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Application of fire and evacuation models in evaluation of fire safety in railway tunnels

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Abstract. The paper describes an application of numerical simulation of fire dynamics and evacuation of people in a tunnel. The software tool Fire Dynamics Simulator is used to simulate temperature resolution and development of smoke in a railway tunnel. Comparing to temperature curves which are usually used in the design stage results of the model show that the numerical model gives lower temperature of hot smoke layer. Outputs of the numerical simulation of fire also enable to improve models of evacuation of people during fires in tunnels. In the presented study the calculated high of smoke layer in the tunnel is in 10 min after the fire ignition lower than the level of 2.2 m which is considered as the maximal limit for safe evacuation. Simulation of the evacuation process in bigger scale together with fire dynamics can provide very valuable information about important security conditions like Available Safe Evacuation Time (ASET) vs Required Safe Evacuation Time (RSET). On given example in software EXODUS the paper summarizes selected results of evacuation model which should be in mind of a designer when preparing an evacuation plan.

1. Introduction

Historically, fire safety has been restricted by prescriptive standards. These prescriptive codes including many requirements are based on traditional fire testing techniques. Using of these codes may lead to more expensive and inefficient solutions. In many countries the performance based design is widely accepted as a natural and inseparable evolution of fire engineering. Fire engineers or structural designers may use knowledge of latest research to optimize their design, not only the cost and life safety, but also environmental impact, in practice. In fire safety engineering, natural evolution is associated with an increase of exact knowledge about the fire dynamics. Development of computational technology, numerical analysis and mathematical modelling has also contributed to change the approach. Using all benefits of the knowledge and computer development, fire safety in railway tunnels is investigated by application of fire and evacuation models.

During a fire in a tunnel there are three-dimensional flows which are influenced by buoyancy effects. In addition, the flow velocity and length scales are sufficiently large that the flow is generally turbulent. At the fire, a combustion process takes place, and so there are chemical reactions going on, producing soot particles and combustion products at high temperatures [1]. Part of the heat is transferred by radiation and part by convection to the tunnel walls. Generally, the problem of fire



safety in tunnels increases with their length. In case of railway tunnel fire dynamics is influenced by high longitudinal flow due to natural ventilation and also supported by moving trains (known as “piston effect”). The problematic of fluid dynamics in case of fire in railway tunnels is therefore very complicated. However it can be solved numerically, when correct method is applied. The degree to which qualitative agreement is achieved varies with the modeller and the situation.

2. Design fire models for tunnels

In the design phase fire safety is evaluated from the length of a tunnel of 350 m, which is considered as the length with higher risk for human safety. Temperature resolution and development of toxic gases in a tunnel are together with visibility considered as the most important parameters affecting the safety of people involved in tunnel accidents. Gas temperature may be evaluated based on the temperature curves and simple empirical equations. However, the aim is to determine the exact behavior of the fire and the spread of toxic gases in the tunnel, which corresponds to reality, and to find the balance between the tunnel safety equipment components and their contribution to improvement of traffic safety at the site. In this case it is advantageous to use a numerical simulation. Findings from the numerical simulation of fire and smoke development enable to improve models of human evacuation during fires in tunnels. Together with the optimization of the elements of safety equipment of tunnels and evacuation scenarios the use of numerical solutions may help to improve emergency procedures of IRS in the case of tunnel fires or to assess the behavior of materials of tunnel lining under fire even with sudden cooling caused by the intervention of firefighters.

3. Numerical modelling of fire

Computational Fluid Dynamics (CFD) modelling is a numerical approach to representing fluids that divides a fluid domain into a number of smaller sub-domains, resulting in the generation of a mesh of cells (control volumes). Three-dimensional, time-dependant partial differential equations of conservation of mass, momentum and energy transfer and conservation of species are written for each control volume based on fundamental equations of fluid dynamics, thermodynamics, chemical reactions and mechanics. Appropriate initial boundary conditions are then applied to find numerical solutions to these equations. Currently available CFD models include sub-models for solution of burning and heat transfer, so they provide a framework for including all phenomena which are present during fire in a tunnel into a calculation.

One of the freely available numerical code, Fire Dynamics Simulator (FDS), developed by National Institute of Standards and Technology (NIST), is frequently used for simulation of fires. It is a numerical solver to simulate a flow and movement of fluids, also caused by burning. FDS solves numerically a form of the Navier-Stokes equation appropriate for low-speed, thermally-driven flow with an emphasis of the transport of heat and smoke from fires [2]. The code consists of several independent models, for example model of burning. To interpret data obtained from FDS postprocessor Smokeview is used.

