Ways of improvements in quantitative risk analyses by application of a linear evacuation module and interpolation strategies

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Abstract

The application of various methodologies of quantitative risk analysis have shown, that the calculation of casualties is either extremely work intensive (in case of models based on the accumulation of flue gases) or cannot cover all required aspects of the self rescue process (in case of limit based models).
Furthermore it is necessary to perform this calculation of casualties subsequently with a variation of fire location vs. nearest emergency exit and based on simulations of fire development and smoke propagation on a certain number of locations in the tunnel and with different traffic scenarios in order to get representative numbers for the assessed tunnel.
In order to understand the necessity of further improvements in the area of egress simulation the paper starts with a short overview of currently available methods and how they are applied.
Then the modified tool for egress simulation in a tunnel environment is presented as well as the application in risk analysis and the strategy of interpolation in order to minimize the amount of time consuming three dimensional simulations of smoke propagation.

Keywords: Qquantitative risk analysis, egress simulation, accumulation model, traffic statistics, interpolation

Current situation

For the calculation of casualties in a tunnel fire as representative input values for the subsequent analysis in an event tree or a probabilistic network there are currently two models available which widely differ in approach and application. The following paragraphs will give a brief summary and outline their strong and weak points:

1. Limit based evacuation simulation

   These models are widely in use (e.g.: Germany, Japan, etc.) because they are relatively simple in application and do not require automated routines for calculation of casualties numbers.
   The idea behind the model is that self rescue fails if visibility drops below a certain level. For this purpose the visibility is derived for a height of 1.8m above walking surface by use of three dimensional fluid dynamics simulation environments.

Pros:

- The calculation of casualties can be easily performed in 'ruler and pencil' style on a printout of the furthest point affected by smoke vs. time if limited to a limited number of scenarios and locations (i.e. the fire is always exactly in front of one emergency exit)
- An extended application can be programmed (quite) easily allowing to subsequently shift the fire location vs. the configuration of emergency exits in order to get representative numbers for the entire tunnel.

Cons:

- Let's assume a tunnel equipped with smoke extraction via air duct and dampers over the entire length. After the fire starts the smoke will be carried away by the longitudinal airflow in the tunnel until the fire is detected, ventilation system is activated and the exhaust fans deliver enough exhausted volume in order to reverse the flow on the downwind side and remove the smoke from the tunnel.
- People in this part of the tunnel will be exposed to the smoke and flue gases only for a short time and would probably survive, even if staying in place until environmental conditions have improved but in the model they are accounted as victims.
- This results in problems when performing relative comparison of a longitudinally ventilated tunnel with a tunnel equipped with smoke extraction or transversal ventilation as the benefits of transversal ventilation systems are underestimated by relying on this method.
- The results will always depend on the chosen limit for successful self rescue. Therefore the casualties' numbers need to be calibrated to real scenarios. (Un)Fortunately the data on this side is still very limited. Furthermore the calibration will only be valid for one type of tunnel (i.e. calibration for a longitudinally ventilated tunnel should not be applied in a transversally ventilated tunnel)
- If the intention is to simulate the egress of different kinds of agents with differing walking speed, reaction times, etc the model gets as tricky to implement as an accumulation based model

2. <u>Accumulation based evacuation simulation</u>

Accumulation based evacuation models are mainly used in commercial evacuation environments such as buildingExodus [3] or open source projects as FDS+Evac. They are normally based on the theory of accumulated intoxication by Purser [1], [2] and assess the effects of concentration and duration of exposure. These programs also allow for simulations on a two dimensional evacuation grid and simulation of bottleneck problems such as doors and sidewalks.
The idea is to calculate the total amount of flue gases the evacuating agent has accumulated over the entire period and compare it to a given threshold or probit funtion.

Pros:

- As the theory is calibrated to human physiology and not to a low number of widely differing incidents that have occurred in the past the model can be applied for comparison of different ventilation systems with a high accuracy.
- Some simulation environments allow the input of gas concentrations for different levels (walking level, crawling level)
- Different kinds of agents can be defined in order to create a set of agents (persons) representing the country's population
- Undesired reactions, drop of egress speed in poor visibility, congestion forming at emergency exits etc. can be included.

