Structural Monitoring and Maintenance, *Vol. 5, No. 3 (2018) 363-377*
DOI: https:// doi.org/10.12989/smm.2018.5.3.363

Computer modelling of fire consequences on road critical infrastructure – tunnels

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(Received August 7, 2018, Revised August 21, 2018, Accepted August 28, 2018)

Abstract. The proper functioning of critical points on transport infrastructure is decisive for the entire network. Tunnels and bridges certainly belong to the critical points of the surface transport network, both road and rail. Risk management should be a holistic and dynamic process throughout the entire life cycle. However, the level of risk is usually determined only during the design stage mainly due to the fact that it is a time-consuming and costly process. This paper presents a simplified quantitative risk analysis method that can be used any time during the decades of a tunnel's lifetime and can estimate the changing risks on a continuous basis and thus uncover hidden safety threats. The presented method is a decision support system for tunnel managers designed to preserve or even increase tunnel safety. The CAPITA method is a deterministic scenario-oriented risk analysis approach for assessment of mortality risks in road tunnels in case of the most dangerous situation – a fire. It is implemented through an advanced risk analysis CAPITA SW. Both, the method as well as the resulting software were developed by the authors' team. Unlike existing analyzes requiring specialized microsimulation tools for traffic flow, smoke propagation and evacuation modeling, the CAPITA contains comprehensive database with the results of thousands of simulations performed in advance for various combinations of variables. This approach significantly simplifies the overall complexity and thus enhances the usability of the resulting risk analysis. Additionally, it provides the decision makers with holistic view by providing not only on the expected risk but also on the risk's sensitivity to different variables. This allows the tunnel manager or another decision maker to estimate the primary change of risk whenever traffic conditions in the tunnel change and to see the dependencies to particular input variables.

Keywords: road tunnel; risk analysis; deterministic approach; scenario oriented method, fire; software tool; CAPITA

1. Introduction

1.1 Risk analysis in road tunnels

When designing a tunnel technology, the decision makers face an important question: "Is the proposed safety technology sufficient and suitable for this particular realisation?" Unfortunately, this question does not have a universal answer, since it is always significantly affected by

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http://www.techno-press.org/?journal=smm&subpage=7 ISSN: 2288-6605 (Print), 2288-6613 (Online)

individual tunnel characteristics and by social risk perception. (Sjoberg 2000) shows how complex the model of human risk perception is and identified the factors (culture, gender, education, and others) that must be taken into consideration. The evacuation experiments performed in road tunnels investigated how motorists behave and emotionally respond when exposed to a fire and how is this behaviour (reaction times and similar) influenced by technical facilities such as fire sensors or information and warning installations (Nilson *et al*. 2009). There are many hidden parameters that play a role in estimating how safe the tunnel is.

The design of the safety facilities in road tunnels is predominantly based on regulations and legislative guidelines (Kohl *et al*. 2010). This approach is known as a standards-based approach or prescriptive approach. Nevertheless, each tunnel is an individual and specific construction. Human behaviour varies also according level of knowledge, nationality and habits of drivers. This is a reason why in addition to the prescriptive approach is complementary applied so called risk-based approach at present.

The purpose of the risk analysis in road tunnel is twofold: (1) To assess the adequate tunnel equipment minimizing impacts of the fire, esp. allowing people to self-escape the tunnel through exits and to survive. The hesitation time and evacuation speed are affected by technologies such as fire detection systems or effective warnings by public address system. Traffic tunnels are generally hostile acoustic environment and public address system must meet sufficiently intelligible speech (Wijngaarden and Verhave 2006) to be sufficiently effective. The CAPITA method presented by (Pribyl and Pribyl 2014) introduces a soft computing-based method, which enables to address the

Table 1 List with abbreviations

CAPITA	Deterministic scenario-oriented risk analysis approach for assessment of mortality risks in road tunnels in case of the most dangerous situation – a fire
CAPITA SW	A SW tool resulting from the proposed CAPITA method suitable for mortality assessment in road tunnels.
CSV	Coma separated value (file format)
CO	Carbon monoxide
CO2	Carbon dioxide
ETA	Event Tree Analysis
FTA	Fault Tree Analysis
HCL	Hydrogen Chloride
LOS	Level Of Service
SBA	Scenario Based Analysis
SCADA	Industrial tunnel control system
SUMO	Traffic microsimulation model
SW	Software
TRANSIMS	Traffic microsimulation model
VISSIM	Traffic microsimulation model
XML	eXtensible Markup Language (markup language that defines a set of rules for encoding documents)

quality of safety facilities even during the design stage. (2) On the other hand, financial aspects of safety facilities design also must be taken into account in order to avoid unnecessary over-equipping and overpricing (Sousa *et al.* 2017). It is generally accepted that minimal risk cannot be reasonably achieved and optimal risk is the goal (Beard 2010). Balance between investment and operational cost and a value of risk to the tunnel user must be targeted. Risk analyses will make it possible to find a mathematical relation between these two opposites while taking into account structural health degradation (Li *et al.* 2014, Nepal and Chen 2015).

