METHODOLOGY OF USING CFD-BASED RISK ASSESSMENT IN ROAD TUNNELS

by

Peter VIDMAR and Stojan PETELIN

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The definition of the deterministic approach in the safety analyses comes from the need to understand the conditions that come out during the fire accident in a road tunnel. The key factor of the tunnel operations during the fire is the ventilation, which during the initial fazes of the fire, impact strongly on the evacuation of people and latter on the access of the intervention units in the tunnel. The paper presents the use of the computational fluid dynamics model in the tunnel safety assessment process. The model is validated by comparing data with experimental and quantifying the differences. The set-up of the initial and boundary conditions and the requirement for grid density found during the validation tests is used to prepare three kind of fire scenarios 20 MW, 50 MW, and 100 MW, with different ventilation conditions; natural, semi transverse, full transverse, and longitudinal ventilation. The observed variables, soot density and temperature, are presented in minutes time steps trough the entire tunnel length. Comparing the obtained data in a table, allows the analyses of the ventilation conditions for different heat releases from fires. The second step is to add additional criteria of human behaviour inside the tunnel (evacuation) and human resistance to the elevated gas concentrations and temperature. What comes out is a fully deterministic risk matrix that is based on the calculated data where the risk is ranged on five levels, from the lowest to a very danger level. The deterministic risk matrix represents the alternative to a probabilistic safety assessment methodology, where the fire risk is represented in detail as well as the computational fluid dynamics model results are physically correct.

Key words: *fire, tunnel ventilation, benchmarking, risk analysis*

Introduction

Fire and smoke behaviour inside the tunnel depend mostly on ventilation, either natural or forced. Different ventilation analyses are present in the literature, empirical models that are often combined with a network approach for complex tunnel networks [1]. Computational fluid dynamics (CFD) models [2, 3] are usually used for the analyses of the ventilation system, the operation regime during the fire and the assessment of the optimal air velocity and the ventilators set-up [4, 5]. Authors like [6] present simple models for the computation of critical velocities, where differential conservation equations are solved in two or at least in one dimension [7]. Mathematical models are generally validated on standard experiments [8] or on small-scale experiments. However, it is clearly noted that findings and results are very rare indicated for the immediate use in practice for tunnel constructors, safety systems project ants, fireman's, and others [9].

Following this idea we believe, that a methodology of fire safety valuation, which improves existing methodologies and is based on deterministic approach, is necessary. The presented analysis includes the fire pirolisys, sharing the tunnel into sectors of different sizes, and the calculation of fire dynamics with a CFD model. The obtained data are still too much scientific, thought they are presented in a graphs and diagrams. The problem comes when 15 or 20 scenarios are required in a safety assessment and a number of graphs become too large. This kind of report should be very comprehensive and difficult to understand by the user (tunnel operator). The idea is therefore to design a tunnel risk analyses tool, which is based on CFD results for different fire scenarios and includes basic human behaviour *e. g.* resistance on height temperature and gas concentration, evacuation velocity, reaction times, and other features [10].

Methodological approach on tunnel safety

In order to identify the interactive and uniting relationships in a system, analysis is necessary to replace the apparent structure of individual statements on the components of a system and their relationships with their underlying common logical structure (system analysis). For example, if we are dealing with a system which we call "a chemical process plant", we get at its various components successively, by means of deductive analysis: the buildings, the operators, the storage tanks, the control systems, the operating procedures, *etc.* [11]. Each such component is thrown into the modelling reality by a distinct act of noticing, and is steadily held together with those components already segregated. The aim of system analysis is to investigate the system's behaviour (*i. e.* the succession of its states over time) on the basis of its components' changes with time. The results of system analysis can be expressed in qualitative and quantitative terms (statements resulting from "qualitative analysis" and numbers resulting from "quantitative analysis").

There are different types of systems with regard to predicting behaviour [12].

- *Deterministic systems* are perfectly predictable. That is, they follow an entirely known rule (law, equation, or fixed procedure) so that the state of each component and of the entire system can be given *at* any time *for* any time in the past and future. The states of deterministic systems can be described by statements or by numbers specifying, for example, physical characteristics of the system (observables, such as length and mass of a physical object).
- *Probabilistic systems* involve some degree of uncertainty in predicting their behaviour and require "random variables" to describe the system's components and their interactions. There is no general agreement on what "randomness" of a system actually means (it could, for example, mean generated by chance mechanism, being unpredictable, showing a lack of an apparent order, *etc.*). By describing the states of probabilistic systems by probability numbers, it uses past knowledge to predict future states [13].

- *Chaotic systems* are systems whose future is difficult or impossible to predict over a long period of time because it strongly depends on arbitrarily small and thus not observable variations in the current state. Small variations in the current state of the system can result in large and unpredictable differences in a subsequent state.

Depending on the available data, possibilities, requirements and results of interest, we should decide the best approach to describe the physical system. If we are able to describe the system with physical equations, the deterministic approach should be applied. Otherwise, if the values of the interesting variables are undefined and only statistical data are available, the probabilistic approach is used. The event of fire inside a tunnel is a very complex phenomenon with a great number of depending variables. However many authors, as we in the following sections, have demonstrated that it should be efficiently modelled and simulated, including the most influential initial and boundary conditions. The deterministic approach breathe into the analysis of the greater part of physical events like fire source characteristic and its dynamics, the operation of the ventilation system and other conditions as well as their reciprocal interactions. The approach leads also to the definition of the technical system "safety efficiency" in the range of possibilities that exist in a real word and are functionally descriptive. When the approach is used in practice, we should define a number of "safety categories" base on events probability and consequences for the individual risk. The example in presented in tab. 1.

Table 1. Deterministic safety analysis – supposed safety categories [12]

(a) Likelihood categories Severity category (frequencies)	Qualitative definition	Underlying quantitative definition (times per year)
A	Probability once in a year	0.3-3
B	Possible but not likely	0.03-0.3
C	Unlikely	0.003-0.03
D	Very unlikely	0.0003-0.003
E	Remote	0.00003-0.0003
(b) Consequence categories Severity category (consequences)	**Qualitative definition**	**Underlying semi-quantitative definition**
1	Catastrophic	Multiple fatalities
2	Major	Single fatality, multiple injuries
3	Very serious	Permanently disable injuries
4	Serious	Serious injury, full recovery
5	Minor	Lost time injury, short absence from work

Note that, in these schemes, a quantitative definition is often given in addition to the qualitative definition, mainly to ensure consistency in the course of the analysis and provide benchmarks ("semi-quantitative analysis"). In schemes of this type, the assessment team, usually comprising members of line management, safety engineers and operations personnel, will first identify all hazards, using HAZOP or similar approaches, and then assigns a severity category to each of these, for both likelihood and consequences [14].

Following the assumptions in tab. 1, a "risk matrix" would then be defined as a 5 5 matrix with each side corresponding to one severity category (tab. 2).

Table 2. Deterministic safety analysis – example of risk matrix [12]

"Likelihood" "Severity category"	Consequences "Severity category"				
	5	4	3	2	1
A	▓	▓	■	■	■
B	░	▓	▓	■	■
C	░	░	▓	▓	■
D		░	░	▓	▓
E			░	░	▓

Different shading in a table indicates different risk levels. Hazards with high assessments, such as A1, B1, and A2 in the black squares, are thought of as being very severe and requiring immediate action to reduce. Hazards with low assessments, such as E5, E4, and D5 in the white squares, are considered to require no further action. Hazards between these two (grey squares) are considered worthy of some improvement if a cost-effective solution can be found.

The two methods of risk analysis (qualitative and quantitative) are often not separable but upgrade each other. Figure 1 shows the event tree for the example of a fuel leak out. The quantitative approach is applied because the event probabilities are defined. The results of the event tree are several predicted scenarios with calculated final event frequencies. Between nine final scenarios, there are three fire scenarios with a major frequency; G2, G5, and G8. Further work leads in two directions, with probabilistic approach on deterministic approach. In the following sections the methodology and requirements of using a deterministic approach is explained more is detail.

