}}) \cdot \theta(\mathbb{l}_s-\hat{x}, \mathbb{r}_s-\hat{x})\, d\bar{x}\, d\bar{\bar{x}}$$

Where $[\mathbb{l}_r, \mathbb{r}_r]$ represent the ‘source’ sections of the traffic jam as with the fire probability above and $[\mathbb{l}_s, \mathbb{r}_s]$ represent the ‘target’ section where people are exposed to the hazard. Of course this function needs to be normalized to 1 for each pair $(x, \hat{x})$ after integration. The procedure of calculation of fire probability and exposure are illustrated in Figure 3.

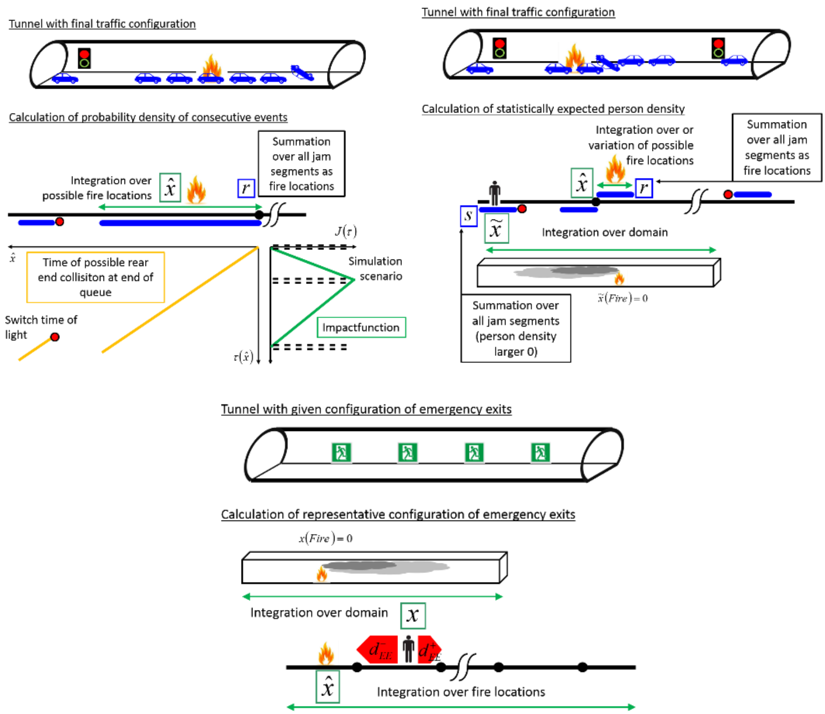

Figure 3. Fire location (top left) and exposure (top right) and emergency exits (bot.)

Once the exposure depending on the fire location $\hat{x}$ (in global coordinates) and the location versus the fire location x (in local domain coordinates) is computed it is easy to derive the representative distribution of emergency exits at a location x_{EE} versus the fire location. The corresponding function for the density of emergency exits $\rho_{EE}(x,d)$ for a scenario of the coarse grid is given by

$$\rho_{EE}(x,d) = \sum_{Scenarios} \mathcal{P}_{\text{Scenario}} \cdot \tilde{\mathcal{J}}_{\text{Scenario}} \cdot \int_{\text{Fire locations}} \Upsilon_{\text{Scenario}}(x,\hat{x}) \cdot \int_{Domain} \delta(x-\bar{\bar{x}}) \cdot \delta\big((x_{EE}-\hat{x}-x)-d\big)\, d\bar{\bar{x}}\, d\hat{x}$$

which again needs to be normalized to 1 for each x (every person needs to evacuate to one emergency exit). The distribution function $\Omega(x,d)$ can be obtained by integration $\Omega(x,d) = \int_{\bar{x}=x}^{\infty} \rho_{EE}(\bar{x},d) \cdot d\bar{x}$ which is the representative distribution density for emergency exits.This function gives the probability that a person starting at the initial position x versus the fire location $\hat{x}$ (in local coordinates $x(\hat{x}) := 0$) has to walk a certain distance in positive or negative evacuation direction. Multiplication of this function with the distances $\mathrm{X}(x,\mathcal{P},\mathcal{T})$ the different types of agents $\mathcal{P}$ at different starting times $\mathcal{T}$ can cover.With the share of a specific type of agent $P(\mathcal{P})$ and the share of a given start time of evacuation $P(\mathcal{T})$ the mortality rate $\Psi(x)$ follows to

$$\Psi(\mathrm{x}) = \sum_{\{\mathcal{P}\}} \sum_{\{T\}} P(\mathcal{T}) \cdot P(\mathcal{P}) \cdot \Omega\big(x, \mathrm{X}(x,\mathcal{P},\mathcal{T})\big)$$