1.2 Uncertainty in risk assessment and availability of assessment results for decision makers

Risk analysis approaches in general distinguish qualitative and quantitative methods (Radu, 2009; Cheliyan and Bhattacharyya 2018). Qualitative methods are suitable for a preliminary rough risks assessment. Typically, they involve a group of experts using different methods such as expert judgment, brainstorming, WHAT-IF analysis and others (Beard 2010). These approaches are relatively straightforward and can be easily adopted for almost any problem field. However, they have a significant disadvantage, since they provide only approximate answers – estimation of expected results. The quantitative methods additionally are composed by two categories:

- Non-deterministic risk assessment presented by probabilistic models, e.g., Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Bayesian models and stochastic models. The output is mostly presented as F-N curve - frequency of event related to veh.km. The accuracy of results is determined by the amount and relevance of data for emergency situations.
- Scenario Based Analysis (SBA) is a deterministic method which uses a traffic simulation model, a physical model for heat and smoke dispersion, and simulation models describing the evacuation process of trapped people in tunnels. The output is number of fatalities for a given scenario.

Probabilistic Fault Tree Analysis and Event Tree Analysis are widely used in tunnel risk assessment; see for example (Xu 2011, Fouladgar *et al*. 2012, Qu *et al*. 2011). Since the frequency of emergency events (especially serious fires) in road tunnels is low, and with respect to fact that each road tunnel has specific structure and operating conditions, the probabilistic risk assessment methods may not be fully suitable for each road tunnel due to the lack of necessary statistical data (FSV 2008, Jin *et al.* 2009, Ferdous *et al*. 2007).).

The scenario-based analysis focuses on particular tunnels and takes into account any specific conditions – concrete tunnel layout and equipment as well as real traffic and environmental conditions. The scenario takes into consideration the heat power and other parameters of the fire (e.g., its development in time) as well as the process of ventilation, human behavior, and many other parameters.

There is one limitation concerning both categories of risk-based approaches highlighted in (Beard 2010). Namely, the resulting numbers cannot be verified by an experiment. Even experiments which are intended to replicate earlier experiments may not produce consistent results. The final outcome of this consideration is that the results of very complex methods are valid only for the specific conditions modeled. The problem of results interpretation for stakeholders are discussed by (Borg *at al*. 2014) with respect to data and models, which are rigid and are presented to the users as a “black box.” The model provides just a single set of numbers as an output based on the very specific boundary conditions for each case. This is a problem for the decision makers, in that they miss the holistic view. They cannot see the big picture, the sensitivity to boundary conditions, nor the input variables and have to make their decision based on a single set of numbers without understanding the context. Numerical outputs indicating the fatalities or frequency of these events are discrete values calculated for a few concrete input variables. It is not possible to judge how the risk changes if, for example, the exits position or traffic intensity is slightly different from the original assignment. For even small changes, it is necessary to repeat complex calculations, costing time and money.

Neither the probabilistic nor deterministic calculations in the current concept provide a user-friendly approach. They do not provide a broader view of the scope of risk because they provide no understanding of the influence of variability in the input variables (Kazaras *et al.* 2012). A further problem is related to the uncertainty of the input parameters. Several authors have addressed the adequacy of risk models from the perspective of an uncertainty-based input parameters. According to Bjelland and Aven (2013), the presented result of risk analysis is subject to many uncertainties, such as uncertainties related to input variables or uncertainties reflected by the presentation of risk. A small change in input parameters requires recompiling of the entire model in traditional approaches. This important problem is overcome by the CAPITA method as it allows investigating sensitivity to various inputs changes.

2. Theory and methods

2.1 The basic consideration

The four criteria for accurate risk estimation are proposed by Hodges and Dewar (1992). They mention (1) observability and measurability, (2) constancy of structure in time, (3) constancy across variations in conditions not specified in the model and (4) ample data collection. The following statement is of importance for the method in this paper: "The situation being modelled must exhibit a constancy of structure in time, i.e., one should have reason to believe that the causal structure of the situation is sufficiently constant so that measurements taken at one time can be reproduced under the same conditions at a later time" (Goerlandt 2018). In this context, the traffic stream and its composition are not a constant value; the traffic demand, the composition of the traffic flow as well as, for example, the occupancy of vehicles varies in a long term perspective. This means that the original results are not necessarily valid in the long run. In order to maintain adequate safety for tunnel users, this would mean reassessing the risk with respect to changes of traffic flow or other parameters.