Computer models and simulations

Deterministic models that would consider all physical parameters are almost unfeasible in practice and if feasible would require very complex and time consuming computations. The application of deterministic analyses results in practice is conditioned by the simplification of some physical phenomena (like turbulence) [15, 16]. The geometry

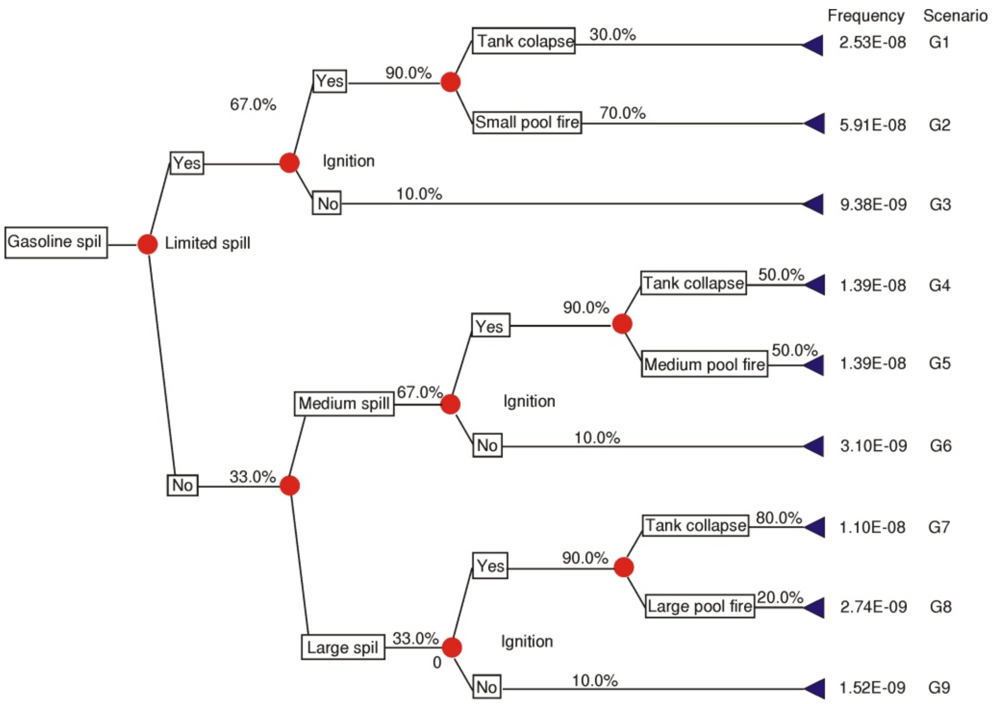


Figure 1. Event tree for fuel leak out scenario [17]

of the tunnel is easily defined, however the definition of wall boundary conditions require a good understanding of tube theory, especially regarding wall friction. In tunnel modelling application and research several modelling approaches exist, whose use depends on the application of results. Here are empirical and lumped parameter models, one-dimensional models, zone models, and CFD models [18]. The last approach and a practical use of results are presented in the following sections.

Physical background

The computer code name is FDS (Fire Dynamics Simulator). The fluid flow is modelled by solving the basic conservation equations. Those are conservation of mass (1), conservation of mixture fraction (2), conservation of momentum (3), and conservation of energy (4) using a form for low Mach number [19, 20]. The approximation involves the filtering out of acoustic waves.

$$\frac{\partial \rho}{\partial t} \quad \rho\vec{u} \quad 0 \tag{1}$$

$$\frac{\partial\rho}{\partial t}(\rho Z) \qquad \rho Z\vec{u} \qquad \rho D \quad Z \tag{2}$$

$$\rho \quad \frac{\partial\vec{u}}{\partial t} \quad \frac{1}{2} \quad |\vec{u}|^2 \quad \vec{u} \quad \omega \qquad \tilde{p} \quad (\rho \quad \rho_\infty)\mathbf{g} \qquad \tau \tag{3}$$

$$\rho c_{\mathrm{p}} \quad \frac{\partial T}{\partial t} \quad \vec{u} \quad T \quad \dot{q}_{\mathrm{c}} \qquad \mathbf{q}_{\mathrm{R}} \qquad k \quad T \tag{4}$$

where ρ is a density, $\vec{u}$ – a velocity vector, Z – the mixture fraction, T – the temperature, and D is a molecular diffusivity. $\tilde{p}$ is the perturbation pressure caused by pressure differences, τ – the viscosity stress tensor, and k – the thermal conductivity. $\dot{q}_{\mathrm{c}}$ and $\mathbf{q}_{\mathrm{R}}$ are the source terms of chemical reaction and radiation, respectively. The radiation term has a negative sign because it represents a heat sink [19].

The effect of the flow field turbulence is modelled using LES (Large Eddy Simulation), in which the large scale eddies are computed directly and the sub-grid scale dissipative processes are modelled [20, 21]. The unknown sub-grid stress tensor τ is modelled by Smagorinsky model [22].

Combustion model

The combustion model is based on the assumption that the combustion is mixing-controlled. This implies that all species of interest can be described in terms of the mixture fraction Z. Heat from the reaction of fuel and oxygen is released along an infinitely thin sheet where Z takes on its stoichiometric value as determined by the solution of the transport equation for Z. The state relations are calculated for a stoichiometric reaction of C_7H_{16} (Oil), which is proposed by [19, 23], and called a crude-oil reaction.

Soot formation

Soot is an important contributor to thermal radiation in fire. In order to calculate the radiation accurately, soot must be considered [24]. Due to the extreme complexity of soot formation process, no very good model is currently available for soot prediction in the combustion of solid fuel, although some significant progress in the soot modelling has been made in the recent years. In this paper the soot was considered by assuming a constant soot conversion factor 3.7%. The soot formation rate was simply assumed to be proportional to the fuel supply rate [2].

Model validation

The section presents the FDS model validation with experimental data from Memorial Tunnel test program 1993 to 1995 in USA. The tunnel is 853 m long and 7.9 m in height with 3.2% slope. Many tests have been conducted with different fire source powers and different ventilation programs. The validation presents two different validation scenarios, with 50 MW fire and natural ventilation and 100 MW fire with forced longitudinal ventilation. The fuel used on the experiment and simulated is oil filled into a flat container [25]. Using the same fuel, different fire heat release rates are obtained only by changing the burning surface [26].

Geometry of the model

The geometry, initial and boundary conditions are arranged to the tunnel geometry and fire parameters. Figure 2 shows the geometry of the tunnel from the external view. The upper closure is just few meters long and is a ventilator room. The fire is located 615 m from the west portal and is symmetrical to the cross-section. The fire is assumed a heat release source with a specific power 2700 kW/m^2, where the oxygen and fuel consumption and the release of combustion products depend on the stoichiometric equation $11O_2 + C_7H_{16}$ $7CO_2 + 8H_2O$. Here C_7H_{16} is a heptane, which burns very similar to a crude-oil just with less soot release. This is additionally added to the combustion model as explained in subsection *Soot formation.* The model includes other combustion products (H_2, N_2, H_2O, O_2, ...) that are default considered and are not matter of our research.

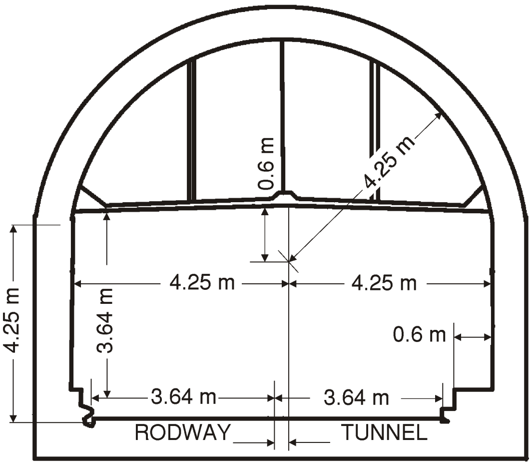


Figure 2. Geometry of the memorial tunnel – north side

Initial and boundary conditions

Initial boundary conditions are divided to geometry obstacle conditions and fluid initial conditions. Walls of the tunnel are defined as thermally thick walls in the model, where heat transfer is computed to and through the walls. The initial temperature of any obstacle is defined the same as ambient (20 °C) temperature. The velocity beside the wall is calculated as the average value of the velocity in the first cell touches the wall and zero velocity on the wall cell (zero velocity). The heat release from the fire source is defined as full power on the beginning of the simulation, because data available from the experiment are only for full-developed fire. Thermal radiation initial conditions are defined with radiation intensity based on the initial temperature of objects (ambient temperature) and the air wavelength that is mostly formed by nitrogen. Heat of radiation emitted from walls is calculated as black wall radiation intensity.

The model simulates the 3.2 % tunnel slope with the additional gravity vector component in the direction of the slope of 0.314 m/s^2.

The portals are defined as open boundary conditions that link the tunnel domain with the ambient.

The applied numerical grid is non-uniform. The geometry is divided in three sections over the tunnel length; 560 m, 120 m and the third 185 m. The reason is the requirement of the combustion model, which compute the reaction and the heat release in the second section where the fire is located. Other parts of the geometry do not require such a dense grid because of lower velocity gradients.

50 MW fire results

The size of the pool is 20 m^2 and the heat release rate is 2700 kW/m^2. The numerical grid density is constant around the fire source area 0.3 0.27 0.3 m in x, y, and z directions.

The initial and boundary conditions used are as defined in the upper section and the results are presented in the following figures.

The first comparison is of the lower and the upper temperature on fig. 3. After 5 min., the upper temperature occurs over the fire and is around 600 °C, the temperature contour 60 °C also agree well comparing experimental and simulation results. The accuracy of the simulation is also confirmed comparing other temperature contours and their distance from the fire. The majority of streamlines move into the slope direction (upstream) and a short tail of 150 m is formed downstream (back layering effect).

Other parameters, measured on the experiment are not presented in the validation because they are strongly dependent of temperature.

