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Research Article
Study on Applicability of FDS+Evac for Evacuation Modeling in Case of Road Tunnel Fire

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Abstract: In this study, fire in a short 2-lane single-directional road tunnel with two different traffic situations is considered and the impact of spread of fire and smoke on people evacuation is investigated. The FDS+Evac system used comprises of FDS (Fire Dynamics Simulator), an advanced CFD (Computational Fluid Dynamics) fire field model supplemented by agent-based FDS evacuation model, Evac. Evac is capable to exploit its direct access to simulated fire characteristics and to model the influence of fire on evacuees' behavior and decision making. In Evac, a modified Helbing's social force model adapted for description of movement of evacuees and their behavior is implemented. Some particularities of FDS+Evac, which must be taken into account to avoid misrepresentation of inputs for evacuation in case of fire, are discussed and the impact of occurrence of higher capacity vehicles on people evacuation is illustrated. Simulation results and some of comments and recommendations included can be useful for those who are engaged in research, development, testing and competent use of FDS+Evac for practical problems of fire safety in road tunnels.

Keywords: Agent-based, evacuation modeling, FDS+Evac, fire simulation, road tunnel

INTRODUCTION

The use of current simulation systems for modeling fire spread and people evacuation in the case of road tunnel fire is a difficult, challenging problem in tunnel fire safety. Recent incidents in tunnels (e.g., in Tauern, Gotthard, Mont Blanc, Viamala) and new contemporary security and safety challenges appeared have turned attention to risks of fires in road tunnels. Such fires can result in casualties as well as in direct and indirect economic and environmental damages. They can cause destruction of the tunnel structure and facilities, vehicles and their loads and endanger lives and health of passengers, firemen and operating staff members in tunnel. Therefore, tunnel safety is now considered as being one of the key elements in tunnel design, development and operation (Kazaras *et al*., 2012). As road tunnels are part of national and international transportation systems and critical infrastructures, safe evacuation of people in case of emergent event belongs to important duties which must be provided by crisis management of tunnel (Lewis *et al*., 2013; Kang, 2010; Bebcak, 2007).

Advances in computers and fire models research have allowed to utilize high computational power of current computers for numerical calculation of tunnel fire simulation. Several program systems capable to simulate complex phenomena associated with fire in various types of structures have been developed, such as for instance SMARTFIRE, FLUENT, SOFIE, JASMINE, PHOENICS and FDS. Such simulations often require parallelization and calculations must be realized in parallel (Vega and Dias, 2008; Betta and Cascetta, 2009; Halada *et al*., 2012). In the literature, several papers related to some specific aspects of tunnel fires have been published; for instance studies dealing with action of emergency ventilation (Carvel *et al*., 2005, 2009; Li *et al*., 2013; Ingason and Li, 2013; Han *et al*., 2013), use of computer simulation for description of course of fire and smoke and their consequences (Bari and Naser, 2005; Hu and Fong, 2007; Ji *et al*., 2012; McGrattan and Hamins, 2006) and modeling of people evacuation in tunnel (Gao-Shang *et al*., 2006; Ronchi *et al*., 2012, 2013a, b). However, most papers consider the same type of vehicles in tunnel and do not take into account the impact of higher capacity vehicles (buses, transporters) in tunnel on the course of evacuation in case of fire.

In this study, we use the FDS (Fire Dynamics Simulator) system, version 5.5.3 for simulation of fire in a short 2-lane single-directional road tunnel and modeling people evacuation. FDS is an advanced CFD (Computational Fluid Dynamics) fire field model capable to simulate fires in various environments incorporating a large variety of specific physical and chemical phenomena related to fire. FDS is supplemented by Evac, the agent-based evacuation model which allows simulating people evacuation. FDS serves for Evac as a platform providing the direct access of Evac to relevant characteristics of simulated

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fire. Thus, Evac is capable to model the influence of fire on evacuees' behavior and decision making. In the literature the system is known as FDS+Evac (Korhonen and Hostikka, 2009). We consider two different traffic situations in the tunnel in order to study the impact of occurrence of higher capacity vehicles on behavior of evacuees. Some particularities of FDS+Evac, which must be taken into account to avoid misrepresentation of inputs for evacuation in case of fire, are discussed.

In Glasa *et al*. (2013), we studied the impact of turned cars on the course of evacuation in case of tunnel fire. This study summarizes our research on the influence of occurrence of higher capacity vehicles in tunnel on evacuation in case of fire. It is substantially extended version of contribution presented at the International Conference on Applied Mathematics and Computational Methods in Engineering in Rhodes (Valasek and Glasa, 2013) which is supplemented by original results and discussion. Simulation results analysis illustrates the influence of higher capacity vehicles in the tunnel on the course of evacuation. Some comments and recommendations included can be useful for those who are engaged in research, development, testing and practical use of FDS+Evac for fire safety problems in road tunnels.

MATERIALS AND METHODS

In this section, the used FDS+Evac simulation system is briefly described and a 3D model of the used road tunnel, fire scenario and emergency ventilation action as well as two different traffic situations and related tunnel evacuation scenarios (24 cars of the same type in the first scenario and 21 cars and two higher capacity vehicles in the second scenario) are introduced.