This represents the probability that the self-rescue process of a person originating at a point x versus the fire location will fail. This number is the statistical average for all scenarios covered – which are also represented in the function of exposure. By multiplication of the mortality rate $\Psi(\mathrm{x})$ with the exposure function

$$\Phi_{\mathrm{i}}(\mathrm{x}) = \sum_{Scenarios} \mathcal{P}_{\text{Scenario}} \cdot \tilde{\mathcal{J}}_{\text{Scenario}} \cdot \int_{Fire\ locations} \Upsilon_{Scenario}(x,\hat{x})$$

the total risk value of the independent case (fire size, system failure etc.) is finally given by

$$\mathcal{R}_{TOT} = \sum_{\substack{Basic\\ scenarios}} \mathcal{R}_i = \sum_{\substack{Basic\\ scenarios}} \mathcal{P}_{\substack{\text{Basic}\\ \text{Scenario}}} \cdot \int_{\text{Domain}} \Phi_{\mathrm{i}}(\mathrm{x}) \cdot \Psi_{\mathrm{i}}(\mathrm{x})\, dx$$

These risk values represent the expected number of fatalities in an average fire scenario which are then used as representative fatality numbers in the following event tree analysis where the coverage of a wide range of variation in the main influencing parameters in the process allows for precise and specific assessment of particular special characteristics of a tunnel system.

4 EXAMPLES

The example shows the impact of the non standard requirement to have a traffic light at the end of the tunnel. As this means that there will be a number of queuing vehicles in the tunnel while the traffic light is red it represents a risk increasing factor. In order to compensate the additional risk caused by this non standard requirement two risk mitigating safety measures have been assessed:

1. The traffic light at the end of the tunnel can be switched by the tunnel surveillance
2. Detection time is reduced by installation of an acoustic incident detection system

In the simulation it is assumed that cars can still exit the tunnel unless the visibility is already reduced by the smoke to less than $10m$ for reflecting objects (corresponding an extinction coefficient higher than $0.3/m$).
Figure 4 shows the statistically expected person density for fire incidents caused by the primary traffic disruption. In such a case the person density on the right side of the fire location should be zero, the vehicles are only queuing on the left side (driving direction left to right). The length of the queue depends on the traffic volume, incident location and time of closure. The characteristic shape in the Figure 4 results from the variation of these parameters. The expected person densityon the right side of the incident location seen here (right row of images) is caused by the traffic light at the exit portal and smoke obscuration before clearance. In the example two main effects of the acoustic incident detection system can be observed:

1. The statistically expected person density on the right (downstream) side of the fire is significantly reduced by faster clearance of the tunnel. This means that there are less people in the endangered zone and the statistically expected number of fatalities is reduced for primary events.
2. The length of the queue behind the incident location is reduced resulting in a lower probability of secondary events (rear-end collisions at the end of the queue) and in case of a fire incident at the end of the queue the number of people in the endangered zone is reduced. So for secondary events the probability as well as the number of fatalities could be reduced.

By application of the additional risk mitigation measure of an acoustic incident detection system the overall expected risk value of the tunnel could be reduced to a level lower than the applicable reference tunnel.

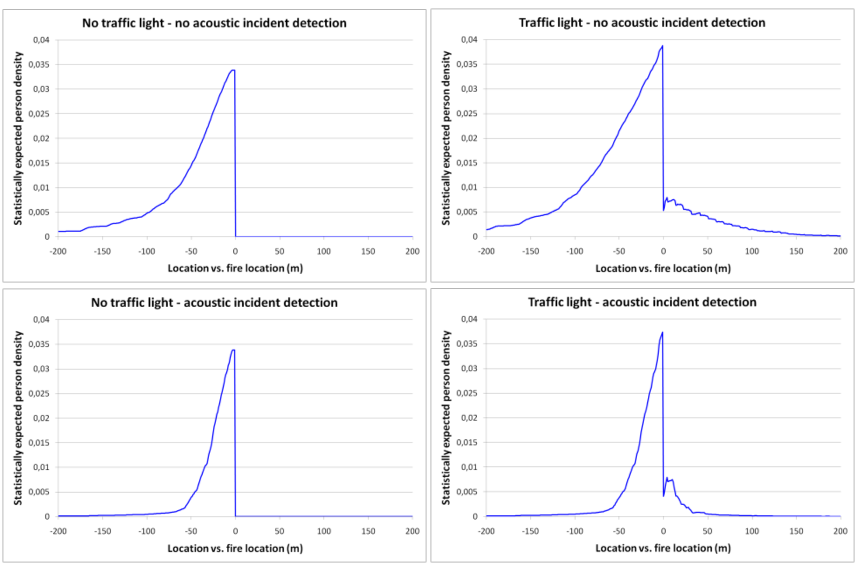

Figure 4. Exposure after primary accident without (left) and with (right) traffic light at exit portal, without (top) and with (bot.) acoustic incident detection

5 CONCLUSION

With the methodologies developed for the new Austrian Risk Model it is now possible to analyse tunnels with various special characteristics. The effects of special characteristics as well as the effects of additional safety measures can be assessed with a minimum of assumptions as their impact is directly included in the underlying distribution density functions. Furthermore the integrated structure and the applied statistical methodologies allow a variation of the most important influencing parameters in order to give robust results in the computed statistically expected risk values. This means that the model represents a large step into the direction of realistic risk modeling and gives reliable result in a wide range of applications.

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