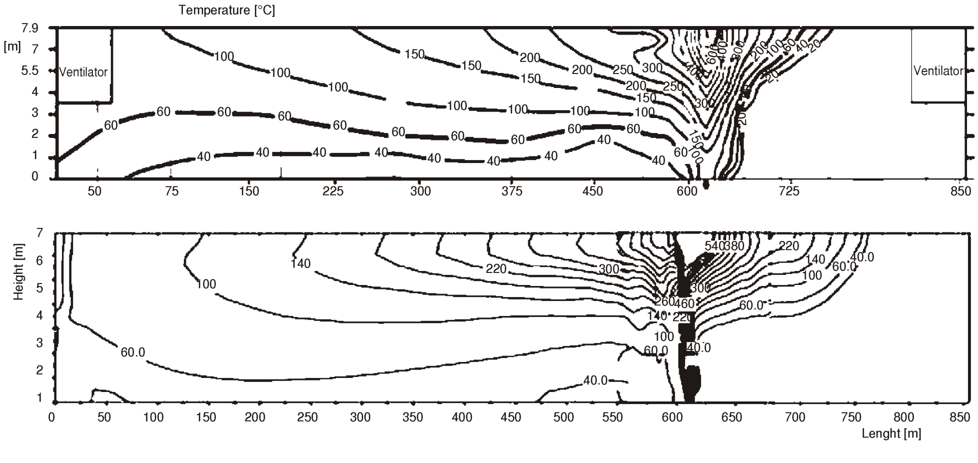


Figure 3. Temperature field along the tunnel centreline for 50 MW fire and 5 min. after the ignition (experiment and simulation)

Figure 4 shows the comparison of temperature fields 15 min. after the ignition. The qualitative estimation of booth results is quite good. Observing the contour of 100 °C we found that its average height is almost the same around 2.5 m. In addition, other contours, for example 300 °C, reach in booth cases the distance around 450 m.

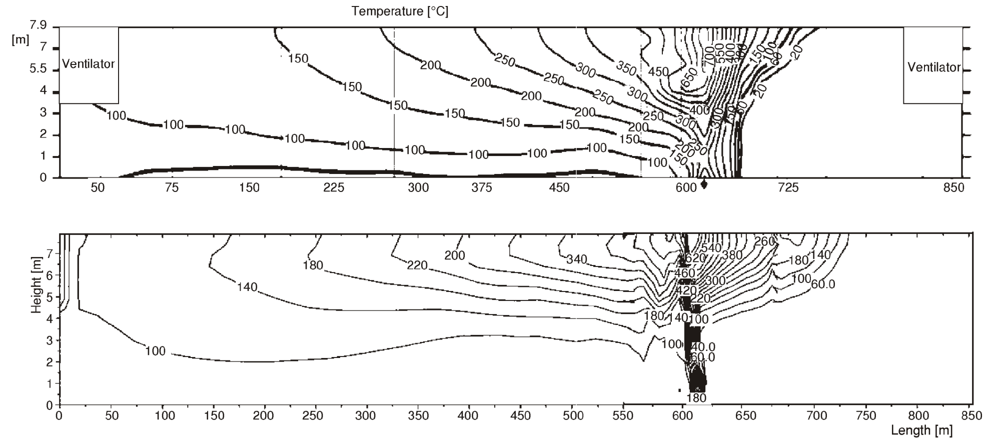


Figure 4. Temperature field along the tunnel centreline for 50 MW fire and 15 min. after the ignition (experiment and simulation)

The conclusion of comparing the results is that the model geometry, initial and boundary conditions and the setting of numerical grid, conform to the numerical requirements for the calculation of fluid dynamics inside the tunnel, against the experimental data. The obtained information's are further used in the construction of other similar models.

100 MW fire results

The validation experiment on Memorial Tunnel Test [25], known under the number 615 B is a 100 MW fire with longitudinal ventilation.

The setting up of ventilators and their signs are presented in fig. 5.

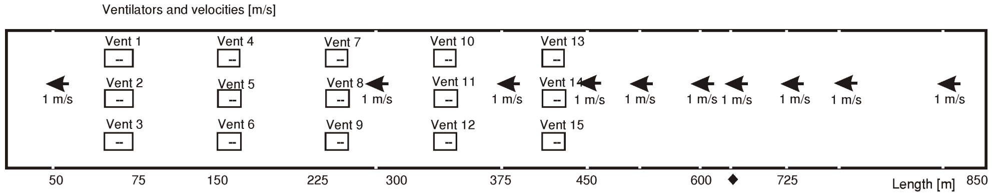


Figure 5. Experiment setup

The size of the fire source is 2 times 24 m^2. The heat release rate is, on other tests, 2700 kW/m^2. The sequence of events, dynamics of fire burnout and the ventilators dynamics is presented in tab. 3.

Table 3. Chronological events sequence on the fire experiment [25]

Memorial tunnel fire ventilation test program		
Summary of test 615B		
Test date:	22.02.1995	
Test type:	Longitudinal ventilation with jet fans 15 jet fans installed	
Fire size:	100 MW (nominal)	
Test events sequence		
	Real time [hr:min.:s]	Elapsed time [s]
Ignitor ignition:	11:50:35	
Fuel oil ignition:	11:50:42	
Full pan engulfment:	11:51:13	00:00
Fuel oil shut-off:	12:16:13	25:00
Pan fuel oil burnout:	12:43:55	52:42
Fan operation		
Fan response time: 2 minutes elapsed time		
Jet fan(s) running	Period of fan operation	
	Real time [hr:min.:s]	Elapsed time [s]
1, 3, 4, 6, 7, 9	11:53:13-12:05:13	2:00-14:00
1, 3, 4, 6, 9	12:05:13-12:13:13	14:00-22:00
1, 3, 4, 6, 7, 9	12:13:13-12:17:06	22:00-25:53
None	12:17:06-12:17:16	25:53-26:03
5, 8, 11 (REV)	12:17:16-12:25:32	26:03-34:19
5, 8, 11, 14 (REV)	12:25:32-12:26:24	34:19-35:11
5, 8, 11, 13, 14, 15 (REV)	12:26:24-12:34:35	35:11-43:22
None	12:34:35 – End of test	43:22 – End of test

The composition of the computer model presented a great effort, because of insufficient knowledge of initial and boundary conditions. Furthermore the minimum requirements for space and time discretization have to be found, to obtain satisfied quality of simulation results against experimental data.

The appropriate numerical grid density was determined above all by continuous simulation repetition and comparison of results. Based upon precedent calculation and predicted velocities around ventilators, which is around 30 m/s, the most optimal grid resolution is:

- in the ventilator surrounding (10 m upstream and 20 m downstream in the direction of ventilation blowing): 0.4 0.3 0.26 m in x, y, and z direction,
- in the fire surrounding (50 m upstream and 50 m downstream): 0.32 0.3 0.33 m in x, y, and z direction, and
- the remnant area, where fluid characteristics are much more stationary: 0.48 0.36 0.39 m in x, y, and z direction.

Initial and boundary conditions are more difficult to prescribe as in the 50 MW fire, especially for ventilators definition. Ventilators are presented as the source and sink of mass flow and are defined as a thin vent in two dimensions. It means that the ventilator geometry is not modelled. The assumption exposed has not a particular effect on the overall fluid dynamics through the tunnel as found during tests. The velocity boundary condition, defining the ventilator, is 30 m/s and has the same sign on both side to allow the throughout flow.

The criterion of the correct space discretization is the comparable simulation of gravity currents [27] that form temperature fields presented in the following figures.

Comparing booth temperature fields measured on the experiment and simulated with FDS after 300 s shows few differences between results. Upstream the fire on fig. 6 (left side) the calculated temperatures field well agrees with experimental results, while downstream (right side) the simulated temperatures are lower for about 40% from experi-

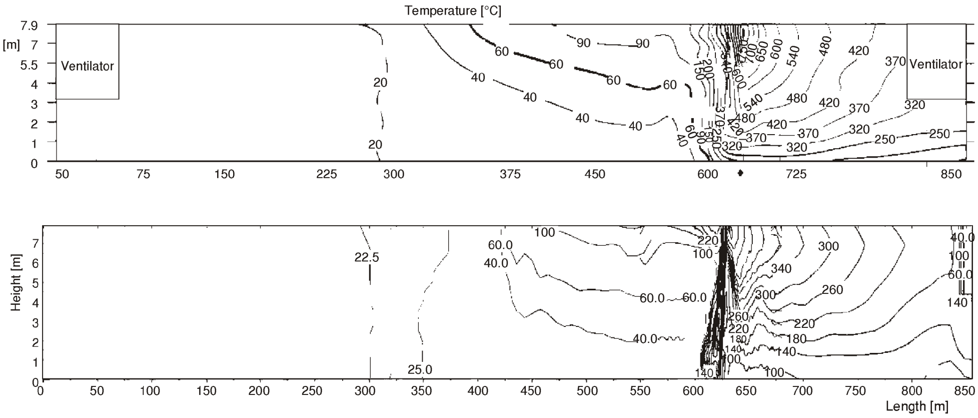


Figure 6. Temperature field along the tunnel centreline for 100 MW fire and 5 min. after the ignition (experiment and simulation)

mental. The main reason found is a transient of grid density from 0.3 to 0.57 m, where a great part of the computation accuracy is lost. Comparing the 50 MW fire with natural ventilation and 100 MW forced ventilation fire we found a great difference of velocity gradients that are higher in forced ventilated test. This implies the requirement of more accurate grid resolution [28], particularly in the fire surrounding. The second is the limit of the mixture fraction model that underestimates the real fire size in the case of coarse mesh and introduces an empirical correlation to the model to correct the fire actual size. This has an important influence on the calculation of the air entrance to the fire surface and consequently to the correct computation of heat release rate and temperatures.

Figure 7 shows the comparison of temperature fields for 100 MW fire, 14 min. after the fire ignition. The major differences are obtained on the upstream (left) side, where the gravity current is not completely inverted downstream as presented on the experimental measurement. The first idea was the differences came from the difficult setting-up of initial and boundary conditions on the model, but after many repeats, similar results have come. Other reasons of such differences should be:
- difficult definition of initial and boundary conditions,
- unsuitable numerical grid density (finest grid would extend the simulation time),
- insufficient understanding of the geometry and experiment performance conditions, and
- defectiveness of the turbulent model.