Cons:

- Data transfer from CFD environment is extremely time consuming unless there is a link between CFD and evacuation environment which is only the case if both are purchased from the same supplier (FDS+Evac)
- Results depend on the density of input data, i.e. the spacing between two zones should not be larger than a maximum of 20m. This is because the data (visibility, concentrations) is constant over the zone which leads to inaccuracy in agents' reaction and intoxication.
- As the distribution of agents in the evacuation grid is arbitrary the simulation has to be rerun a certain number of times in order to obtain a representative average
- The simulation has to be rerun with different fire location vs. nearest emergency exit in order to obtain a representative value for the entire tunnel

Requirements for evacuation tool

Because of these limits in application the intention was to develop a new easily applicable tool for the simulation of the self rescue process during tunnel fires which combines the benefits of both approaches. Basically the requirement was the design of an integrated tool for egress simulation in direct combination with quantitative risk analysis methodologies for road tunnels.

This leads to the following requirements for the evacuation tool:

- Capability of dealing with different types of hazards (such as convective heat, radiating heat, carbon monoxide, carbon dioxide, hydrogen cyanide, visibility, etc.)
- Capability of simulation of different types of agents with different attributes (such as age, walking speed, etc.)
- Possibility of defining a number of people which react the wrong way (like staying in their vehicles, walking the wrong direction, etc.)
- Possibility of defining the exact positions of emergency exits
- Possibility of direct data import from CFD simulation results
- Compatibility with office applications as MS Excel

On the other hand there are a number of features which are available in complex evacuation environments which are not needed in this case. These are:

- 2-dimensional evacuation grid (the width of the tunnel is negligible against the distance to the next emergency exit)
- Simulation of congestion in front of bottlenecks (the total number of people in a road tunnel is not large enough and they don't arrive at the door at the same time)
- Simulation of crowd behavior such as patience, social interactions, etc. (experience with application of two dimensional accumulation based simulation environments has shown that the density of people is not large enough in road tunnels)

Implementation

Based on these requirements a linear evacuation tool was implemented in VBA with the following functionality:

The input data is imported from .csv files containing the local environmental parameters for various inclinations covering the tunnel's minimal and maximal inclination. Ideally the data should be available in time steps as short as possible. Same is true for the spacing in between the locations the environmental parameters are recorded. If the spacing is larger than one the data has to be interpolated in order to get environmental data at the agent's position with an accuracy of 1m at every second.

The effects of gas concentrations are evaluated by the following formulas based on the research of Purser [1], [2], [4], [5]:

Intoxication by carbon monoxide:

$$FICO = \frac{3.317\times10^{-5}\times CO(t)^{1.036}\times RMV}{PID} \tag{1}$$

Intoxication by hydrogen cyanide:

$$FICN = \frac{e^{\frac{HCN(t)}{43}}}{220} \tag{2}$$

Intoxication by carbon dioxide:

$$FICO_2 = \frac{1}{e^{6.1623-0.5189\times CO_2(t)}} \tag{3}$$

Effects of hypoxia (lack of oxygen):

$$FIO_2 = \frac{1}{e^{8.13-0.54\times(20.9-O_2(t))}} \tag{4}$$

Increased respiratory volume by increased concentration of carbon dioxide:

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

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

$$FIN = \int_{t_{exp}} (FICO + FICN + FICO_2)\times VCO_2 + FIO_2 \, dt \tag{6}$$

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

Convective heat:

$$FIH_C = 2.0*10^{-8}\times T(t)^{3.4} \tag{7}$$

Radiant heat

$$FIH_R = \frac{60\times q(t)^{1.33}}{D_r} \tag{8}$$

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

$$FIH = \int_{t_{exp}} (FIH_c + FIH_R)\, dt \tag{9}$$

Furthermore the impairment of flue gases, heat and poor visibility have negative influence on the agents' egress velocity [3]:

Effects of intoxication on agents' mobility:

$$M_I = \begin{cases} 1,\ FIN \in [0;\ 0.9[\\ 0.9,\ FIN \in [0.9;\ 0.95] \\ 0.8,\ FIN \in]0.95;\ 1] \end{cases} \tag{10}$$

Effects of poor visibility on agents' mobility:

$$M_S = 1.105 - 0.488\times K - 0.161\times K^2 \tag{11}$$

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

$$V = V_I \times M_I \times M_S \tag{12}$$

If one of the impairing effects - total intoxication or heat - reaches the threshold of 1 the agent is accounted as incapacitated and the egress cannot be completed without assistance.