Literature review has shown only one method which provides a basic idea about the size of risk for different input values without the need for very specific knowledge. EvacTunnel 3.0 is web application of scenario-oriented model for risk analysis which estimates the smoke moving inside a tunnel and predicts number of fatalities. The model includes a stochastic simulation of evacuation using a Monte Carlo method. The program is available at (http://www.gidai.unican.es/), and the basic principles of evacuation models are discussed in (Capote *et al.* 2013, Alonso *et al*. 2014 or Alvear *et al*. 2013).

In the rest of this paper, the scenario-based risk assessment method – CAPITA – is explained. The method aims to provide better support for decision makers in their decisions through implementing sensitivity analysis for a variety of input variables. It was implemented in a software tool CAPITA, currently version 1.5.

The basic idea behind the proposed procedure is to avoid the need to use real-time microsimulation models to simulate the number and position of vehicles in the tunnel at the moment of fire under varying traffic conditions. Furthermore, it also does not use any microsimulation model for the movement of the trapped people. These models are replaced by databases that include the results of both microsimulations that were made in advance, i.e. off-line.

To reduce the dimension of the calculations, the input variables are discretized. CAPITA 1.5 SW processes 9 input variables that are divided into categories whose number is provided in Table 2. For example, the distance between evacuation exits is 150, 250, 350 or 450 m. The results for other distances between exits are interpolated. Likewise, the traffic flow of 160 veh/h/lane corresponds to night hours, 800 veh/h/lane is an average daily traffic (LOS 2-3) and 1600 veh/h/lane is close to the tunnel capacity (LOS 3-4). These three states cover the scale of values that can occur in the tunnel. Intermediate values are interpolated. The number of scenarios that were calculated in advance is given by the amount of discrete inputs, Table 1. It can be computed as an n-fold Cartesian product of the input variables

$$|X_1 \cdot X_2 \cdot \ldots \cdot X_N| = |X_1| \cdot |X_2| \cdot \ldots \cdot |X_N| \tag{1}$$

The overall number of combinations for the provided case is 5184.

2.2 The model structure

The CAPITA method is a deterministic scenario-oriented method that allows varying several input parameters of the model and calculation of potential mortality under given boundary conditions (PIARC 2012).

The method considers occurrence of the most dangerous scenario in road tunnel safety, a fire, which stops the traffic and produces toxic pollutants. The traffic conditions (traffic flow rate, speed, percentage of trucks, presence of bus) and the tunnel's parameters (length and number of lanes) determine the number of vehicles trapped inside the tunnel before the automated fire detection system identifies the fire and directs the industrial control system SCADA or operator to close the tunnel. The number of vehicles and their composition and occupancy determine the number of trapped persons.

Table 2 Number of discrete input variables for the CAPITA model; the free-value is entered by the user

Input	Input Name	Nr. of categories
1	Emergency exits distance	4
2	Number of traffic lines	2
3	Longitudinal gradient	3
4	Traffic flow rate	3
5	Speed	4
6	Trucks percentage	3
7	Bus presence	2
8	Critical concentration at exits	free
9	Evacuation model	3

After a certain period (so called hesitation time) the people realize the risk and start self-evacuation through the emergency exits. The number and distance of the exits directly affects the evacuation time. During evacuation, smoke is spreading from the fire based on the physical characteristics of the tunnel and atmospheric conditions. Once the concentration of pollutants at the exits at head level reaches a toxic level, people will not be able to survive. The total evacuation time and the rate of dense smoke propagation have therefore a crucial impact on the overall mortality. The above-mentioned degrees of freedom of inputs generate particular scenarios whose input data are entered by users of the CAPITA system. Besides the preset inputs (Table 2), the user chooses freely configurable inputs such as time to tunnel closure, the average hesitation time, and the critical concentration at emergency exits.

The simulation results which have been obtained by prior off-line simulations are stored in three databases which provide input data for selected parameters of specific scenarios to be assessed:

- Tunnel filling (DB1): length of queue in time between the fire occurrence and stopping the cars and closure the tunnel. It is corresponding number of vehicles that serves as a basis for calculating number of trapped people; simulations of scenarios were done in micro-simulation software VISSIM;
- Smoke propagation (DB2): critical concentration of CO, CO2, HCL or dense smoke at exits in time units; implicit values coming from simulation program SMARTFIRE;
- Evacuation (DB3): number of persons remaining in particular parts of the tunnel from the beginning of the evacuation (in time units) according to the micro-simulation tool EXODUS.