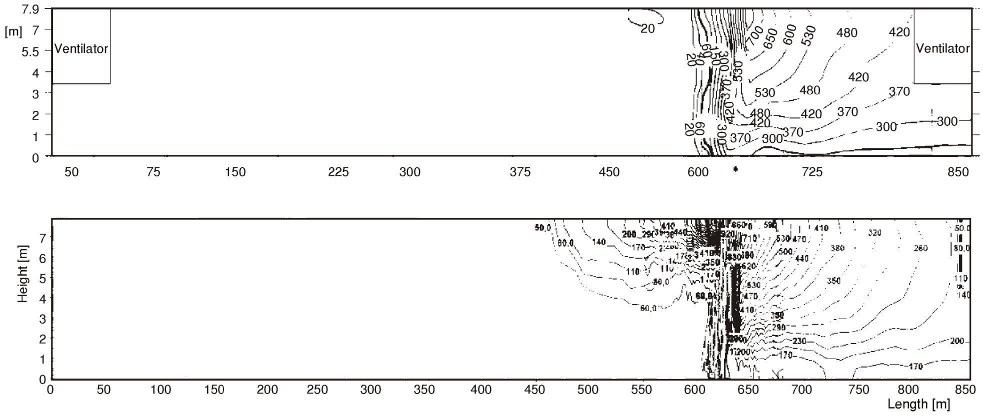


Figure 7. Temperature field along the tunnel centreline for 100 MW fire and 14 min. after the ignition (experiment and simulation)

The setting of finest mesh was difficult to execute, because the simulation would require a long computation time. Furthermore, results should be treated conservatively with a certain degree of deviation [29]. The difference should be quantified from the figure where the major deviation is presented in a 100 m upstream flow.

The conclusions of validation tests are that results from forced ventilation models have to be handled with care and with a good degree of conservation. Simulation models with low velocity gradients *e. g.* natural or low speed forced ventilations should be accepted with a good degree of accuracy. The obtained knowledge in setting-up different models is then used in the preparation of other model scenarios, theirs geometry characteristics and other conditions.

Tunnel fire analysis

The search for a universal method is practically impossible because of the problems complexity and the safety conception. Most researchers are avoiding the universal methods because of their high complexity level and their relatively low result reality level. It is known that universal methods turn out right only as theories but their application is hard to transfer to real problems.

The methodology presented in the dissertation is based on a model accession. The reality of the methodology is proved with valid model results and numerous scenarios with which a whole spectre of tunnel fire problems is taken into account, considering different types of ventilation and different fire sizes. Other parameters like: environment influence, traffic density, and other characteristics of the tunnel are handled separately.

The idea is based on the making of a deterministic risk matrice as it is showed in tab. 2. The safety category is represented by the power of the fire and the type of ventilation at different strengths. The consequences are evaluated in the time during the progress of the fire. The risk criteria are defined as a relation between the hot smoke layer height, the distance from the fire position, and the evacuation time of the users. In case the speed of the smoke is higher than the speed of the evacuation and in case the height of the hot layer is higher than the speed of the evacuation, the risk is high.

Tunnel fire scenario

Validation tests from the section *Model validation* show the first successful simulation measure because they define the reliability of the results. The first simulation reliability condition, are suitable physical models and the numeric reliability of the transfer equations rescue method. These facts are shown within the subsection *Computer models and simulations*. The computer program FDS is a consolidated program that encloses physical models needed for the list of circumstances during the fire in a tunnel. The precision while solving the transfer equations is very dependent on the geometry and the initial and boundary conditions. In greater fire forces or high starting speed the scale of the numeric net represents a key condition for the accuracy of the results. That is why validation tests are of key importance in the search for suitable models discretization.

All together 12 tunnel fire scenarios are presented. Three levels of fire force are simulated, each with four different types of ventilation. The span of the fire force is between 20, 50, and 100 MW whilst the ventilation is sorted from the less to the more effective: 1 – natural, 2 – longitudinal, 3 – semi transverse, and 4 – transverse or improved transverse ventilation.

The whole section of the simulated tunnel is 650 m long, the other dimensions are: width 10 m and height 8 m or 6 m when the roof is lowered. Though the dimensions and shape of the tunnel tube partly differenciate among them that does not influence what happens during the fire. That is why ordinary skeleton measurements are chosen. The geometry of the tunnel model, the type of ventilation, and the location of the fire are shown in fig. 9.

The fire is placed on a distance of 300 m in all the models, it differs only in the size of the burning area. The focus point is defined as the heat source to which the combusted model calculates the mass transfer on the base of the accorded combusting reaction and the oxygen consumption. The focus point is shown in sketch (fig. 8). When we define the base igniting temperature, heat conductivity, calorific value, *etc*. (depending on the models demands) it is treated in the model as combustible substance and it cooperates with the generation of heat in the combusting model. In case of the described scenarios, the base is relatively small or of small volume, that is why the heat contribution of the burning base is only a few percent of the defined freed heat of the boundary condition.

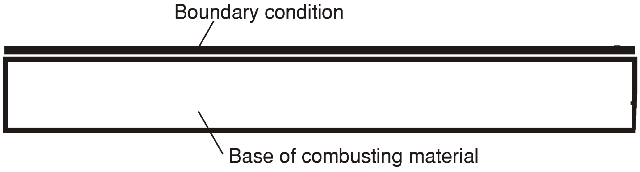


Figure 8. Sketch of the focus point and way of laying the boundary conditions

Fire simulation

As previously mentioned in previous chapters, for the simulation of current dynamics and combustion during a fire, the computer program FDS version 4 is used which is developed by the NIST, USA. The CFD rescue model on personal computers is in wider use only in recent years because of the sufficient capacity of these computers. Until then such simulations could only be executed on working stations that were not available to everyone. Parallel connections between computers in a local network are used frequently because each personal computer has limited hardware capacity. Because the limitation in available memory of each computer is important we acquire multiple increases in computer memory with a parallel connection. This means that we can comprise grater geometry of the tunnel or a more dense numeric net in a given sector.

Even though the capacity of the memory increases so many times as there is more working memory available, that does not count for the calculation speed of the model. In the division of the model in separate sectors or partitions, the exchange of boundary conditions between partitions is defined by program. This demands additional computer capacities, especially because of the convergence of solutions on limits of two partitions. In this case it is recommended to perform a partition cover on the limits with which we achieve a more accurate solution on crossings. To the weaknesses of parallel modelling, we can add the time spent on exchanging the data over the network connection in case it is not fast enough.

For the calculation of the 12 presented scenarios were used 4 connected computers – PC 2.8 MHz with a join memory capacity of 2.5 GB. The discretization of each model amounts to near 800.000 computer points which does not occupy all of the available working memory. From a computers viewpoint this is important because while calculating each operation there is no writing on the computer disk, which takes additional calculating time. Optimal relation between numerical grid density, calculation time and result reliability has been chosen after multiple simulation repetitions, calculation times comparison, and result validation (numeric and sensitive computer model analysis is not presented in this paper).

Initial, boundary conditions and discretization

The definition of the initial and boundary conditions is a peculiarity of each model. Four elementary types of ventilation are discussed: natural, longitudinal, semi transverse, and transverse. In definition of the geometry of the tunnel tube, the natural and longitudinal ventilation are discussed together and the semi transverse and transverse ones also in the same way. The comparison is shown in fig. 9.

It is clear that the tunnel models with natural and longitudinal ventilation take the whole section of the tunnel, however the tunnel models with semi transverse and transverse ventilation consider only the light section of the tunnel (without the ventilation drains). The suction flaps are defined with the speed margin condition on the limit of the calculating domain. The same goes for the intake canals in the transverse ventilation with the difference that the current has the opposite direction. The boundary and initial conditions of all of the four models shows tab. 4.

The space discretization of the mass equations, motive quantity and heat energy is derived with the method of finite difference in the central differential scheme in a square net. The time discretization of the transfer equations is made on an explicit scheme of predictor-corrector.

Parameters and approach to the result analysis

The simulation results are presented on levels of fire force and types of tunnel ventilation shown in fig. 9. The consequences of the distance of the smoke and the temperature are qualitatively evaluated from the current and temperature field. With this, it must be noted that mistakes are possible in calculating the average value in different time

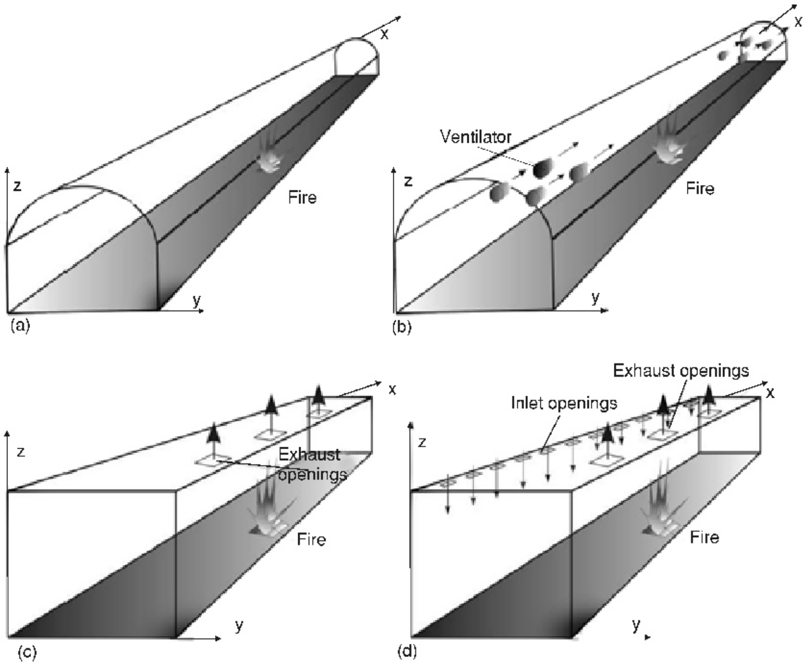


Figure 9. Model geometry in different types of ventilation
(a) natural ventilation, (b) longitudinal ventilation, (c) semi transverse ventilation, (d) transverse ventilation

and space steps, which are limited with the unified way of average calculating. With that, it is true that the risk of exposure to smoke is that the participant is exposed in the moment when the smoke reaches him. The most risky examples are the ones when the participant does not start with the immediate self-rescue procedure after the start of the fire and the second when the spreading speed of the smoke is higher then the self-rescue procedure speed of the participants in the tunnel. The other risk criterion is high temperature that usually has a lower contribution to the risk than smoke. In most cases this depends on the way of ventilation.