Definitions:

t .... Time [min]

$CO(t)$ .... Concentration of carbon monoxide [ppm]

$CO_2(t)$ .... Concentration of carbon dioxide [% Vol.]

$HCN(t)$ .... Concentration of hydrogen cyanide[ppm]

$O_2(t)$ .... Concentration of oxygen [% Vol.]

$T(t)$ .... Temperature [°C]

$q(t)$ .... Radiant heat [kW/m^2]

RMV .... Respiratory volume per minute (50 during high activity)

PID .... Personal incapacity dose of CO

D_r .... Limit for lethality caused by radiant heat

K .... Linear extinction coefficient [1/m]

V_I .... Agents' initial walking speed [m/s]

Application for a given tunnel

This procedure is repeatedly applied for each of the 6 types of agents with 3 different initial walking speeds each and at all initial positions in the tunnel resulting in zones without the chance of self rescue for a given fire location. By moving the fire location along the tunnel in 1m steps a risk map of the tunnel can be drawn if sufficient data is available. This means that the simulation of smoke propagation normally has to be simulated for different locations in the tunnel and traffic situations. Particularly in case of bidirectional tunnels the location of the fire and the distribution of traffic (symmetric of highly asymmetric) have a large influence on the longitudinal velocity and therefore the propagation of smoke.

An overview of influencing factors is given in *Figure 1*.The effects of these influencing factors is calculated by means of a relatively simple one dimensional fluid model and applied as boundary condition to a representative section of the given tunnel in the three dimensional simulation of smoke propagation.