FDS+Evac: FDS (Fire Dynamics Simulator) system, version 5.5.3 (McDermott *et al*., 2010; McGrattan and Hamins, 2006) is an advanced CFD-based field model of fire devoted to simulation of fires in various environments. The system incorporates a large variety of specific physical and chemical phenomena related to fire. FDS solves a form of conservation equations for low speed, thermally driven flow. Smoke and heat transfer from fire is the main concern of this system, which also includes thermal radiation, pyrolysis, combustion of pyrolysis products, flame spread, turbulence, suppression and sprinklers activation. FDS was developed by NIST (U.S. National Institute of Standards and Technology) in the U.S.A. in collaboration with VTT Technical Research Center of Finland. Since the first validation study related to FDS elaborated by the U.S. NRC (Nuclear Regulatory Commission) (Hill *et al*., 2007), systematic verification and validation of FDS continue until now to enhance quality and reliability of simulations and to provide its applicability on practical fire safety problems (McDermott *et al*., 2010; McGrattan *et al*., 2010). FDS can run on single-processor PCs as well as on multi-processor (multi-core) computer systems utilizing MPI (Message-Passing Interface) or Open MPI (Open Message-Passing Interface). Visualization of simulation results is provided by Smokeview (Forney, 2009) which is capable to visualize 3D simulations of fire and smoke spread and 2D slices of selected quantities and export the visualized results in the form of graphs, tables, pictures and sequences of pictures. We utilize our experience in the field of computer simulation of fires in various environments; we have studied fires in compartment and family house (Weisenpacher *et al*., 2012b), cinema hall (Glasa *et al*., 2012; Valasek, 2013), automobile (Halada *et al*., 2012; Weisenpacher *et al*., 2012a), tunnel (Weisenpacher *et al*., 2011a, b) and garage (Weisenpacher *et al*., 2013). We also studied the impact of parallelization of calculation on accuracy and efficiency of tunnel fire simulation (Halada *et al*., 2012; Weisenpacher *et al*., 2011a, b; 2012a; 2013).

The FDS system contains the agent-based evacuation module, Evac (Korhonen and Hostikka, 2009). In Evac, a modified Helbing's social force model (Helbing and Molnar, 1995; Helbing *et al*., 2000; Werner and Helbing, 2003) is adapted for description of movement and behavior of evacuees. People are represented as independent, autonomous entities (agents) with their own personal properties and escaping strategies. Body of an evacuee is represented by combination of three overlapping circles (Langston *et al*., 2006; Korhonen and Hostikka, 2009). This approach enables to consider translational as well as rotational motion of evacuees. At present, several advanced program systems are available, e.g., Pathfinder, buildingEXODUS, STEPS, Simulex, etc., which are capable to simulate the egress of people from various structures in case of emergency event. However, most of these systems are devoted rather to fire drill simulation than to simulation of evacuation in case of fire. Some of current evacuation simulators are able to import the information about fire from FDS (or from some another fire simulator) and utilize it partially for modeling of evacuation. In FDS+Evac, fire characteristics are accessed directly and utilized for modeling evacuees' behavior. Therefore, the system is capable to simulate the spread of fire as well as the impact of fire and smoke on the course of evacuation and evacuees' decision making. Thus, the fire field model FDS and the agent-based evacuation model Evac interact and the system is able to take into account the information about fire and smoke in every place of computational space at arbitrary time of calculation. The system calculates 3D fire simulation (on 3D computational meshes) and 2D evacuation simulation (on single 2D computational mesh) and is able to include consequences of simulated fire characteristics on movement of evacuees, their escaping strategies and visibility of emergency exits in tunnel. In order to model people intoxication and incapacitation during evacuation, a modified Purser's FED (Fractional Effective Dose) model (Purser, 1995) is adapted in FDS+Evac.

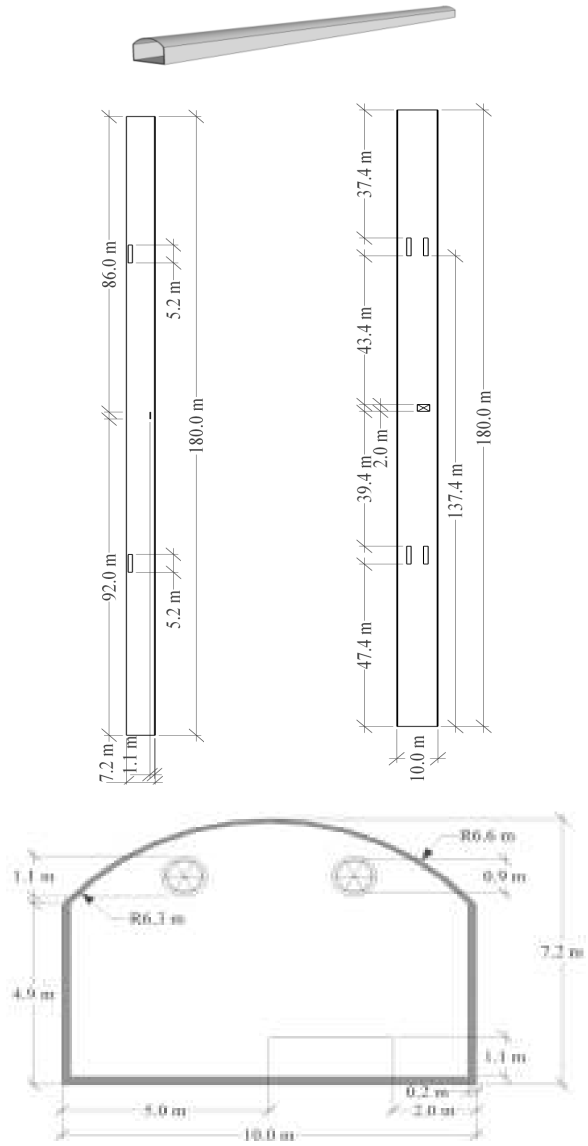


Fig. 1: 3D tunnel model

Road tunnel model: We consider a typical short single-directional 2-lane road tunnel with longitudinal ventilation which is about 180 m long, 10 m wide and 7.2 m high, as shown in Fig. 1. Structure of the tunnel consisting of vertical walls and a curved ceiling is represented using FDS orthogonal obstacles (OBSTRUCTIONs) composed of concrete with the 20 cm THICKNESS. The SAWTOOTH feature of FDS is used for curved ceiling representation to smooth the ceiling surface. Such procedure helps to avoid the occurrence of unwanted turbulent phenomena related to gases flow around sharp corners and edges of obstacles (OBSTRUCTIONs) by which the concrete ceiling is represented. We do not assume any flammable materials influencing the course of fire in simulation.