Despite the huge advantage of numerical simulations, a level of reliability and accuracy of numerical predictions must be always evaluated. Therefore, when using numerical simulation verification and validation is always recommended. Verification and validation examples of prediction of gas temperature resolution and smoke distribution during the fire in a railway tunnel are presented in [3].

Considering tunnel fires, the thermo-fluid-dynamics behaviour is affected by several internal and external factors, such as the barometric pressure at the portals, the tunnel slope, the set-point of the ventilation system, and others [4]. Reliability of computer predictions of such complex system has been evaluated in many studies. Ventilation velocity and backlayering distance was validated in [5] and [6]. In [5] and [7] local field data as velocity and gas temperature in the vicinity of the fire source were predicted and validated to experimental results. Based on results of these and other studies Colella stated [8] that CFD method can be used to produce sufficiently accurate results of flow pattern

and temperature gradient located in close areas of the fire. However, as it was mentioned above reliability of numerical solution and accurateness of results have to be checked.

4. Numerical modelling of passengers evacuation

Applied simulation tool in this case is EXODUS, developed by a team Fire Safety Engineering Group at the University of Greenwich. The model geometry is filled with network nodes that are normally spaced at a constant interval of 0.5 m. Each node is connected with neighbours and represents elementary space that can be occupied by one person only (see Figure 1). Any change in cell size has noticeable effect on the model behaviour and can be carried out only in well-justified cases.

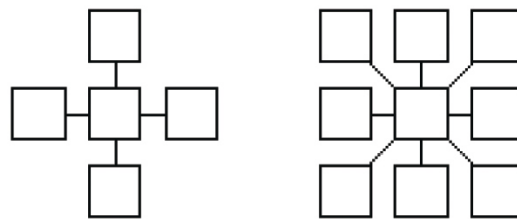


Figure 1. Elementary space represented by nodes with spacing 0.5 m.

Model also takes into account the particular passenger's parameters describing the age profile, reaction time and movement speed [9]. If it is necessary to apply Czech national standards, it is possible to use the inputs according to CSN 73 0802 [10].

Time before the movement is equally or more important than the movement time and includes activities difficult to calculate. *Time to recognize the danger* is the period from the start of the alarm the moment when people begin to respond to an alarm triggered. During this time, people continue with an activity before the alarm appeared. Variability of this time interval is very high, generally ranges from several seconds to many minutes and is different also among individuals in the same space. The *time of response to the danger* lasts from the moment a person realizes formation of critical situations, until the moment when they decide for a particular method of evacuation strategy. Among the typical activities in this period include luggage collecting, searching of other family members, informing others or assessing the appropriate escape routes. For the purpose of the model was therefore assigned persons reaction time in the interval 0-30 s with normal distribution.

5. Application to a railway tunnel

5.1. Fire model

A 1747 m long tunnel with an arc shape cross-section of 6.97 m width and 5.33 m high is undertaken to numerical study in FDS. Computational domain of dimensions 1747 m x 6.97 m x 5.33 m consists of five meshes. Size of mesh is determined according to rules given in [2]. Cell size in axis (x, y, z) equals to (0.345 m, 0.348 m and 0.355 m). In the region of fire source the grid is refined to half size, in axis (x, y, z) cell size equals to (0.182 m, 0.174 m, 0.178 m). Detail of meshing in the location of fire source is shown in Figure 2. The total number of cells is 1 530 600.

The tunnel lining is formed by 0.4 m thick layer of concrete with density of 2200 kg/m³, conductivity of 1.3 W/mK and specific heat of 1.02 kJ/kgK. Tunnel portals are opened throughout the whole cross-sectional area (in FDS code plane surface type VENT is OPEN). In the tunnel there is negligible natural gas flow as the high difference of both portals is very small. Initial gas flow velocity is therefore set to 0 m/s. Gas temperature before fire ignition is considered as 10°C.