The limit value of the concentration of smoke particles (PM10 heavy particles with the diameter up to 10 μm) is 1000 mg/m^3 [18] and the limit temperature is 50 °C [18]. Though the smoke particles are less problematic from a poisonous point of view, than other combustible products (CO_2 – carbon dioxide, CO – carbon monoxide, HCN – hydrogen cyanide, HCl – hydrogen chloride, *etc.*) their relation to the concentration is conditional and often very similar. From different experiments in the Memorial Tunnel [26] it can be found, for example, concentrations of smoke particles and CO in relation around 10:1. A similar relation can be also found on toxic levels of these products. LC_{50} (lethal concentration 50%) for soot particles is 30 g/m^3 in a 30 min. exposure or 1-3 g min./m^3 LC_{50}, for CO is 2000-3500 ppm, which is 2300-4000 mg/m^3 in a 30-60 min exposure [18]. The limit temperature values of human endurance are according to Gann [18] 100 °C for 30 min. and 75 °C for 60 min. of exposure.

Table 4. Boundary and initial conditions for different types of ventilation

Ventilation/ boundary and initial conditions	Natural	Alongside	Semi transverse	Transverse
Portals	Open boundary condition	Open boundary condition	Open boundary condition	Open boundary condition
Walls	$T_{\text{initial}} = T_{\text{environment}}$ $I_{\text{radiation}} = I_{\text{black body}}$ $v_{\text{wall}} = 1/2\ v_0$	$T_{\text{initial}} = T_{\text{environment}}$ $I_{\text{radiation}} = I_{\text{black body}}$ $v_{\text{wall}} = 1/2\ v_0$	$T_{\text{initial}} = T_{\text{environment}}$ $I_{\text{radiation}} = I_{\text{black body}}$ $v_{\text{wall}} = 1/2\ v_0$	$T_{\text{initial}} = T_{\text{environment}}$ $I_{\text{radiation}} = I_{\text{black body}}$ $v_{\text{wall}} = 1/2\ v_0$
Focus point	20 MW– 6 3 m – 1333 kW/m^2 50 MW – 10 3m – 1666 kW/m^2 100 MW – 15 4 m – 1666 kW/m^2	20 MW – 6 3 m – 1333 kW/m^2 50 MW – 10 3 m – 1666 kW/m^2 100 MW – 15 4 m – 1666 kW/m^2	20 MW – 6 3 m – 1333 kW/m^2 50 MW – 10 3 m – 1666 kW/m^2 100 MW – 15 4 m – 1666 kW/m^2	20 MW – 6 3 m – 1333 kW/m^2 50 MW – 10 3 m – 1666 kW/m^2 100 MW – 15 4 m – 1666 kW/m^2
Longitudinal ventilators	–	6 2 ventilators $v_{\text{vent.}} = 30$ m/s	–	–
Transverse ventilators	–	–	Exhaust: 3 53 m^3/s	Intake: 101 0.64 m^3/s Exhaust: 3 53 m^3/s
Smoke exhaust	–	–	–	–
Air intake	Through portals	Through portals	Trough portals	Trough import ventilators Through portals
Source dynamics	$T = 0.0$,* $F = 0.5$* $T = 120.0$, $F = 1.0$ $T = 500.0$, $F = 1.0$ $T = 900.0$, $F = 1.0$	$T = 0.0$, $F = 0.5$ $T = 120.0$, $F = 1.0$ $T = 500.0$, $F = 1.0$ $T = 900.0$, $F = 1.0$	$T = 0.0$, $F = 0.5$ $T = 120.0$, $F = 1.0$ $T = 500.0$, $F = 1.0$ $T = 900.0$, $F = 1.0$	$T = 0.0$, $F = 0.5$ $T = 120.0$, $F = 1.0$ $T = 500.0$, $F = 1.0$ $T = 900.0$, $F = 1.0$
Longitudinal ventilation dynamics	–	$T = 0.0$, $F = 0.0$ $T = 500.0$, $F = 0.0$ $T = 560.0$, $F = 0.5$ $T = 720.0$, $F = 1.0$ $T = 1800.0$, $F = 1.0$	–	–
Transverse ventilation dynamics			$T = 0.0$, F = 0.0 $T = 60.0$, F = 0.0 $T = 120.0$, F = 1.0	$T = 0.0$, $F = 0.0$ $T = 60.0$, $F = 0.0$ $T = 120.0$, $F = 1.0$

* T = time [s], F = max. variable value factor [0...1]

Because this information is true for an adult man it is the most optimal. But within the same research there are difficulties in breathing already at 65 °C of air temperature. Taking this into account there are two values that are used in the result analysis. The chosen limit concentration of smoke particles is 1000 mg/m^3 and the limit temperature is 50 °C.

The risk or consequences are divided in five categories that are shown in tab. 1:

1. LR – low risk: smaller injury
2. MR – medium risk: serious injury with full recovery
3. SR – serious risk: permanent injury
4. VHR – very high risk: low casualty number (1-3), numerous injured
5. EHR – extremely high risk: numerous casualties

In the result analysis each category matches a logical inscription and it conditions with the time from the start of the simulation, any distance from the fire area, fire force, way of ventilation, limit value of the concentration of smoke particles, and the limit temperature. Then follow the conditional clauses of each category:

LR: ASD < 500.
MR: ASDL > 500. SLH > ASLH
SR: ASD > 500.
VHR: ASDL > 500. SLH < ASLH
EHR: ((SR VHR) AT > 50.) ATL > 50.

where the abbreviations mean:

ASD – average smoke density value in profile, [mg/m^3],
ASDL – average smoke density value in layer, [mg/m^3],
SLH – smoke layer height, [m],
ASLH – allowed smoke layer height, [m],
AT – average temperature in profile, [°C],
ATL – average temperature in layer, [°C],
TLH – temperature layer height, [m], and
ATLH – allowed temperature layer height, [m].

The CFD simulation results are discreet in space and time with extremely small space and time steps. An analysis of so many information is logical only in a graphic form either with a graphic intermediate starting point (smokeview, ...) or with discreetness in only one variable (space and time) in form of diagrams. From a safety view point and from a point of view of intervention during the fire in the tunnel such a large quantity of information is illogical, unclear, and as such useless. From the whole data base mostly spatially average values in height longitudinal the tunnel axis are important together with the time average values with the interval of 60 seconds. The information is average also in the tunnel height with that the tunnel is divided in four equal layers in which an average value for layer height is calculated for each spatial step. For an easier understanding the accession is presented graphically on fig. 10.

The marked points in fig. 10 represent the average value of the variables that is used in the result analysis. In the horizontal direction the number of points is equal to the number of the CFD model divisions but in the vertical direction the number is reduced to four average values for each layer. Depending on the discreetness in the horizontal direction where the numeric net is usually denser in the area with higher gradients the higher number of information describes the smaller physical distances.