Due to the stochastic nature of the traffic flow and the composition of escaping people, both simulations are repeated ten times (this number was determined based on statistical sample size estimation). The statistical values of the mean and the standard deviation are used in the model.

Fig. 1 depicts seven steps of CAPITA process workflow including links to the off-line simulation databases, scenario parameters (user inputs) and both numeric and visual outcomes of each step. The figure is being further referenced from the text hereunder. The final step (not depicted in Fig. 1) is interpretation of the outcomes done by the risk analyst.

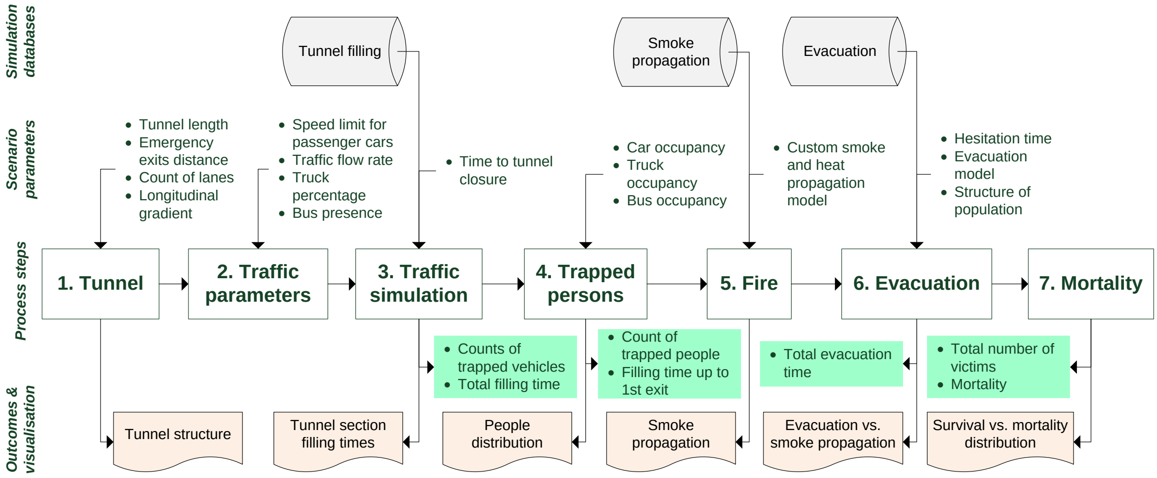

Fig. 1 The workflow of the CAPITA method

Setting the scenario parameters according to a specific tunnel enables calculation of mortality under the given conditions. A typical example illustrating how a user to can get a picture of how the mortality depends on distance between exits and on traffic flow is shown in Fig. 2. The traffic flow 160 veh/h is typical for night hours and highway tunnels. The corresponding average distance between cars is about 600 m. The fire and smoke physical model was elaborated for 50 MW heat release and a rectangular tunnel profile with a cross section of 60 m2. The figure suggests that the first critical point with one death is at the 800 veh/h traffic flow and a distance between exits of 450 m. With the traffic density increasing to 1600 veh/h (about 72% of the maximum flow capacity of one line wide 3,5 m), the corresponding risk rises for a distance between exits of only 350 and in case of 450 m the number of expected casualties is significantly higher. It is important to note that this visualization enables investigation of the risk sensitivity to arbitrary inputs shown in Table 2. This example also demonstrates, that the defined tunnel fire does not represent a fatality risk for any traffic flow values for distance between exits of up to 250 m, taking into account all others boundary conditions.

This ability to demonstrate the link among the number of fatalities and other input parameters is a novel and really important feature of the CAPITA method. It allows the decision maker to have a clear understating of the sensitivity to changes of the input parameters. This cannot be achieved by the other risk assessment methods.

The decision makers and stakeholders are not presented with a single fatality risk value for selected the combination of boundary conditions, but rather are given information that allows them to see dependencies among the variables and to assess their influence on the resulting risk. This can be used to assess the optimum cost of the tunnel equipment (number of emergency exists in particular) with better understanding of the resulting risk.

2.3 Tool design and architecture

Once the basic structure of the CAPITA method was understood, the realization team developed an implementation of the CAPITA 1.5 SW that allowed validating the approach, calibration of the method, and testing of the outcomes. The implementation consisted of:

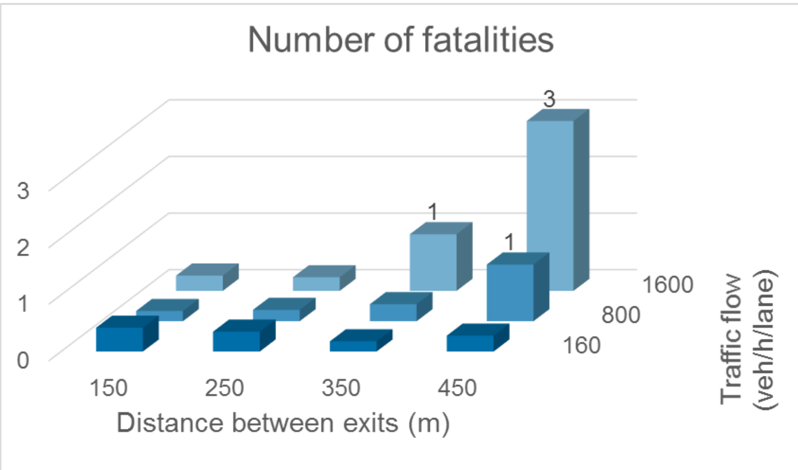

Fig. 2 An example showing the number of fatalities as related to distance between exits and traffic density

- Implementation analysis: identification of functional and non-functional requirements.
- Architecture design: specification of modules, their interfaces and selection of suitable technologies.
- Input data preprocessing: adaptation of simulation results from methodological team.
- Development: coding of the modules divided between two programmers.
- Calibration and testing: re-performing certain simulations and amending calculation formulas.

The implementation analysis identified all inputs and outputs shown in Fig. 1 which helped to split the analysis workflow into a sequence of 7 subsequent states. Functional requirements (i.e., links between inputs and outputs, corresponding formulas and output charts) were specified based on CAPITA method documentation and layout of individual states' screens was designed. Finally, non-functional software requirements were also taken into account: simple distribution and installation, multilingual interface, possibility for users to adjust and save initial configurations and an embedded tutorial that guides users through the workflow.

To fulfill both functional and non-functional requirements, the CAPITA 1.5 SW was implemented as Windows desktop application in .NET Framework 3.5; the programming language was C#. The tool was designed to consist of two top level modules:

- Calculation Core: dealing with simulation/input data processing and calculations (further described in section Implementation description).
- User Interface: implementing process workflow, gathering user inputs, handling application events and visualizing outputs based on core functions invoked accordingly.

The resulting modular architecture (depicted in Fig. 3) allowed splitting work among team members and facilitating change management.

The following secondary modules were involved (rationale of the chosen technology follows):

- Simulation databases (CSV tables): tunnel filling, smoke propagation and evacuation; CSV files embedded as .NET resources in the resulting application allow easy distribution.

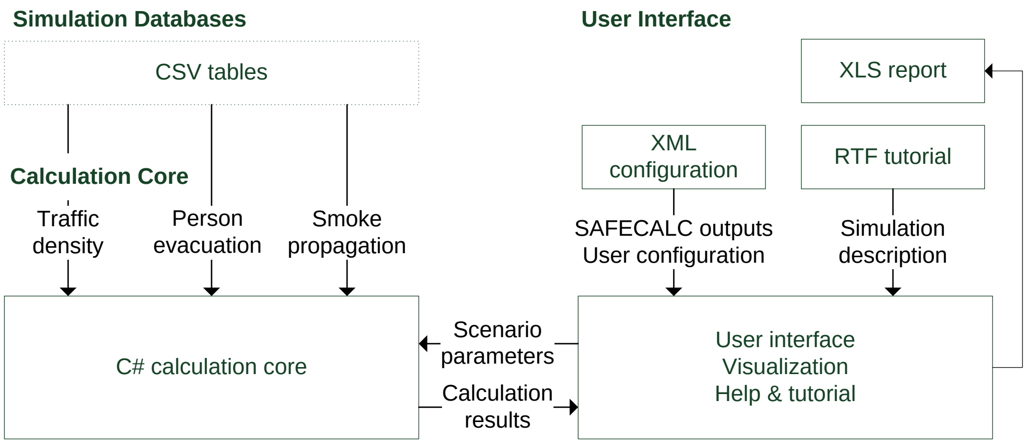

Fig. 3 Modular architecture of the CAPITA SW

- User setup (XML configuration): stores inputs from SAFECALC program (Pribyl, 2017) and other user inputs that persist after program closure; native .NET Framework XML solution.

CAPITA method guide (RTF tutorial): description of the method and workflow; RTF files allow easy text editing and translation (both EN/CZ version was delivered).

- Output report (XLS report): exports all user inputs and calculation outcomes to be further evaluated by the risk analyst and archived; XLS file allows easy distribution and printing.

3. Example results of a case study

The CAPITA method and its results are demonstrated on a case study of a 750 meter long tunnel. The tunnel is virtually divided into 50 m long sections. Filling time and ultimate count of vehicles for each section are obtained by traffic micro-simulation software VISSIM. The number of vehicles and composition of traffic flow follow a stochastic distribution and are randomly generated. VISSIM is a widely accepted program applied for complex network modeling (Saidallah 2016). Comparison with other simulation models as TRANSIMS and SUMO discussed in (Maciejewski 2010) demonstrated the benefits of VISSIM for this task.