The ventilation system of the tunnel consists of two couples of jet fans placed about 1 m under the tunnel ceiling at the distances of 47.4 and 137.4 m from the left tunnel portal. The fans are placed 3 m far from each other. Their effective diameter and length is 0.9 and 5.2 m, respectively. The fans are represented standardly using “thin obstructions” (OBSTRUCTONs with the 0 m THICKNESS with the POROUS =.TRUE.parameter). In order to provide the proper ventilation action, the square cross-section area related to fans representation in simulation corresponds to the circular cross-section area of standard tunnel jet fan (Fig. 1).

Ambient temperature in the tunnel is assumed to be 20°C. We also assume a steady flow in the tunnel at the beginning of simulation consisting of a flow caused by the tunnel super-elevation as well as by the movement of vehicles (contribution of traffic). In simulation, such quasi-steady flow is formally represented by fans

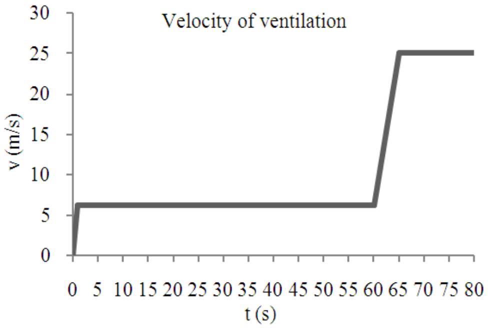


Fig. 2: Ventilation action

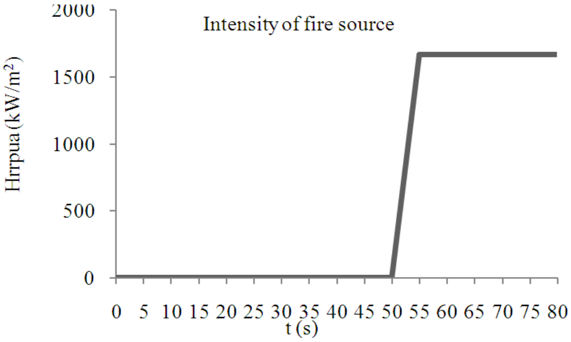


Fig. 3: Fire source HRRPUA curve

blowing at 6.25 m/s velocity during the first 60 s of simulation. By such procedure, a quasi-steady air flow under the ceiling with approximately 2 m/s velocity is created (Fig. 2).

Fire scenario: We assume the following fire scenario. Fire is initiated at the 50th s of simulation; increases linearly up to the maximal HRR (heat release rate) value of 10 MW reached at the 55th s (Fig. 3). Since that time, the fire source intensity is not changed until the end of simulation. The source of fire is represented by a 2×3 m surface placed about 1.1 m above the road at 92 m distance from the left tunnel portal (Fig. 1). It produces heat with 1666.667 kW/m^2 HRRPUA (heat release rate per unit area).

We consider the following action of emergency ventilation (Fig. 2). After the fire detection (at the 60th s), all fans start to work with linearly increasing velocity (from the value of 6.25 to 25 m/s); the maximal value of the fans blowing velocity is reached at the 65th s and remains unchanged until the end of simulation. In order to avoid unnecessary presentation complexity, we assume the simple fire scenario and simplified ventilation action.

The aim of this research was not to study or optimize emergency ventilation action in the considered tunnel. Several papers on critical ventilation velocity studying various aspects of emergency ventilation have been published (Megret and Vauquelin, 2000; Atkinson and Wu, 1996; Kunsch, 2002; Tetzner *et al.*, 1999; Vauquelin and Wu, 2006; Kang, 2010). According to these studies, actual values of critical ventilation velocity vary from tunnel to tunnel and are determined and influenced by various factors such as tunnel structure, ventilation system, traffic, fire source intensity and location, etc. This study aims to show applicability of FDS+Evac for modeling people evacuation in case of tunnel fire and to indicate some specific problems related to such simulations. Note that reaction times of fire detection and alarm system considered in simulation are also relatively short to keep the total computational time of simulation acceptable considering the available computational

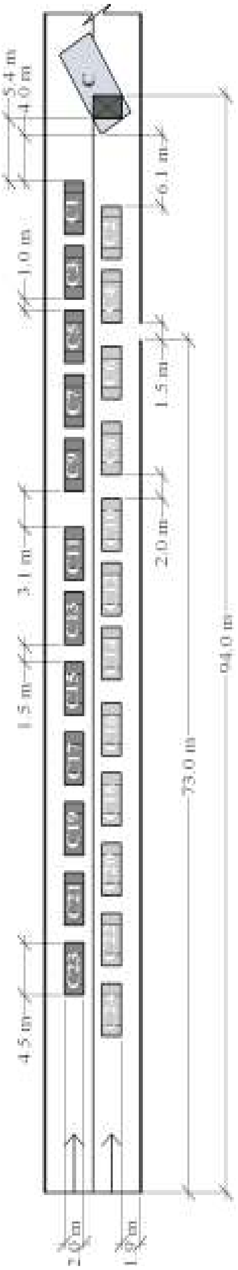


Fig. 4: Scheme of traffic (scenario 1): positions of cars C1-C24 and the fire source