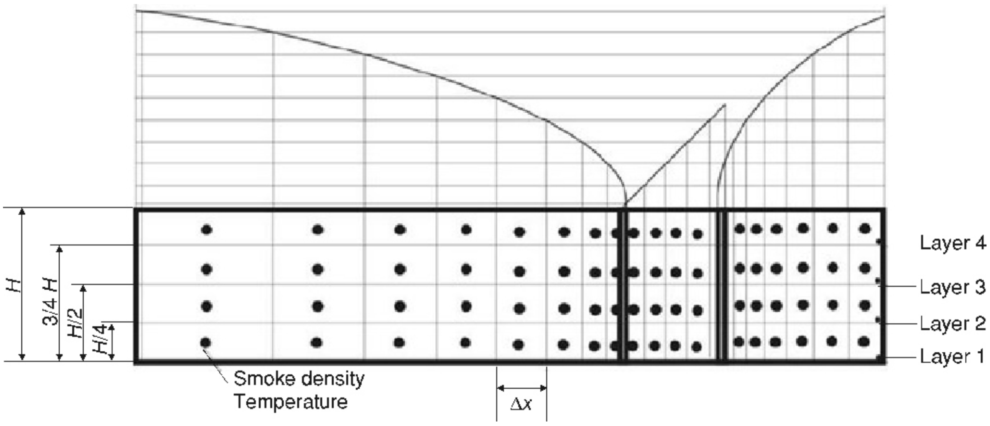
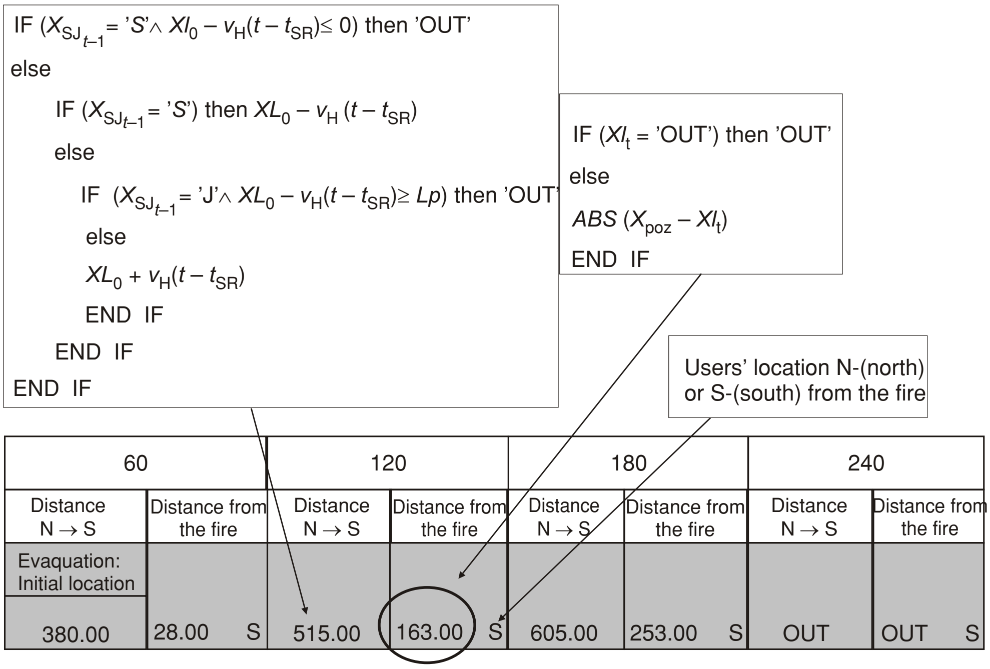


Figure 10. Method of calculating the spatial average in height longitudinal the tunnel axis

Evacuation model

The easier discussing of results is enforced with the understanding of the peoples behaviour during a fire in the tunnel which after the spotted fire begin with the self-rescue procedure. This is a withdrawal from the tunnel or to the first transverse passage in two tube tunnel scenarios. The movement of the people in similar conditions is very unpredictable, some become immediately aware of the danger and begin with the self-rescue procedure others do not perceive the danger in time and start with the self-rescue procedure too late. On self-rescue there is a simplified model of people movement in the tunnel. The model takes into consideration the elementary movement parameters as: start of the self-rescue, walking speed, tunnel length, and logical curiosity that in the initial location north or south arranges the movement direction north or south. With this the possibility of a tunnel user approaching the fire during the self-rescue procedure is excluded in the model. With a program the self-rescue procedure is defined with the following conditional note (fig. 11).

The marks in the note represent:



```
IF ($X_{\mathrm{SJ}_{t-1}}$ = 'S' ∧ $XI_0 - v_\mathrm{H}(t - t_\mathrm{SR}) \le 0$) then 'OUT'
else
    IF ($X_{\mathrm{SJ}_{t-1}}$ = 'S') then $XL_0 - v_\mathrm{H}(t - t_\mathrm{SR})$
    else
        IF ($X_{\mathrm{SJ}_{t-1}}$ = 'J' ∧ $XL_0 - v_\mathrm{H}(t - t_\mathrm{SR}) \ge Lp$) then 'OUT'
        else
        $XL_0 + v_\mathrm{H}(t - t_\mathrm{SR})$
        END IF
    END IF
END IF
```

```
IF ($XI_t$ = 'OUT') then 'OUT'
else
$ABS\ (X_\mathrm{poz} - XI_t)$
END IF
```

Users' location N-(north) or S-(south) from the fire

60		120		180		240	
Distance N → S	Distance from the fire	Distance N → S	Distance from the fire	Distance N → S	Distance from the fire	Distance N → S	Distance from the fire
Evaquation: Initial location							
380.00	28.00 S	515.00	163.00 S	605.00	253.00 S	OUT	OUT S

Figure 11. Evacuation model

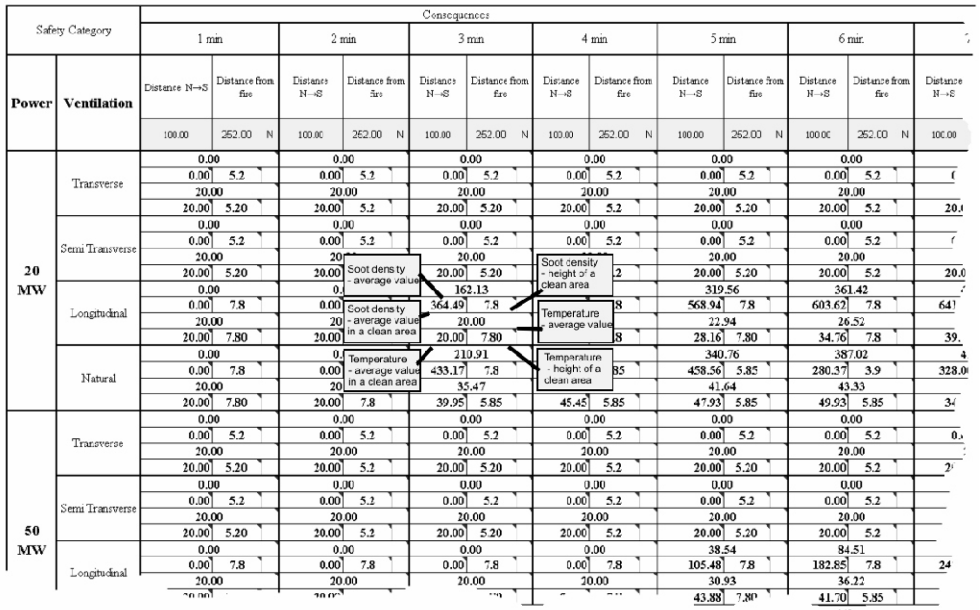
$X_{\mathrm{SJ}_{t-1}}$ – position of the user regarding the location of the fire (N or S) in precedent time step, [m],
XL_0 – starting location of the self-rescue observed from a starting portal, [m],
XL_t – users location in the observed time period, [m],
X_poz – locations of the fire observed form a starting portal, [m],
v_H – walking speed, [m/s],
t – momentarily observed time period, [s], and
t_SR – delay of the self-rescue after the start of the fire, [s].

With the presented model the possibilities of the analysis or the following of the movement of the users in the tunnel increase additionally. The calculated locations are then used for checking the temperature and the smoke concentration on the ground in these places and consequently the level of risk.

Results

The presentation of the results in a form of current characteristic graph has proved to be unsuitable. The shape of the current profile can give useful information only to an experienced user and an expert of the tunnel ventilation problems. More useful information is the numerical value of the requested variable that is given in a spatial and time step as it shows in tab. 5. In the table, the temperature and smoke values are given as the most influential risk parameters in the tunnel. In the second part the matrix gives a risk level on the basis of numerical values and conditional dependence presented in subsection *Parameters and approach to the result analysis* . The first level of risk is presented by the presence of smoke that includes the first four risk stages, the presence of high temperature contributes additional (the highest) risk stage. Table 6 presents a deterministic matrix of risk during a fire for a constant location in a tunnel that is 252 m north of the fire. The picture that we get whit this is very representative because it confirms the theory on safety analyses from the section *Methodological approach on tunnel safety*. From the table the safety categories can be seen and appropriate consequences can be allocated.

Table 5. Matrix of soot density and temperature (cut-out)