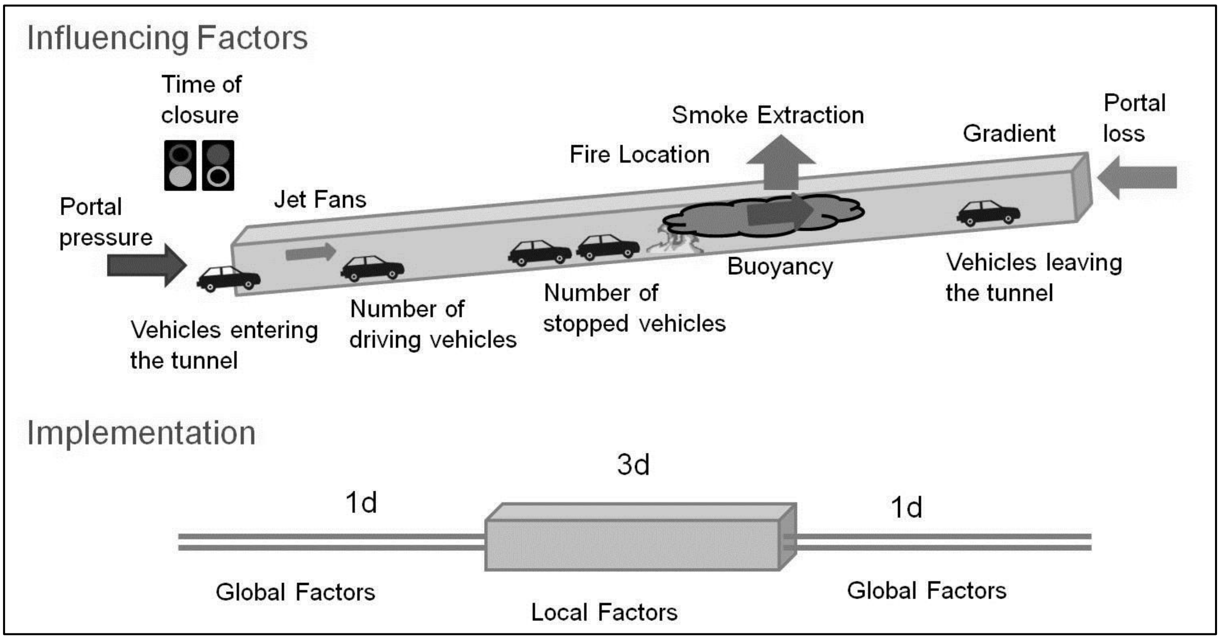


Figure 1: Influencing Factors and application in CFD model

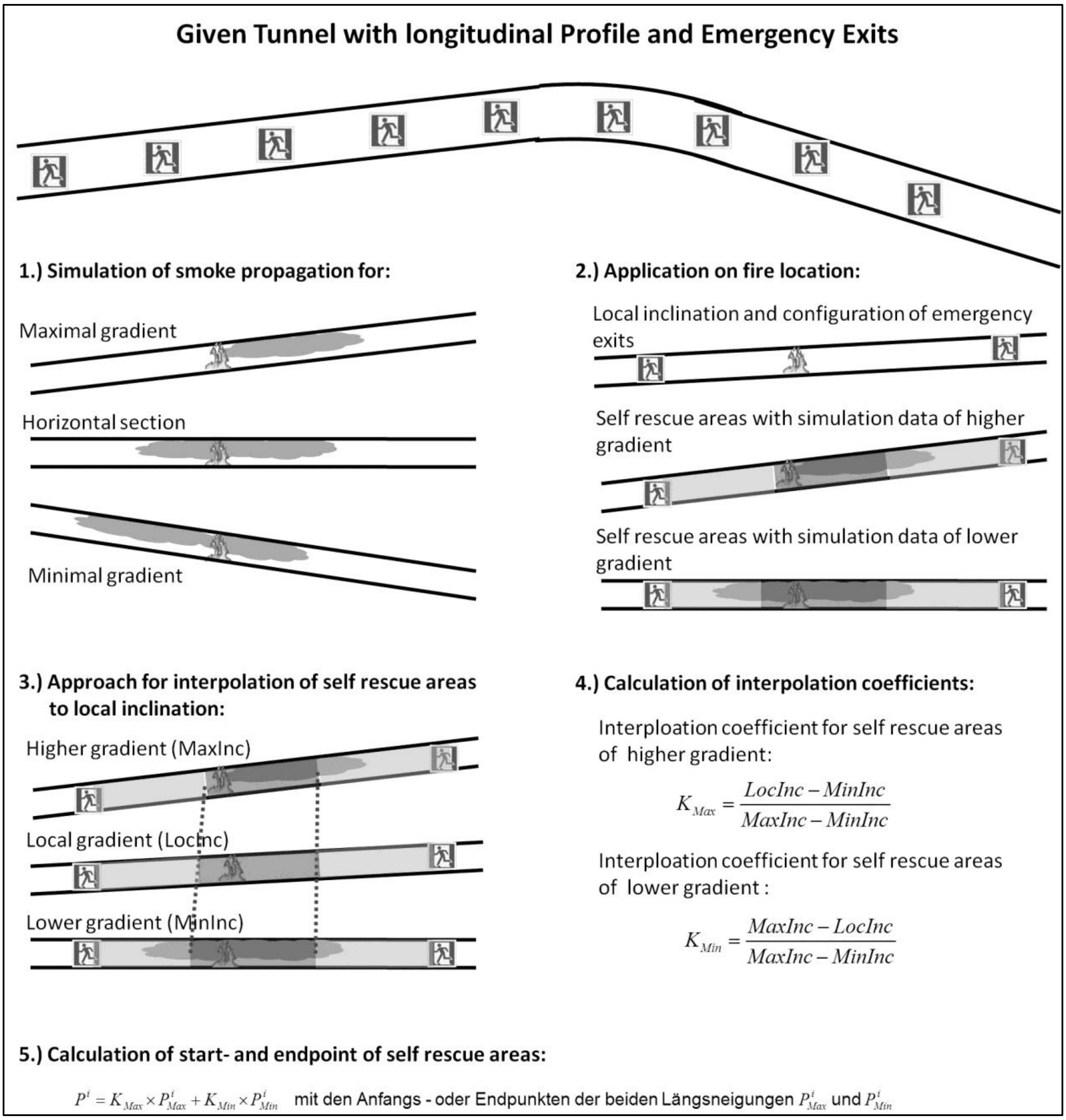


Figure 2: Interpolation between two simulated fire locations with different gradient

Some of the listed factors such as time of closure, reaction time of the ventilation system etc. can be assumed as constant as they are either physical properties of the tunnel or defined in the methodology. Other factors such as traffic volume and symmetry show large variations and have a significant impact on the longitudinal airflow in the tunnel.