	C1	**AT**	**ET**	**C2**	**AT**	**ET**	**C3**	**AT**	**ET**	**C4**	**AT**	**ET**	**C5**	**AT**	**ET**	**C6**	**AT**	**ET**
LFD	1 A	53	58	1 A	54	59	1 M	55	60	1 F	56	61	1 A	57	62	1 M	58	63
RFD	1 A		58	1 E		60	1 F		60	1 F		61	1 E		63	1 F		63
LBD	-		-	1CH		60	1 CH		60	-		-	-		-	1 M		63
RBD	-		-	-		-	1 CH		60	-		-	-		-	1 F		63
	C7	**AT**	**ET**	**C8**	**AT**	**ET**	**C9**	**AT**	**ET**	**C10**	**AT**	**ET**	**C11**	**AT**	**ET**	**C12**	**AT**	**ET**
LFD	1 A	59	64	1 M	60	65	1 M	61	66	1 M	62	67	1 M	63	68	1 M	64	69
RFD	1 A		64	1 F		65	1 A		66	1 A		67	1 A		68	1 A		69
LBD	1 E		65	-		-	1M		66	-		-	1 M		68	1 M		69
RBD	1 E		65	2 CH		65, 66	1 A		66	-		-	1 CH		68	-		-
	C13	**AT**	**ET**	**C14**	**AT**	**ET**	**C15**	**AT**	**ET**	**C16**	**AT**	**ET**	**C17**	**AT**	**ET**	**C18**	**AT**	**ET**
LFD	1 M	65	70	1 M	66	71	1 E	67	73	1 M	68	73	1 M	69	74	1 M	70	75
RFD	1 F		70	-		-	1 E		74	1 F		73	1 A		74	1 A		75
LBD	-		-	-		-	-		-	1 E		74	1 M		74	1 M		75
RBD	-		-	-		-	-		-	-		-	-		-	-		-
	C19	**AT**	**ET**	**C20**	**AT**	**ET**	**C21**	**AT**	**ET**	**C22**	**AT**	**ET**	**C23**	**AT**	**ET**	**C24**	**AT**	**ET**
LFD	1 F	71	76	1 M	72	77	1 M	73	78	1 M	74	79	1 E	75	81	1 M	76	81
RFD	-		-	1 A		77	1 M		78	1 A		79	-		-	1 A		81
LBD	-		-	1 M		77	-		-	1 M		79	-		-	1 M		81
RBD	-		-	-		-	-		-	-		-	-		-	-		-

Fig. 5: Description of vehicles evacuation in scenario 1
A, E, CH, F and M: Adult, elderly, child, female and male, respectively; C1,…, C24: Cars; AT: Vehicle stop time; ET: Individual passenger evacuation time from vehicle; LFD, RFD, LBD and RBD: The left front, right front, left back and right back door, respectively

power. In real situations, however, many other factors were observed which influence the fans activating times and smokiness of tunnel tube even before open flames appear (Han *et al*., 2013) and various psychological, physiological and physical impacts on evacuees' behavior, movement and decision making were investigated (Ronchi *et al*., 2012; 2013a, b; Kutilova *et al*., 2013).

Evacuation scenarios: In order to study the impact of occurrence of higher capacity vehicles on evacuation in case of tunnel fire, we assume two traffic situations and the corresponding two evacuation scenarios (in the following they will be referred to as Scenario 1 and Scenario 2). The scenarios differ from each other by number of vehicles and number of evacuees considered. In Scenario 1, we consider 24 cars C1-C24 of the same type with variable numbers of passengers (Fig. 4 and 5). In Scenario 2, we consider 21 cars (cars C1, C3, C5, C7, C8,…, C24 as in Scenario 1) with 1-4 passengers, one bus with 30 passengers and one transporter with 9 passengers (Fig. 5 to 7).

Scenario with cars: Distances between cars C1-C24 and position of the fire source are shown in Fig. 4. The number of passengers of individual cars, times when vehicles stop, evacuation times from vehicles for individual passengers and doors by which they escape are shown in Fig. 5. The cars arrive through the left tunnel portal and stop at positions shown in Fig. 4. The first car stopped at the 53rd s, i.e., three seconds after the fire origin; the next cars stopped at every second, until the 76th s (Fig. 5). The total number of passengers is 65. We do not assume any higher capacity vehicles in this scenario.

We suppose that evacuees will choose one from two available escaping routes, the 10 m wide left tunnel portal and the 1.5 m wide emergency exit located near the cars C4 and C6. We assume that all passengers know (are familiar with) the portal (they came through it) and passengers of cars C1-C7 know the portal as well as the exit (they saw the exit before stopping the vehicle).

Our simulation experiments indicate that it is important to properly represent all possible exit routes to avoid distortion of evacuees' behavior. The exit is placed at 73 m distance from the left tunnel portal and is represented by a VENT object with given width, assigned evacuation mesh and "visibility point" (i.e., the corresponding point placed in the middle above the exit). Parameters of the exit are used as input of agents' decision algorithm and for calculation of the preferred directions field which directs the agents' movement. The left tunnel portal is represented by three individual exits of 2 m width which allow agents to escape through the portal. Simulation experiments indicate that such representation does not lead to distortion of expected agents' behavior. Note that the actual version of FDS+Evac does not allow sufficiently representing "low obstacles", i.e., the obstructions which obstruct agents in their movement but do not obstruct them to see exits (to see the visibility points assigned to the

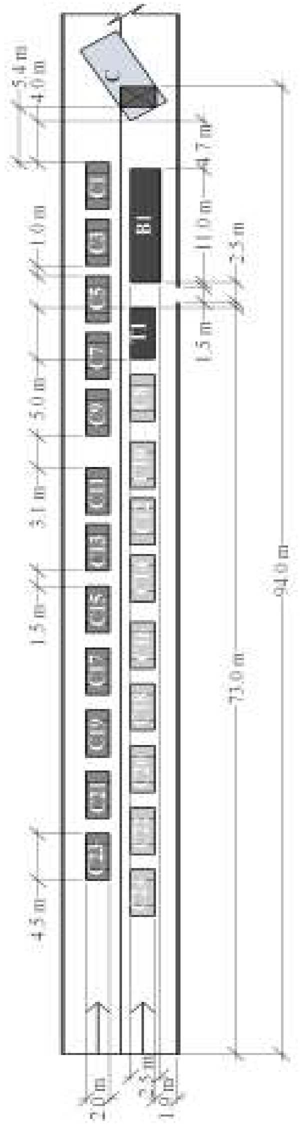


Fig. 6: Scheme of traffic (scenario 2): positions of cars C1, C3, C5, C7-C24, bus B1, transporter T1 and fire source

exits). Simulation experiments show that the portal representation using a single exit with the portal width (i.e., a single visibility point) would cause that agents at side parts of the tunnel would not see the portal because the cars standing in the tunnel would obstruct them to see the portal visibility point. Therefore, we represent the portal by three exits, the width of which is determined by the width of free "corridors" available for escape of agents towards the portal. Such representation makes agents able to see the portal escaping in the direction to it.