Safety Category		Consequences												
		1 min		2 min		3 min		4 min		5 min		6 min		
Power	**Ventilation**	Distance N→S	Distance from fire	Distance N→S	Distance from fire	Distance N→S	Distance from fire	Distance N→S	Distance from fire	Distance N→S	Distance from fire	Distance N→S	Distance from fire	Distance N→S
		100.00	252.00 N	100.00	252.00 N	100.00	252.00 N	100.00	252.00 N	100.00	252.00 N	100.00	252.00 N	100.00
20 MW	Transverse	0.00		0.00		0.00		0.00		0.00		0.00		
		0.00	5.2	0.00	5.2	0.00	5.2	0.00	5.2	0.00	5.2	0.00	5.2	
		20.00		20.00		20.00		20.00		20.00		20.00		
		20.00	5.20	20.00	5.2	20.00	5.20	20.00	5.2	20.00	5.20	20.00	5.2	20.
	Semi Transverse	0.00		0.00		0.00		0.00		0.00		0.00		
		0.00	5.2	0.00	5.2	0.00	5.2	0.00	5.2	0.00	5.2	0.00	5.2	
		20.00		20		20.00		[illegible]		20.00		20.00		
		20.00	5.20	20.00	[illegible]	20.00	5.20	[illegible]	2	20.00	5.20	20.00	5.2	20.0
	Longitudinal	0.00		0.		162.13		[illegible]		319.56		361.42		
		0.00	7.8	0.00	[illegible]	364.49	7.8	[illegible]	8	568.94	7.8	603.62	7.8	64
		20.00		20		20.00		[illegible]		22.94		26.52		
		20.00	7.80	20.00	[illegible]	20.00	7.80	[illegible]	8	28.16	7.80	34.76	7.8	39.
	Natural	0.00		0.		210.91		[illegible]		340.76		387.02		4
		0.00	7.8	0.00	[illegible]	433.17	7.8	[illegible]	85	458.56	5.85	280.37	3.9	328.0
		20.00		20		35.47		[illegible]		41.64		43.33		
		20.00	7.80	20.00	7.8	39.95	5.85	45.45	5.85	47.93	5.85	49.93	5.85	34
50 MW	Transverse	0.00		0.00		0.00		0.00		0.00		0.00		
		0.00	5.2	0.00	5.2	0.00	5.2	0.00	5.2	0.00	5.2	0.00	5.2	0.
		20.00		20.00		20.00		20.00		20.00		20.00		
		20.00	5.20	20.00	5.2	20.00	5.20	20.00	5.2	20.00	5.20	20.00	5.2	2
	Semi Transverse	0.00		0.00		0.00		0.00		0.00		0.00		
		0.00	5.2	0.00	5.2	0.00	5.2	0.00	5.2	0.00	5.2	0.00	5.2	
		20.00		20.00		20.00		20.00		20.00		20.00		
		20.00	5.20	20.00	5.2	20.00	5.20	20.00	5.2	20.00	5.20	20.00	5.2	
	Longitudinal	0.00		0.00		0.00		0.00		38.54		84.51		
		0.00	7.8	0.00	7.8	0.00	7.8	0.00	7.8	105.48	7.8	182.85	7.8	24
		20.00		20.00		20.00		20.00		30.93		36.22		
		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	43.88	7.80	41.70	5.85	

Table 6 has especially a comparative purpose for finding the influence of different types of ventilation on the fire dynamic, smoke, and temperature development. We can logically assume that the risk in low fire force is lower in comparison with bigger fires. Following the same logic along with the consideration of different types of ventilation and manner of management it soon becomes difficult. One of the noticeable differences is the level of the calculated risk (MR – medium risk) in longitudinal ventilation of a 20 MW fire. It is expected that the increased risk also appears in the 50 MW fire but it is not so. The search for a cause is difficult because this is hidden in the fluid dynamics dur-

Table 6. The deterministic risk matrix for the chosen observer location (part 1)

1	Safety category		Consequences													
			60		120		180		240		300		360		420	
	Power	Ventilation	Distance N S	Distance from fire	Distance N S	Distance from fire	Distance N S	Distanc from fire	Distance N S	Distanc from fire	Distance N S	Distanc from fire	Distance N S	Distance from fire	Distance N S	Distance from fire
			330.00	22.00 N	350.00	2.00 N	0.00	352.00 N	500.00	148.00 S	50.00	302.00 N	0.00	352.00 N	0.00	352.00 N
			People initial location		People location		People location		People location		People location		People location		People location	
			100.00	252.00 N	100.00	100.00 N	100.00	252.00 N	100.00	252.00 N	100.00	252.00 N	100.00	252.00 N	100.00	252.00 N
			Evaquation: Initial location													
			0.00	352.00 N	OUT	OUT N	OUT	OUT N	OUT	OUT N	OUT	OUT N	OUT	OUT N	OUT	OUT N
2	20 MW	Transverse	LR		LR		LR		LR		LR		LR		LR	
			LR		LR		LR		LR		LR		LR		LR	
		Semi transverse	LR		LR		LR		LR		LR		LR		LR	
			LR		LR		LR		LR		LR		LR		LR	
		Longitudinal	LR		LR		LR		MR		MR		MR		MR	
			LR		LR		LR		MR		MR		MR		MR	
		Natural	LR		LR		LR		LR		LR		LR		LR	
			LR		LR		LR		LR		LR		LR		LR	
3	50 MW	Transverse	LR		SR		LR		LR		LR		LR		LR	
			LR		SR		LR		LR		LR		LR		LR	
		Semi transverse	LR		LR		LR		LR		LR		LR		LR	
			LR		LR		LR		LR		LR		LR		LR	
		Longitudinal	LR		LR		LR		LR		LR		LR		LR	
			LR		LR		LR		LR		LR		LR		LR	
		Natural	LR		LR		LR		SR		SR		SR		SR	
			LR		LR		LR		EHR		EHR		EHR		EHR	
4	100 MW	Transverse	LR		SR		LR		SR		SR		SR		SR	
			LR		SR		LR		SR		SR		SR		SR	
		Semi transverse	LR		SR		LR		LR		SR		SR		SR	
			LR		SR		LR		LR		SR		SR		SR	
		Longitudinal	LR		LR		LR		LR		LR		LR		LR	
			LR		LR		LR		LR		LR		LR		LR	
		Natural	LR		LR		SR		SR		SR		SR		SR	
			LR		LR		EHR		EHR		EHR		EHR		EHR	

Table 6. The deterministic risk matrix for the chosen observer location (part 2)

	Consequences															
1	480		540		600		660		720		780		840		900	
	Distance N S	Distance from fire	Distance N S	Distance from fire	Distance N S	Distance from fire	Distance N S	Distance from fire	Distance N S	Distance from fire	Distance N S	Distance from fire	Distance N S	Distance from fire	Distance N S	Distance from fire
	0.00	352.00 N	0.00	352.00 N	0.00	352.00 N	0.00	352.00 S	0.00	352.00 N	0.00	352.00 N	0.00	352.00 N	0.00	352.00 N
	People location		People location		People location		People location		People location		People location		People location		People location	
	100.00	252.00 N	100.00	252.00 N	100.00	252.00 N	100.00	252.00 N	100.00	252.00 N	100.00	252.00 N	100.00	252.00 N	100.00	252.00 N
	OUT	352.00 N	OUT	OUT N	OUT	OUT N	OUT	OUT N	OUT	OUT N	OUT	OUT N	OUT	OUT N	OUT	OUT N
2	LR		LR		LR		LR		LR		LR		LR		LR	
	LR		LR		LR		LR		LR		LR		LR		LR	
	LR		LR		LR		LR		LR		LR		LR		LR	
	LR		LR		LR		LR		LR		LR		LR		LR	
	MR		MR		LR		LR		LR		LR		LR		LR	
	MR		MR		LR		LR		LR		LR		LR		LR	
	LR		LR		LR		LR		LR		LR		LR		LR	
	LR		LR		LR		LR		LR		LR		LR		LR	
3	LR		LR		LR		LR		LR		LR		LR		LR	
	LR		LR		LR		LR		LR		LR		LR		LR	
	LR		LR		LR		LR		LR		LR		LR		LR	
	LR		LR		LR		LR		LR		LR		LR		LR	
	LR		LR		LR		LR		LR		LR		LR		LR	
	LR		LR		LR		LR		LR		LR		LR		LR	
	SR		SR		SR		SR		SR		SR		SR		SR	
	EHR		EHR		EHR		EHR		EHR		EHR		EHR		EHR	
4	VHR		VHR		VHR		VHR		VHR		VHR		VHR		VHR	
	VHR		VHR		EHR		EHR		EHR		EHR		EHR		EHR	
	SR		SR		SR		SR		VHR		VHR		VHR		VHR	
	SR		SR		SR		EHR		EHR		EHR		EHR		EHR	
	SR		SR		VHR		LR		LR		LR		LR		LR	
	EHR		EHR		VHR		LR		LR		LR		LR		LR	
	SR		SR		SR		SR		SR		SR		SR		SR	
	EHR		EHR		EHR		EHR		EHR		EHR		EHR		EHR	

ing the fire, taking into account that the geometry, the discreetness, and the initial and boundary conditions (except the force of the fire) are unaltered.

The second important result in the table is the possibility of analysing the influence of turning on the ventilators on the forming of the smoke curtain. It is especially noticeable in the transverse ventilation of 50 and 100 MW fires where on the turning on, local increased temperatures and smoke concentrations occur.

Further observations and analyses are possible with changing the observed location in different time intervals.

Table 6 is made as a functionally dependent dynamic matrix, which chooses the calculated values from the data base with the changing of the observed location and on the basis of the conditions from subsection *Parameters and approach to the result analysis* calculates the risk. The table is made with the programme Excel.

The fields that include the easier evacuation model are marked in the table in a row – Evacuation: Initial location. With it is possible to define the tunnel users location in time intervals of one minute on the bases of the starting users position, delay with the self-rescue procedure and the walking speed. In this way it is possible to predict the tunnel users movement for the following 15 min. and check the smoke concentration and the temperature height to which they will be exposed or establish the risk level.

The table represents a conceptual model for a general presentation of the risk in tunnels with different types of ventilation and different fire forces. The applicable use for the chosen tunnel would discuss for example different fire locations instead of the different types of ventilation.