Fire scenario of a 20 MW fire in a passenger train wagon is simulated by time dependant heat release rate corresponding results of fire test of passenger train wagon described in [11]. The heat flux is released through four window openings, each of area of 1.44 m², situated 2 m above the ground level. The fire (areas releasing the heat flux) is located in the third wagon from the total of five

wagons. The train stopped after 935 m after entering its portal (stands between 810 m and 935 m of the tunnel length). In FDS burning is simulated by mixed-fraction ratio of polyurethane (defined by fractions of carbon, hydrogen, oxygen, nitrogen and soot yield particles - 'C_6.3 H_7.1 O_2.1 N_1.0 SOOT_YIELD_0.10'). Development of rate of heat release is based on t-quadratic curve for ultra-fast fire.

In the model there are sensors to measure high of smoke layer ('SMOKE LAYER HEIGHT'), temperature of hot gas layer and temperature of gas layer below the smoke level ('UPPER TEMPERATURE' a 'LOWER TEMPERATURE'). These sensors are situated in 50 m span sections in the axis of the tunnel tube and in the position of 0.6 m from the side lining, which should control the area of safety evacuation path.

In FDS turbulence model is applied by Smagorinski formulas of large eddy simulation (LES) with coefficient C_s equals to 0.2. Heat transfer by radiation is applied by 100 discrete angles.

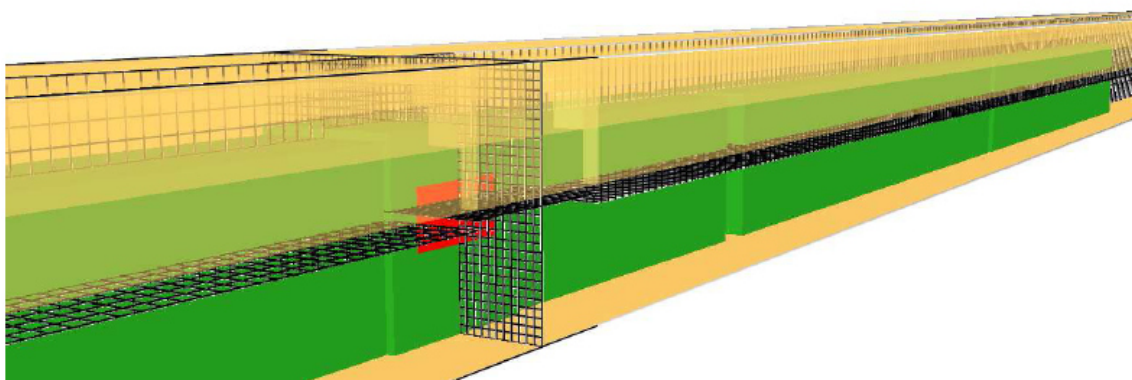


Figure 2. Meshing of the model.

5.2. Discussion on selected results of fire model

As it was expected, after fire ignition layer of hot smoke gases accumulated below the tube arch. The tunnel linings cooled hot gases down and smoke sank to lower level of the tunnel. Visualisation of smoke originated from the fire of passenger train wagon in 2 min and 5 min is given in Figures. 3 - 4. In 10 min from the ignition the entire tunnel cross section is full of smoke. The speed of smoke spread is slowing down closer to the portals. In 20 min smoke reaches a distance of 340 m from ignition sources.

Temperature of hot smoke layer calculated in the axis of the fire source reaches the peak value of 800°C. Figure 5 illustrates the comparison of calculated hot smoke layer temperature in the numerical model and temperature curves which are usually used in the stage of design. From the figure it is obvious that numerical model gives lower temperatures. Hydrocarbon temperature curve as well as RABT ZTV temperature curve for trains gives too conservative estimation.

Figure 6 shows decrease of smoke layer high along the tunnel length in 10 min. In the diagram three curves are introduced – curve of smoke layer high calculated by numerical model in the axis of evacuation path (0.6 m from the tunnel linings), curve of smoke layer high calculated in the axis of the tunnel cross-section and a curve indicating the level of maximal smoke layer decrease according to ČSN 73 7508. In the figure proves that the calculated high of smoke layer in the axis of evacuation path and also in the axis of the tunnel is lower than the level of 2.2 m. This level is considered as the maximal limit for safe evacuation. From the view of safe evacuation temperature of 80°C should be also controlled in the high of 2 m above the evacuation path.



Figure 3. Visualization of smoke development during passenger train fire in 2 min.



Figure 4. Visualization of smoke development during passenger train fire in 5 min.