The CAPITA method includes the following four traffic aspects affecting the filling time of segment:

- Speed limits for passenger cars (50 or 70 kph for city tunnels; 80 or 100 kph for highway tunnels)
- Traffic flow rate (1600 or 800 vehicles/hour for daily traffic; 160 vehicles/hour for night traffic)
- Truck percentage (0, 10 or 30%; for highway tunnels only)
- Bus presence (true or false for 1600 vehicles/hour and 0% trucks only)

The above degrees of freedom generate 28 scenarios that were simulated for 10 replications in VISSIM (for 2-lane tunnel), and the average values and standard deviations were entered into the database. Moreover, 4 additional scenarios were simulated for the 3-lane tunnel in case of bus presence, since the bus is considered always in the first 50 m section of the slow lane and the number of vehicles in the other lanes cannot be interpolated. The remaining 24 scenarios for 3-lane tunnel were extrapolated.

In total, the average filling time [s] and number of passenger cars/trucks plus their standard deviation were determined for 56 scenarios in the first section and the subsequent section after the fire. Table containing these values was stored within the CSV database to be loaded by calculation core which calculates total filling time and number of persons for arbitrary tunnel of given length (300 – 1000 m) and number of lanes (2 or 3). Time when each 50 m section is filled (up to time to tunnel closure) for one particular scenario is shown in Fig. 4.

Unlike for the traffic and evacuation model it is not possible to implement a general fire model. It is necessary to build a physical model for each examined tunnel with its specific conditions. The model output is time development of concentration of smoke and pollutants at exits. Threshold values causing death of trapped people are entered by the user. The survey of fire model literature yielded many articles. The smoke control strategy in the case of fire is described by (Hua *et al.* 2011). Simulation of fire scenarios is discussed in (Caliendo *et al.* 2013). This work is extended by (Bari and Nasser 2005) for traffic jam situations. A simplified model of fires and comparison with three-dimensional models and full-scale measurements is described by (Migoya *et al.* 2009).

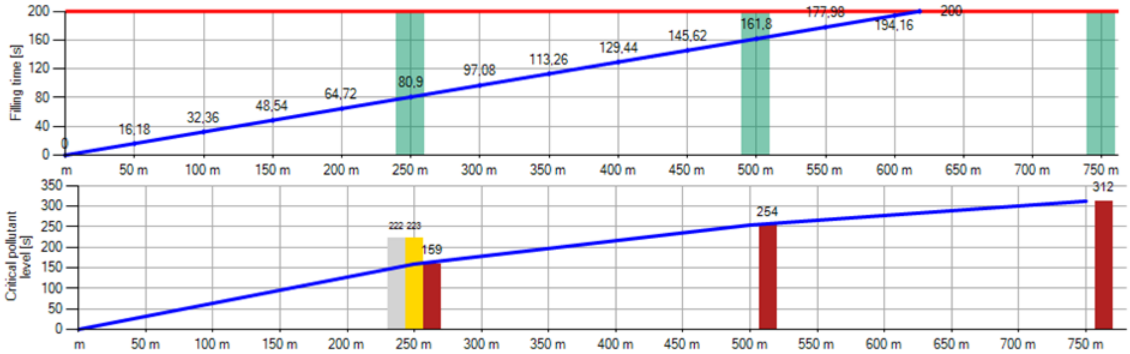

Fig. 4 (above) The tunnel filling time as result of traffic microsimulation model. Exits located every 250 m are highlighted in green. The time to the tunnel closure (200 s) is depicted as a red line); (below) Critical times [s] for CO propagation in grey and HCL propagation in yellow according to smoke propagation model and the custom physical model in brown

The CAPITA method includes an implicit model of smoke propagation valid for a reference tunnel. The simulation was performed using Computation Fluid Dynamics (CFD) software SMARTFIRE for 50 MW fire. The output is the matrix with time (5 s step) and spatial (0,4 m step) distribution of CO (carbon monoxide) and HCL (hydrogen chloride) concentration [ppm] in height of 160 cm at exits. Concentrations at distances corresponding to emergency exits positions were extracted for 4 scenarios (for emergency exits distance 150, 250, 350 and 450 m). The scenario were stored within CSV database thus the calculation core can read the concentrations and, comparing them with threshold values, to determine moment when the particular exit will be no more usable for the evacuation (due to too high toxic concentration). The default values of toxic critical concentration is 6400 ppm CO. Headache and dizziness occur in one to two minutes. All these default toxic values are configurable and might be adjusted for concrete conditions. Time when each emergency exit is reached by critical concentration (if ever) is shown in Fig. 4 for one particular scenario.