Scenario with higher capacity vehicles: In Scenario 2, we replaced cars C2 and C4 by bus B1 and car C6 by transporter T1 (Fig. 6). The rest of parameters of the traffic situation is left unchanged. This scenario allows us to test the impact of higher capacity vehicles on the course of people evacuation. Passengers' evacuation times from B1 and T1 and stop times of B1 and T1 are shown in Fig. 7. The rest of parameters for evacuation of passengers from cars C1, C3, C5, C7-C24 is the same as in Scenario 1.

	B1	AT	ET	T 1	AT	ET
LFD	-	54	-	1 M	55	60
RFD	10 A		60, 61,..., 69	2 A		60, 61
LBD	-		-	-		-
RBD	20 A		60, 61,..., 79	6 A		60, 61,..., 65

Fig. 7: Description of evacuation of higher capacity vehicles in scenario 2
A: Adult; M: Male; B1: Bus; T1: Transporter; AT: Vehicle stop time; ET: Individual passenger evacuation time; LFD, RFD, LBD and RBD: Left front door, right front door, left back door and right back door, respectively

We assume that all passengers know the portal (similarly as in Scenario 1) and that passengers from vehicles C1-C7, B1 and T1 know both the portal and exit (they saw the exit before stopping the vehicles). The exit is located at the same place as in Scenario 1. The total number of passengers is 95.

RESULTS AND DISCUSSION

In order to realize the calculations in parallel, the computational domain was divided into three 3D computational meshes of 10 cm mesh density, on which the fire was resolved. One additional 2D computational mesh of 10 cm mesh density was assigned to evacuation calculation. The total number of cube cells for fire simulation was 12960000 (4320000 cube cells for each mesh); the meshes parameters fulfilled the conditions required for efficient calculation of the FDS pressure solver (McDermott *et al*., 2010). The total number of cells for evacuation calculation was 180000. The calculations were realized on a PC (6-core i7-3930K, 3.20 GHz, 64 GB RAM). Each computational mesh was assigned to one CPU core. Thus, the calculation was performed in parallel on 4 CPU cores. The total computational time of 3-min period of fire and evacuation was 95.87 and 98.82 h for Scenario 1 and Scenario 2, respectively.

Course of simulated fire (scenario 1): The course of simulated fire and smoke spread are illustrated in Fig. 8 and 9. The fire started at the 50th s. Already at the 53rd s, hot gases hit on curved part of the tunnel ceiling and spread under the ceiling. The quasi-steady flow in the tunnel caused that the smoke was drifted more towards the right tunnel portal than towards the left portal. Figure 8 also illustrates how the individual cars stopped during the period between the 53rd and 56th s. Since the 60th s the ventilation started to act reaching its maximum velocity of 25 m/s at the 65th s. The

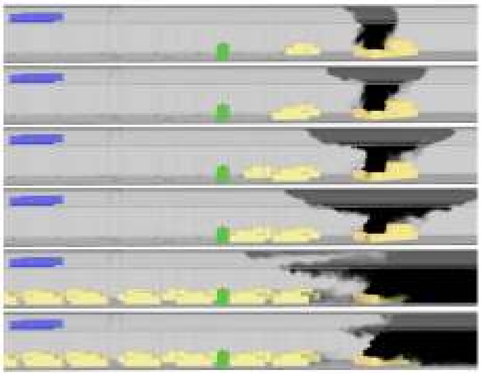


Fig. 8: Simulation of the course of fire and traffic situation at the 53rd, 54th, 55th, 56th, 90th and 99th s (scenario 1)

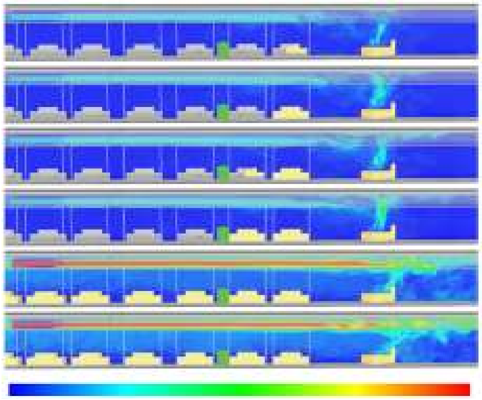


Fig. 9: Gas velocity distribution slices at the 53rd, 54th, 55th, 56th, 90th and 99th s of simulation (scenario 1): The color scheme values vary from 0.0 m/s (blue) to 25.0 m/s (red)

ventilation action caused that smoke began to spread more rapidly towards the right tunnel portal. At the 90th s, cars C1-C4 were still threatened by smoke. However, even at the 99th s, the tunnel was devoid of smoke at the left from the fire source position.

In order to demonstrate the fire dynamics in the tunnel, a sequence of selected slices of air velocity (at the same times as in Fig. 8) is shown in Fig. 9. It can be seen in the figure that the quasi-steady air flow under at the ceiling (in the beginning of fire) is affected by fire as well as by emergency ventilation action. Mixing of hot and cold gases can also be easily observed there. The gas temperature distribution at the same times is illustrated in Fig. 10.