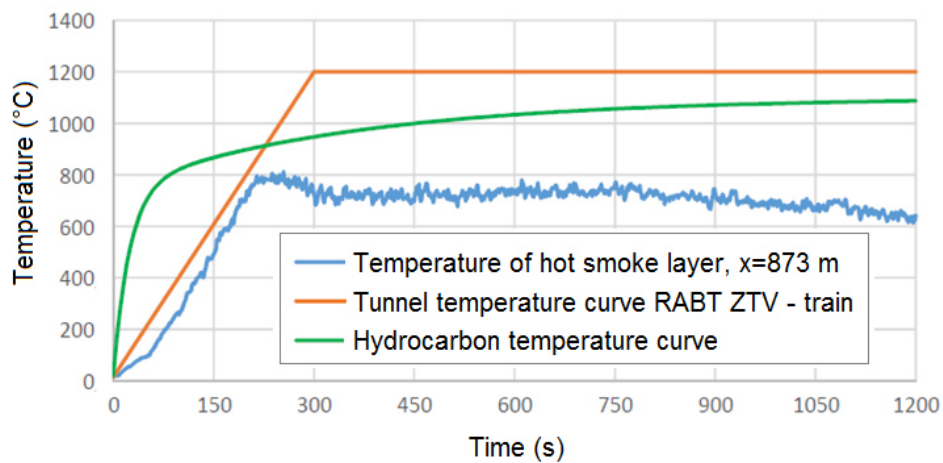


Figure 5. Comparison of temperature of hot smoke layer from FDS with simplified temperature curves.

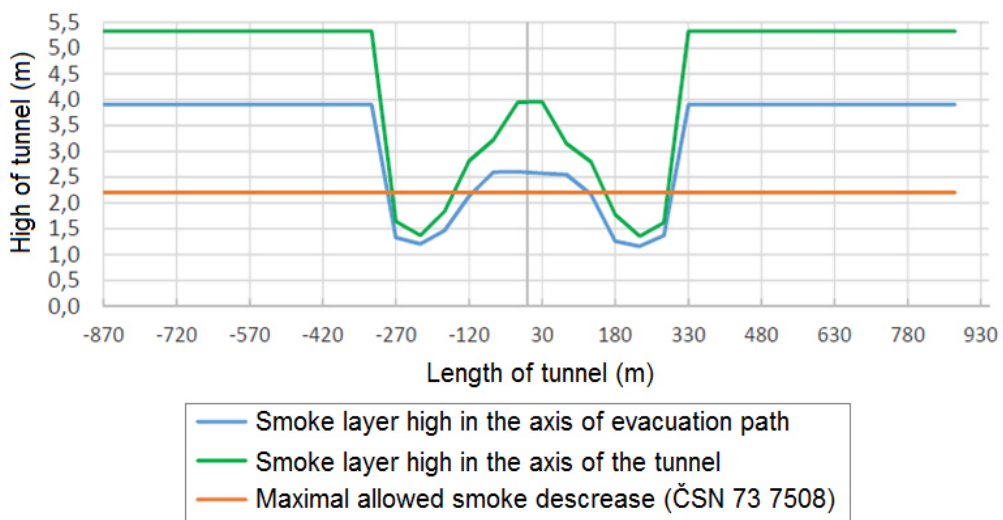


Figure 6. Smoke layer high above the tunnel floor during passenger train fire in 10 min.

5.3. Selected results of passenger's evacuation model

The key advantage of using simulation tools in such situations is the ability of statistical processing of the results of several tens or hundreds of the same simulation with random sweep key parameters and the initial position of persons, while evacuation experiment can be performed at the best for only a small number of repetitions. The sensitivity analysis of the results is also quite easy. Comprehensive evaluation of the model behavior is therefore beyond the scope of this text, so the results with more general impact on safety were selected.

The simulation results show, moreover, that the course of evacuation significantly affects the order of the vehicle carriage. People escaping from the first and last carriages are very significantly restricted in movement by persons that are no longer found on the sidewalk, and have traveled in wagon closer to the set. On the Figure 7 there is a comparison during the evacuation of people from the first and the third carriage, wherein it is clearly evident slowing the process of evacuation of the first wagon in the second half of the time interval when the sidewalk in front of the carriage is already full of persons mainly from other carriages.