Unfortunately it is not possible to cover all these parameters with high resolution variation and perform three dimensional simulations. Therefore the focus is to cover important factors with a certain number of variations in the numerically intensive CFD and egress simulations and to use interpolation strategies in between these support points.

Figure 4 and *Figure 5* illustrate how such an approach can increase accuracy and quality of a risk analysis for a given tunnel.

Scenario selection and interpolation strategy

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 the fire location in the tunnel needs to be altered. This is to take effects into account that occur when the traffic comes to stop behind the fire. Especially in bidirectional tunnels this can have high influence on the longitudinal airflow and therefore the propagation of smoke. The minimum required number of locations in a tunnel depends on the tunnel's properties but should be at least 2 in case of a tunnel with constant longitudinal gradient and 3 in case of tunnels with changing gradient (tunnels with high point).

For each of these scenarios the smoke propagation is simulated in a three dimensional CFD environment (FDS) and the environmental data is recorded in 1m and 1s spacing for use in the egress model described above.

As the next step the egress simulation is performed with an alteration of the fire location in 1m steps over the tunnel. If more than one location has been simulated in 3d the smoke data (visibility, concentrations, etc.) from the first simulation is applied from the left portal to the first scenario location. In between first and second scenario location the data (lengths of zones without self rescue) is interpolated in a linear way. This approach of interpolating zone lengths is also a valid approach in case of changing gradient in the tunnel the interpolation of local concentrations on the other hand is not. This results in a precise risk map which shows the potential casualties for a fire at any place in the tunnel and with the traffic volume selected as representative scenarios.

By combining the risk map for each type of agent and the share of the agent in the tunnel's population the average number of casualties for the selected traffic scenario can be calculated.

Finally the traffic statistics can be used to obtain a distribution of the frequency of events by combining the histogram of traffic volume with the accident rate/fire rate as a function of traffic volume. In order to apply the data obtained by the simulation of egress for the selected scenarios in the most precise way the numbers of casualties are interpolated in a linear way for traffic volumes in between the minimal and maximal scenario. Below the minimal and above the maximal scenario the numbers are constant.

This results in a fairly accurate number of victims per fire incident. At the moment the limit of accuracy is the availability of computational power and therefore the number of numerical simulations that can be run for one risk analysis.

Example for benefits of higher accuracy

The approach of interpolation of results of three dimensional smoke propagation and application to a wide range of traffic volume was applied in terms of the dangerous goods risk analysis of a motorway tunnel in Germany (ref. *Figure 3*).

The methodology for dangerous goods risk analysis compares the calculated FN curves to an accepted line. If the FN curve is entirely below the accepted line the tunnel can be opened to dangerous goods vehicles. On the other hand the tunnel needs to be closed to either certain groups.