Course of simulated fire (scenario 2): The spread of fire and smoke in Scenario 2 is illustrated in Fig. 11 and 12. The course of fire is similar as in Scenario 1. Hot gases hit on curved part of the ceiling even at the 53rd s and then spread under the ceiling. In both scenarios, the smoke was drifted more towards the right tunnel portal than towards the left portal; however, the occurrence of higher capacity vehicles in Scenario 2 affected the quasi-steady air flow under the ceiling and later the whole air circulation in the tunnel. It caused that the smoke in Scenario 2 was drifted to the right

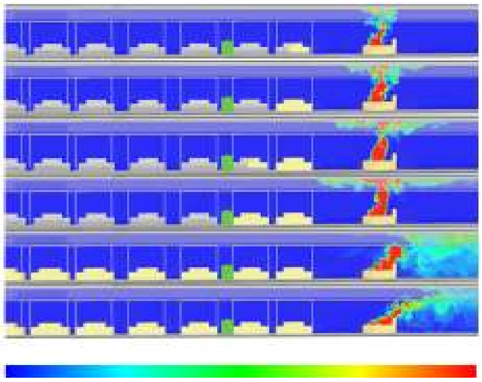


Fig. 10: Gas temperature distribution slices at the 53rd, 54th, 55th, 56th, 90th and 99th s of simulation (scenario 1): the color scheme values vary from 20°C (blue) to 220°C (red)

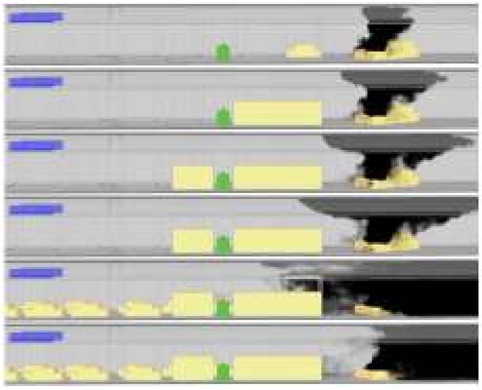


Fig. 11: Simulation of the course of fire and traffic situation at the 53rd, 54th, 55th, 56th, 90th and 99th s (scenario 2)

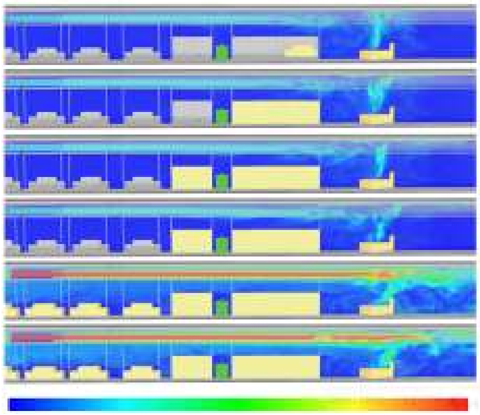


Fig. 12: Gas velocity distribution slices at the 53rd, 54th, 55th, 56th, 90th and 99th s of simulation (scenario 2): the color scheme values vary from 0.0 m/s (blue) to 25.0 m/s (red)

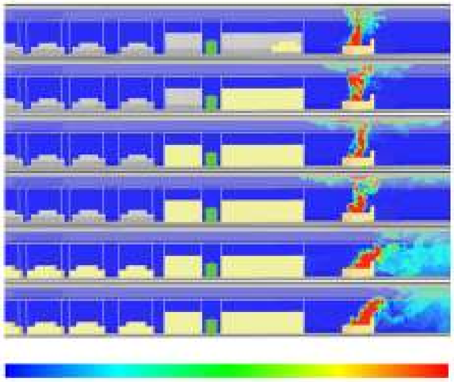


Fig. 13: Gas temperature distribution slices at the 53rd, 54th, 55th, 56th, 90th and 99th s of simulation (scenario 2): the color scheme values vary from 20°C (blue) to 220°C (red)

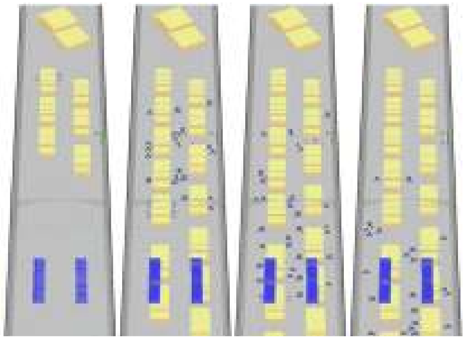


Fig. 14: Simulation of people evacuation at the 58th, 66th, 70th and 78th s (scenario 1)

more than in Scenario 1. On the other hand, the higher obstacles (bus and transporter are higher than cars by about 1.4 m) in Scenario 2 affected the air flow and caused that the spread of smoke tended to be more dangerous for passengers escaping from vehicles standing closer to the fire source. Similarly to Fig. 8, Fig. 11 illustrates individual cars, bus and transporter arriving between the 53rd and 56th s. At the 90th s, cars C1 and C3 and bus B1 were still threatened by smoke and at the 99th s, the tunnel has not yet been completely devoid of smoke at the part left from the fire source (some residual smoke can be seen in Fig. 11).

In Fig. 12 and 13, a time sequence of gas velocity and temperature slices at the same times as in Scenario 1 is shown, respectively. The pictures demonstrate the dynamics of fire and air flow in the tunnel. It can be seen there that the quasi-steady air flow under the ceiling at the beginning of fire is affected by the fire and by emergency ventilation. Mixing of hot and cold gas can also be observed. Detailed analysis of fire spread in Scenario 1 and 2 (Fig. 9 and 12) indicates relatively small differences in the air flow and smoke spread in Scenarios 1 and 2; however, the small differences can influence evacuees' behavior and decision making during evacuation significantly.