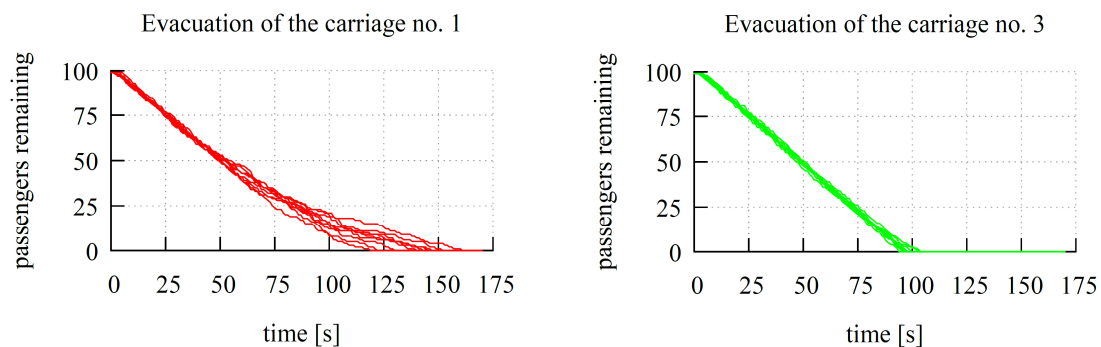


Figure 7. Influence of the order of the vehicle carriage on evacuation of wagon no. 1 and no. 3. Each variant shows results of 10 separate simulations of the model.

From an overall comparison of Figure 8 it is then clear that the time differences of evacuation can vary between different carriages significantly. Rather than a specific time of the evacuation of the wagon it is precisely this fact that generally applicable and it is important to have it in case of evacuation plan in mind.

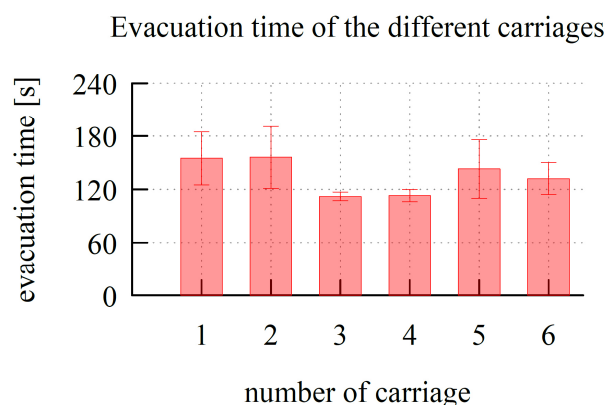


Figure 8. Evacuation time of each carriage. For each wagon the mean value of the time required for evacuation and the standard deviation of this time as the result of 10 simulations is shown. It is obvious that the evacuation time is significantly different and depends on the carriage position.

High density of people, which can lead to serious injury or death even without the presence of high temperatures and toxic fumes is also an important security risk during the evacuation process. Density of people usually shown through so-called Level of Service and using the six-scale A-F, where A is the ideal stage, grade D or higher is already regarded as an area of increased risk of injury. On the Table 1 the particular pedestrian densities for different environments and levels of services are shown.

Table 1. Level of service according to Fruin [12].

Sidewalks		Stairs		Waiting areas		LoS
Min	Max	Min	Max	Min	Max	
0	0.308	0	0.538	0	0.828	A
0.308	0.431	0.538	0.718	0.828	1.076	B
0.431	0.718	0.718	1.076	1.076	1.538	C
0.718	1.076	1.076	1.538	1.538	3.588	D
1.076	2.153	1.538	2.691	3.588	5.382	E
2.153	-	2.691	-	5.382	-	F

The situation is modeled in Figure 9, which captures the area around the middle carriage no. 4. On the picture the pedestrian density is described with equidistant time step 30 s. The color scale corresponds to levels of quality pedestrian traffic, while the red shows the worst situation of people with a density of over 2,153 persons.m⁻². The results can be identified as being critical points around the evacuated wagons on the sidewalk and in niches.