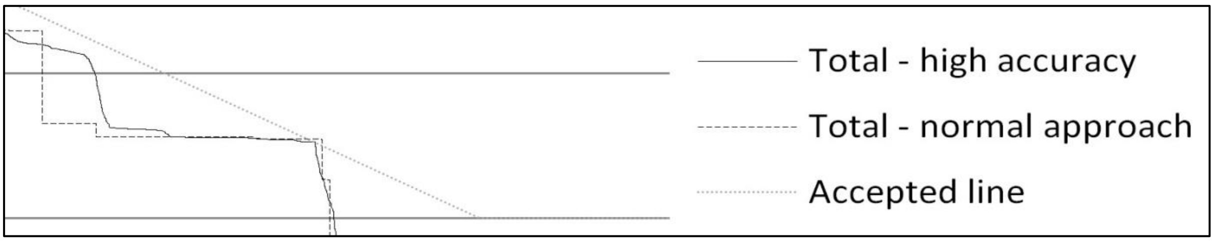
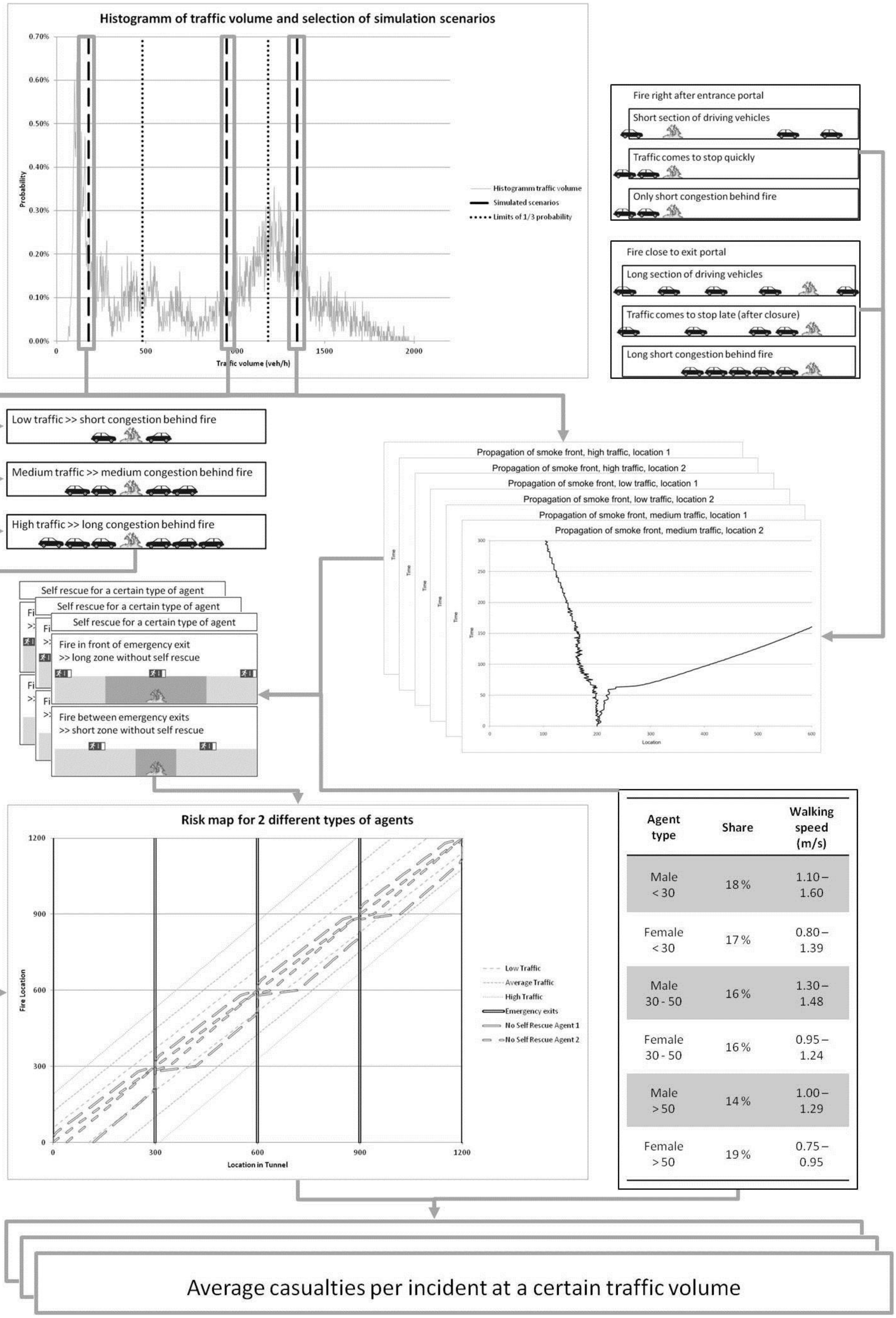


Figure 3: Example where the normal approach does not fulfill the criteria but the accurate one does



Agent type	Share	Walking speed (m/s)
Male < 30	18 %	1.10 – 1.60
Female < 30	17 %	0.80 – 1.39
Male 30 - 50	16 %	1.30 – 1.48
Female 30 - 50	16 %	0.95 – 1.24
Male > 50	14 %	1.00 – 1.29
Female > 50	19 %	0.75 – 0.95