The evacuation process can be divided into two main parts: the process needed for human cognition and relevant reaction (awareness and reaction time) and physical process of walking (Person 2002). While the escape process, where people walk to an emergency exit is basically deterministic, the human cognition includes many different stimuli (Boer 2003). The movement time is the component were common simulation (typically micro-simulation) models can be successfully used, for example deterministic simulation models SIMULEX, STEPS, EXODUS or Pathfinder. Walking is described by complex physical and behavioral movement models. Comparison analysis of four models in (Ronchi *et al*. 2012) demonstrates that there is no significant difference in the evacuation time estimation between these micro-simulation models.

EXODUS software was deployed for simulation of three evacuation speeds (0.5 m/s as per Czech national standard ČSN 73 0802; speed 1.3 m/s or statistically distributed speed according to prof. Wiedmann's models) and four distances of emergency exits (150, 250, 350 and 450 m), in total leading to 12 different scenarios (Weidmann 1992). Simulations for all scenarios were run 10 times in order to produce statistically relevant evacuation curves showing the number of persons remaining between emergency exits and decreasing in time as people are escaping. Finally, mean plus standard deviation of evacuation curves was calculated and stored in CSV database.

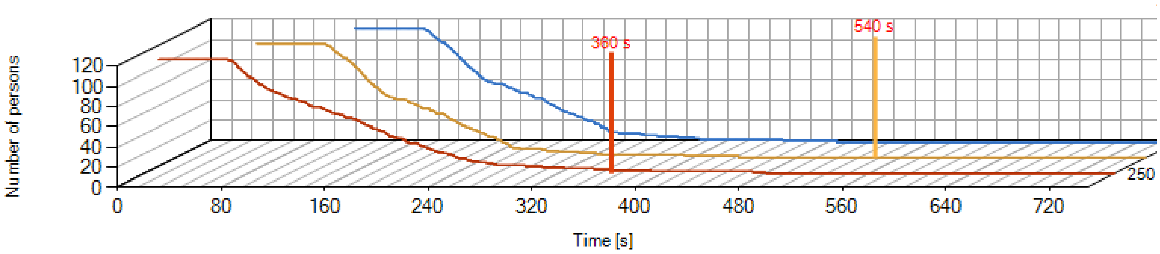

Fig. 5 The number of people leaving the tunnel in time (evacuation process) for different distances between exits (red - 250 m, yellow - 500 m and blue - 750 m). Vertical lines depicts the critical time when the particular exit is blocked due to critical pollutant concentration

Finally, the number of victims is determined by evaluation of the evacuation curves and the smoke propagation curves - at the moment when concentration of toxic pollutants reaches the fatal threshold (critical time is different for each exit), the relevant emergency exit is no longer usable for the evacuation. Chart in Fig. 5 depicts evacuation curves for three exits (250 m, 500 m and 750 m). In case there was no fire and pollutants, initial counts of trapped persons (e.g., 80 people in section of exit 250 m) would decrease in time as the curves depict. The curves for more distant exits (e.g., 750 m) are shifted in time, because the initial maximum count of trapped persons is reached later due to the longer filling time of that section, while the evaluation of people through the first exit 250 m is already in progress.

The vertical lines depicts the time when the particular exit is blocked due to critical pollutant concentration (e.g., 360 s for exit 250 m). This is crucial for a survival of people evacuating through the exit, because once the pollutant concentration reaches the critical threshold, people who did not manage to escape are counted as fatalities.

The Table 3 shows input variables chosen by the program user for a 750 m long tunnel and one of scenarios.

Table 3 Input variables chosen by the program user

Tunnel parameters		**Traffic parameters**	
Tunnel length	750 m	Traffic flow rate	1600 veh/h/lane
Emergency exists distance	250 m	Speed limit for passenger cars	80 kph
Count of lanes	2	Truck percentage	30 % (in the slow lane)
Longitudinal gradient	0 % (in traffic flow direction)	Bus presence	no
Occupancy of cars		**Time to closure and hesitation time**	
Personal car	2 persons	Time to tunnel closure	300 s
Truck	1 person	Hesitation time	50 s
Fire			
Smoke and heat propagation model	custom model of 50 MW fire		
Critical pollutant:	at EX1 in 360 s; EX2 in 540 s; EX3 in 750 s		