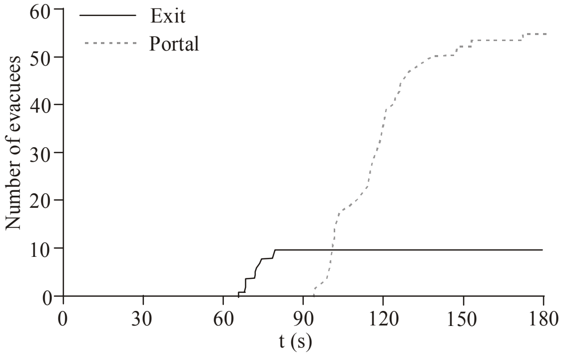


Fig. 15: Using the exit and portal in time (scenario 1)

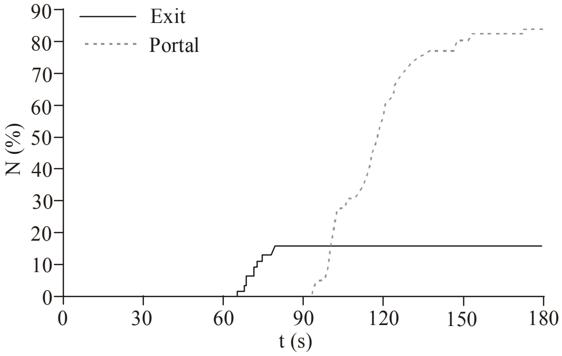


Fig. 16: Using exit routes in time (scenario 1); N is relative number of evacuees escaping through a particular exit route in regard of the total number of agents

Course of evacuation (scenario 1): Simulation results show that the evacuation started at the 58th s (Fig. 5) and ended at the 180th s. The course of evacuation is illustrated in Fig. 14. Detailed analysis of the simulation results indicates that passengers escaping from cars C1 and C7-C24 used the left tunnel portal, passengers from cars C2 and C4 used the exit and passengers from cars C3, C5 and C6 used both the exit and the portal.

In Fig. 15, the graph of using the exit and the portal in time is shown. In this scenario, most evacuees used the portal (55 evacuees) and less agents used the exit (10 evacuees).

In Fig. 16, we illustrate a measure of using particular available exit routes in the simulation. The portal was used by more than 84% of the total number of evacuees; the exit was used by less than 16% of the total number of evacuees (65 evacuees).

Detailed analysis indicates that passengers getting out of the left doors of the cars stopped in the left tunnel lane escaped towards the tunnel portal. This was caused by the fact that they knew and saw the portal. Therefore, the portal became their preferred exit route, unlike the exit which was not seen by agents over stopped vehicles (because the cars were not "low obstacles"). Since the passengers from the cars C1-C7 knew the exit (as well as the portal), it was possible to assume that a part of the agents would choose the exit

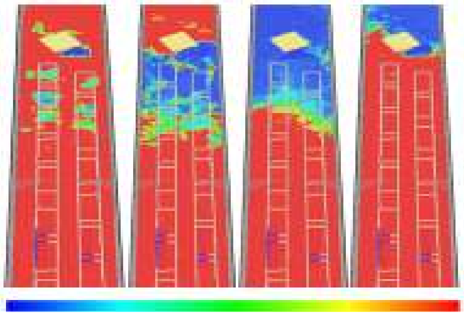


Fig. 17: Slices of soot visibility at head level at the 66th, 69th, 76th and 90th s (scenario 1); the color scheme values vary from 0.0 to 30.0 m

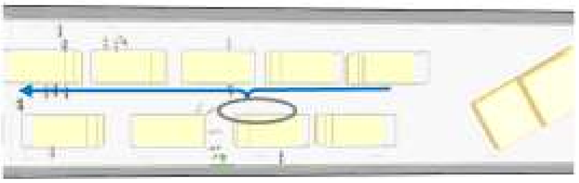


Fig. 18: Trajectory of the passenger escaping from the right front door of car C1 (scenario 1): the agent has to bypass the highlighted area afflicted by toxic smoke

rather than the portal in the case that they would see the exit through cars. Note that low obstructions are to be included in the next FDS+Evac version. In the actual FDS+Evac version, it is possible to achieve a similar behavior by setting the corresponding parameters of individual agents and/or exits.

Some of the agents in the mid part of the tunnel between two chains of vehicles (i.e., passengers from cars C2-C5) escaped through the exit because they knew and saw it; passengers from cars C6 and C7 escaped through the portal because they did not see the exit because of standing cars; and passengers from the car C1 escaped through the portal because he/she did not see the exit because of dense smoke. Passengers from cars C8-C24 escaped through the portal because they neither saw nor knew the exit. However, behavior of selected passengers (or crews of selected cars) could be influenced by setting their parameters and/or parameters of exits in order to choose the exit (as mentioned above).

Passengers in the right tunnel lane getting out of the right doors of cars C2, C4 and C6 escaped through the exit. It follows from settings of the passengers of cars C8-C24 that the portal became their preferred exit route (they saw and were familiar with it) rather than the exit (it was seen only). As noted before, in order to influence the agents' behavior, it is enough to change settings of the agents and/or exits.

In Fig. 17, a time sequence of soot visibility slices at passengers' head level is shown. The toxic smoke influenced the ability of evacuees to see the exit and caused a change of their behavior. Some of evacuees were intoxicated and their movement velocity decreased. In Fig. 18, an example of such passenger's behavior is illustrated. The agent of the type of adult inhaled the smoke at the place highlighted in the picture and his/her speed was decreased. Moreover, he/she did not see the exit because of decreased visibility and had to bypass the area endangered by smoke (Fig. 18). The agent behavior caused that total evacuation time in this scenario was relatively long (he/she was the last evacuated passenger in the simulation).