Figure 4: Procedure of calculating average casualties for a given traffic distribution - part 1

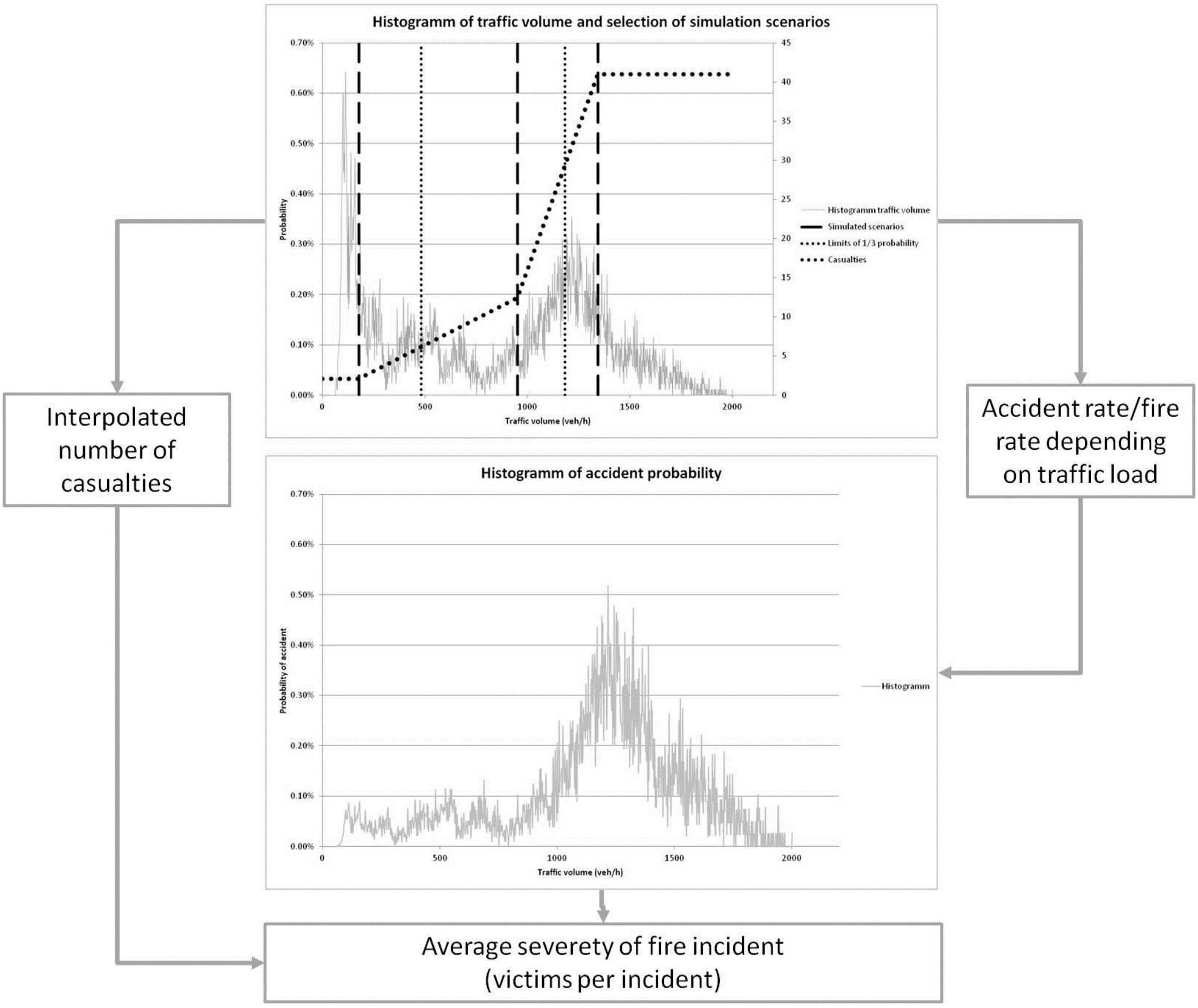


Figure 5: Procedure of calculating average casualties for a given traffic distribution - part 2

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