Table 4 Results provided by the CAPITA SW

Result of traffic simulation			
Count of trapped cars	141,9 ± 8,77	Count of cars before 1st exit	47,3 ± 2,92
Count of trapped trucks	54,89 ± 4,72	Count of trucks before 1st exit	18,3 ± 1,57
Count of trapped buses	0 ± 0	Total filling time	155,85 s
Count of trapped cars	141,9 ± 8,77	Count of cars before 1st exit	47,3 ± 2,92
Trapped persons		**Result of evacuation model**	
Count of trapped people	339	Evacuation model	Weidman (statistically distributed speed)
Count of people before 1st exit	113	man	50%
Filling time up to first exit	51,95 s	women	50%
		children	0 %
		Total evacuation time	584 s
Mortality			
Trapped persons after tunnel closure		339	
Total number of victims		4	
Mortality		1,17%	

The results provided by the CAPITA program are depicts in Table 4. The total number of victims and mortality which is a ratio of victims and a total number of persons trapped in the tunnel after the fire occurrence is shown also in Fig. 6 for this scenario.

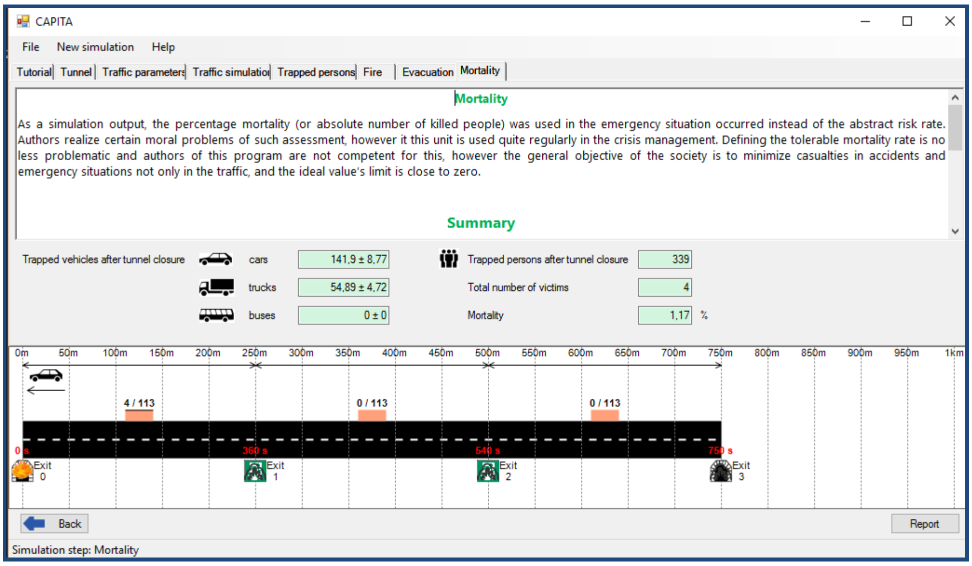

Fig. 6 CAPITA 1.5 user interface - final workflow step with tunnel visualization and mortality calculation (critical times on particular exits in red, victims shown as black columns)

4. Conclusions

Tunnels and bridges belong to the critical infrastructure points, and therefore it is necessary to evaluate the safety across the entire lifetime of the tunnel. Certainly, the risk varies for different situations, such as different number of vehicles, the ratio of trucks and busses or number of passengers. It is very difficult to determine whether or how a certain change in input parameters will affect safety, expressed as the probable number of fatalities. This problem overcomes the risk assessment method CAPITA presented in this paper. A SW tool CAPITA 1.5 resulting from the proposed approach can be used in real time by tunnel managers without any significant time or resource investment to estimate the risk level based on actual input parameters. In case a higher risk is indicated, detailed risk analysis must be provided. CAPITA is therefore a complementary method to standard risk analysis methods.

CAPITA method is the first approach that enables risk assessment using predefined scenarios based on micro-simulation models. This approach significantly simplifies the overall complexity and thus enhances the usability of the resulting risk analysis, which allows the decision makers to assess the risk any time before or during tunnel operation. This is not possible with the traditional risk assessment approaches. Also, it provides the decision maker with holistic view by providing not only on the expected risk but also on the risk's sensitivity to different variables. This is all done in a simple way based on predefined scenarios.

The factors critically effecting potential mortality include the number of and distance between emergency exits (directly impacts the speed of the evacuation), the time required for the fire detection system to detect the fire and close the tunnel, and the system for informing people about the emergency situation. The proposed approach is universal and can be applied for analysing any specific road tunnel.

The CAPITA 1.5 SW tool was built on the theoretical foundations presented in this paper, the CAPITA method. It was developed at the Czech Technical University in Prague, Faculty of Transportation Sciences. It allows the risk analysts to compute and analyse various scenarios for the investigated tunnel in order to assess adequacy of its technical facilities and construction cost with respect to operational safety. Furthermore, the decision makers get not only a single value for risk, but they also get the sensitivity of the risk to changes in the input parameters.

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