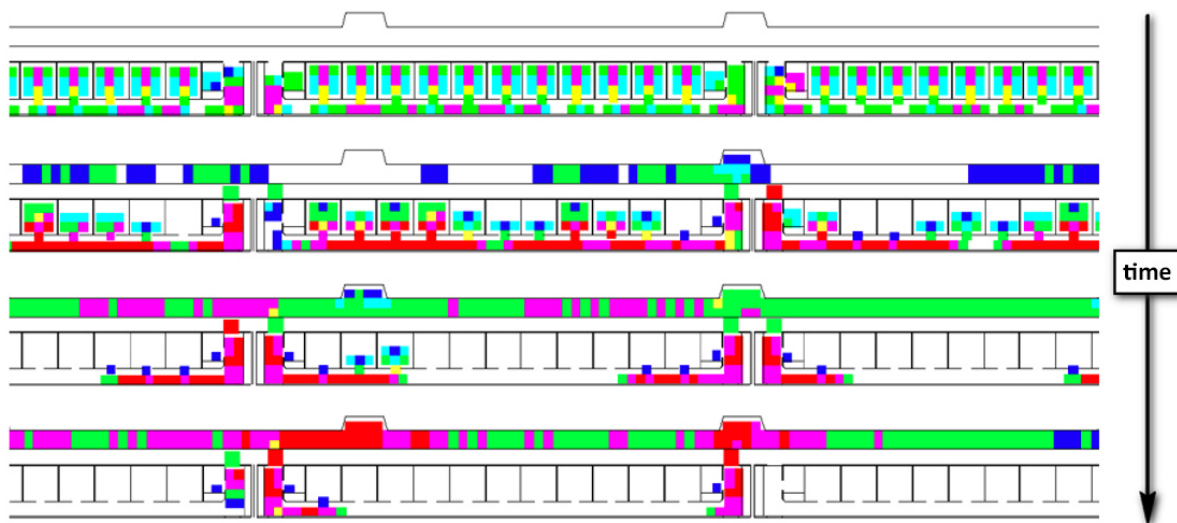


Figure 9. Displaying the pedestrian density around the carriage no. 4. Especially in the later stages evacuation is critical due to increase of the density of people evacuated around cars and thus the risk of injury is increased.

6. Conclusion

Commission Regulation (EU) no. 1303/2014 from November 2014 concerning the technical specification for interoperability relating to safety in railway tunnels rail system (TSI) has brought many new facts. These facts also include the possibility to develop an evacuation plan with respect to the above described safety risks. The models of evacuation and fire are the optimal tools.

Using these models, it is possible at present to analyse the evacuation process and its results are substantially wider than it is using classical engineering calculations based on prescriptive standards.

In the same way as evacuation models, correctly applied CFD models may reproduce the qualitative behavior of fire in each tunnel. The degree, to which qualitative agreement is achieved, is necessary to find out by the aid of verification and validation process. Accurate prediction of fire and smoke spread in tunnels on the bases of physical properties is a promising approach how to stress the human safety and fire design economy.

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References

- [1] Rhodes N 2005 CFD modelling of tunnel fires *Handbook of Tunnel Fire Safety* (London: ICE Publishing) p 329-46
- [2] McGrattan K et al 2016 Fire Dynamics Simulator (Version 6.4) *Technical Reference Guide* (NIST Special Publication 1019-6 US Government Printing Office) p 86
- [3] Cábová K, Apeltauer J and Wald F 2016 Verification and validation of a numerical model of fire and smoke development in a railway tunnel *Acta Polytechnica* **56**(6) pp 432-9
- [4] Beard A and Carvel R (ed) 2005 *Handbook of Tunnel Fire Safety* (London: ICE Publishing)
- [5] Vauquelin O and Wu Y 2006 Influence of tunnel width on longitudinal smoke control *Fire Safety Journal* **6** vol 42 pp 420-6
- [6] Van Maele K and Merci B 2008 Application of RANS and LES field simulations to predict the critical ventilation velocity in longitudinally ventilated horizontal tunnels *Fire Safety Journal* **8**(43) pp 598-609
- [7] Vega M G, Arguelles Diaz K M, Oro J M F, Ballesteros T R and Morros C S 2008 Numerical 3D simulation of a longitudinal ventilation system: Memorial Tunnel case *Tunnelling and Underground Space Technology* **5**(23) pp 539-51
- [8] Collela F, Verda V, Borchiellini R and Rein G 2005 One-dimensional and multi-scale modelling of tunnel ventilation and fires *Handbook of Tunnel Fire Safety Chapter 17* (London: ICE) pp 365-90
- [9] RIMEA 2009 Richtlinie für Mikroskopische Entfchtungs-Analysen
- [10] Úřad pro technickou normalizaci, metrologii a státní zkušebnictví (ÚNMZ) 2009 Požární bezpečnost staveb - Nevýrobní objekty (ČSN 73 0802)
- [11] White N 2010 *Fire development in passenger trains* (Victoria University, Melbourne)
- [12] Fruin J. J. 1987 *Pedestrian Planning and Design* (Elevator World, Inc.) p 206