50 MW tunnel fire scenario with natural ventilation

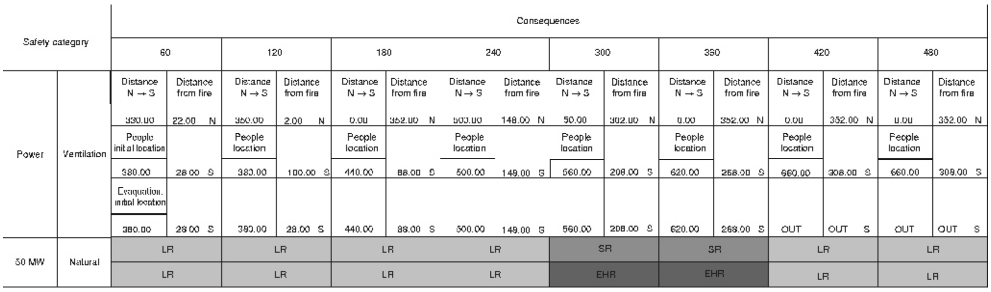
A 50 MW fire in a 650 m long tunnel is assumed. The fire location is on 352 m. The reaction and starting self-rescue time are estimated to 120 s after the start of the fire. The location of the observed tunnel users is on 380 m or 28 m south of the fire. The average walking speed is estimated to 1 m/s.

The model calculates the location in time intervals on the bases of conditions from subsection *Parameters and approach to the result analysis*, and the risk on the bases of the present smoke density and temperature.

From the model it is clear that the smoke and high temperature threaten the escaping people when they have not yet reached the tunnel portal. This happens 300 s after the start of the fire. Because of the delayed start of the self-rescue procedure the evacuation time is over 6 minutes long and with it a successful escape out of the tunnel is very questionable (fig. 12).

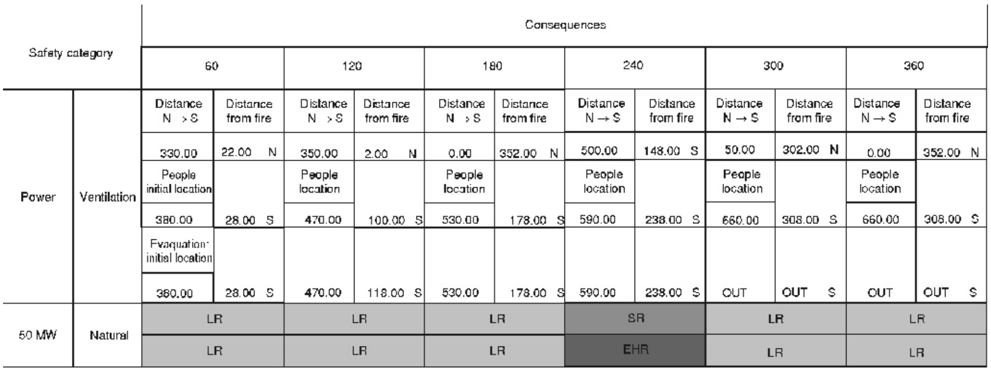
Provided that the self-rescue procedure begins 30 s after the start of the fire, the evacuation time reduces to less than 5 minutes. The escape success is essentially greater which proves the simulation scenario on the fig. 13.

With the increase of the walking speed to 1.5 m/s the evacuation time reduces to app. 3.5 min. with which we avoid high smoke concentration and high temperature. In these conditions it can be assumed that the self-rescue procedure is successful.



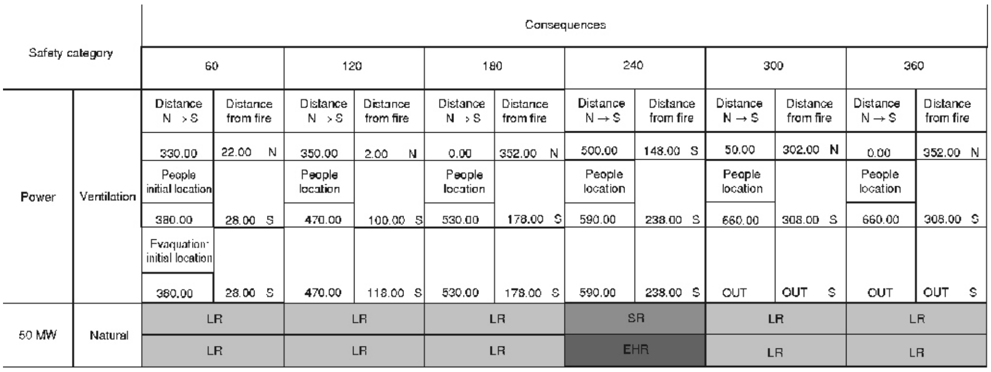
Safety category		Consequences															
		60		120		180		240		300		360		420		480	
Power	Ventilation	Distance N → S	Distance from fire	Distance N → S	Distance from fire	Distance N → S	Distance from fire	Distance N → S	Distance from fire	Distance N → S	Distance from fire	Distance N → S	Distance from fire	Distance N → S	Distance from fire	Distance N → S	Distance from fire
		330.00	22.00 N	350.00	2.00 N	0.00	352.00 N	500.00	148.00 N	50.00	302.00 N	0.00	352.00 N	0.00	352.00 N	0.00	352.00 N
		People initial location		People location		People location		People location		People location		People location		People location		People location	
		380.00	28.00 S	380.00	100.00 S	440.00	88.00 S	500.00	149.00 S	560.00	208.00 S	620.00	268.00 S	660.00	308.00 S	660.00	309.00 S
		Evacuation: initial location															
		380.00	28.00 S	390.00	28.00 S	440.00	88.00 S	500.00	149.00 S	560.00	208.00 S	620.00	268.00 S	OUT	OUT S	OUT	OUT S
50 MW	Natural	LR		LR		LR		LR		SR		SR		LR		LR	
		LR		LR		LR		LR		EHR		EHR		LR		LR	

Figure 12. Use of the model for evacuation (start of self-rescue procedure 120 s)



Safety category		Consequences											
		60		120		180		240		300		360	
Power	Ventilation	Distance N >S	Distance from fire	Distance N >S	Distance from fire	Distance N >S	Distance from fire	Distance N → S	Distance from fire	Distance N → S	Distance from fire	Distance N → S	Distance from fire
		330.00	22.00 N	350.00	2.00 N	0.00	352.00 N	500.00	148.00 S	50.00	302.00 N	0.00	352.00 N
		People initial location		People location		People location		People location		People location		People location	
		380.00	28.00 S	470.00	100.00 S	530.00	178.00 S	590.00	238.00 S	660.00	308.00 S	660.00	308.00 S
		Evaquation-initial location											
		360.00	28.00 S	470.00	118.00 S	530.00	178.00 S	590.00	238.00 S	OUT	OUT S	OUT	OUT S
50 MW	Natural	LR		LR		LR		SR		LR		LR	
		LR		LR		LR		EHR		LR		LR	

Figure 13. Use of the model for evacuation (start of self-rescue procedure 30 s)



Safety category		Consequences											
		60		120		180		240		300		360	
Power	Ventilation	Distance N >S	Distance from fire	Distance N >S	Distance from fire	Distance N >S	Distance from fire	Distance N → S	Distance from fire	Distance N → S	Distance from fire	Distance N → S	Distance from fire
		330.00	22.00 N	350.00	2.00 N	0.00	352.00 N	500.00	148.00 S	50.00	302.00 N	0.00	352.00 N
		People initial location		People location		People location		People location		People location		People location	
		380.00	28.00 S	470.00	100.00 S	530.00	178.00 S	590.00	238.00 S	660.00	308.00 S	660.00	308.00 S
		Evaquation-initial location											
		360.00	28.00 S	470.00	118.00 S	530.00	178.00 S	590.00	238.00 S	OUT	OUT S	OUT	OUT S
50 MW	Natural	LR		LR		LR		SR		LR		LR	
		LR		LR		LR		EHR		LR		LR	

Figure 14. Use of the model for evacuation (start of self-rescue procedure 30 s and walking speed 1.5 m/s)

The results obtained are useful for users and especially to tunnel directors for planning fire procedures and fire drills and for firemen and rescuers.

Conclusions

For a matrix of a fire in a tunnel and a safety evaluation, the probability accession is too general because a greater event number of physical legality is shown with a statistical probability. A relatively accurate fire dynamics matrix, which is possible with mathematical models, is often meant only for science. That is why the dissertation is ideally oriented in the use of mathematical CFD models for the making of a system of scenarios that can be further used for developing an effective fire plan or fire management, fire drills, *etc*. A complex of fire scenarios in different tunnel ventilations and fire forces is presented in the work. The work includes a qualitative analysis of the current circumstances in four different ventilation conditions; natural, longitudinal, transverse, and semi transverse. In this way a comparison of individual types of ventilation systems, ventilation plans and their effectiveness in assuring sufficient evacuation times is possible. Also a possibility of usage on a singular tunnel is presented, for which a deterministic safety analysis within a selected number of scenarios would be made. Such an accession requires a lot of calculating time but it is changeable in the development of the safety analysis and fire plan. The geometry and some ventilation plans are "constants" in this case and only the fire location can be changed.

Apart from the number and way of setting the scenarios, the simulation results are values of the selected variables. The discussed variables are mostly the smoke density and the temperature which define the different risk levels on the basis of the human endurance in increased values and conditional interacting dependence. On this basis the deterministic risk matrix is made which is the key element of the dissertation. The matrix presents a passage between a practical way of using the CFD model and the user who needs clear and fast accessible data of the situation during a fire in a tunnel.

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Authors' address:

P. Vidmar, S. Petelin
University of Ljubljana,
Faculty of Maritime Studies and Transportation
4, Pot pomorščakov, Portorož, Slovenija

Authors' e-mails: peter.vidmar@fpp.edu, stojan.petelin@fpp.edu

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