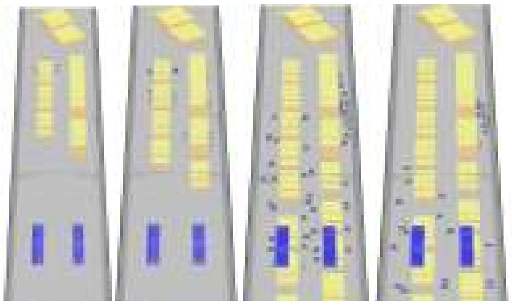
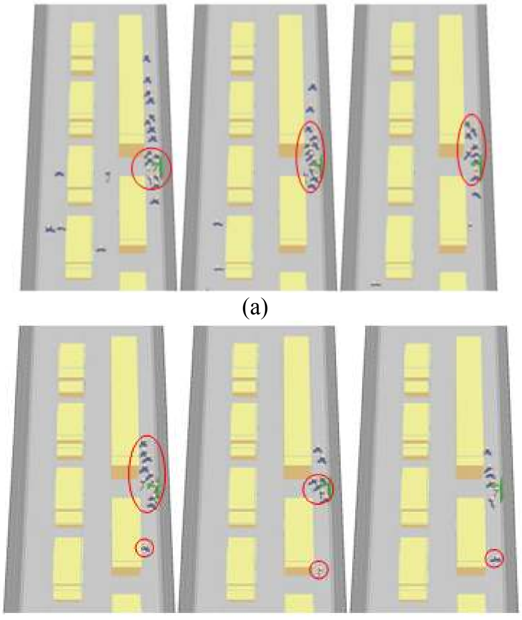


Fig. 19: Simulation of people evacuation in the tunnel at the 58th, 60th, 70th and 80th s (scenario 2)

Course of evacuation (scenario 2): It was expected that in Scenario 2, in which two higher capacity vehicles occurred, total evacuation time would be longer than in Scenario 1. This hypothesis was supported by the fact that the number of evacuees in Scenario 2 was greater by about 45% than in Scenario 1. However, simulation results show that total evacuation time in Scenario 2 was 169 s (shorter than in Scenario 1).

The obtained simulation results indicate that passengers from cars C1-C3 and transporter T1 used both the portal and exit, passengers from cars C4-C21 used the portal and passengers from bus B1 escaped through the exit. The course of evacuation is illustrated in Fig. 19. Detailed analysis of the simulation results shows a jam originated in front of the exit which could endanger the evacuation of people from the bus and transporter (Fig. 20a). The queuing in front of the exit caused a slowdown of evacuees' movement and increase of emergency risk (unwanted collisions of evacuees, injuries). The queuing also influenced the behavior of some other evacuees escaping from other vehicles. In Fig. 20b, an agent escaping from transporter T1 moving towards the portal is highlighted. At first, the agent selected the portal as the best way to escape taking into account waiting in the queue in front of the exit. However, already at the 83rd s he/she turned round and escaped towards the exit because the queue in front of the exit was reduced. Therefore, the exit became the fastest escaping route for him/her.

In Fig. 21, using the exit and portal in time is shown. Most evacuees used the portal (54 evacuees). A slightly less number of evacuees (41 evacuees) used the


(a)

(b)

Fig. 20: Queuing in front of the exit at the 71st, 75th, 80th, 81st, 83rd and 86th s (scenario 2)

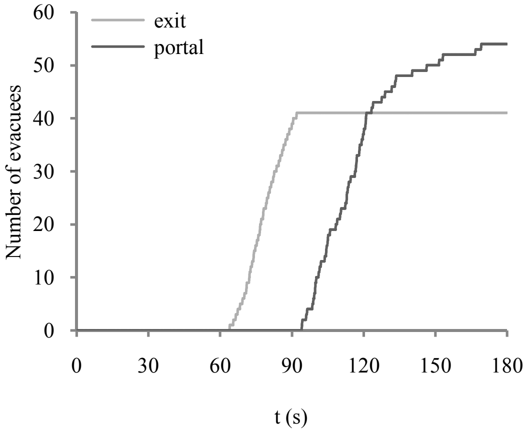


Fig. 21: Using the exit and portal in time (scenario 2)

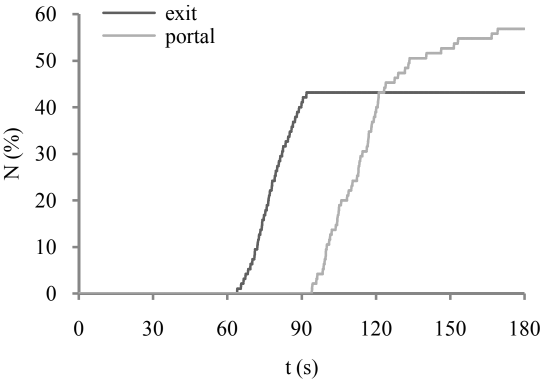


Fig. 22: Using exit routes in time (scenario 2); N is relative number of evacuees escaping through a particular exit route in regard of the total number of agents

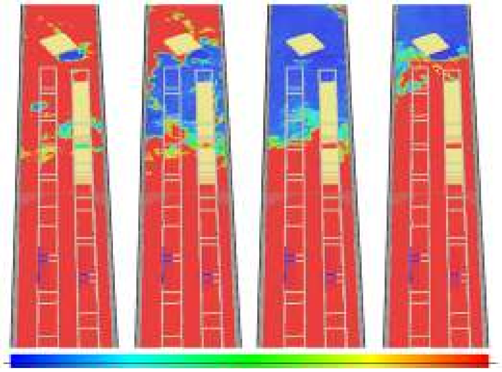


Fig. 23: Slices of soot visibility at head level at the 66th, 69th, 76th and 90th s (scenario 2); the color scheme values vary from 0.0 to 30.0 m

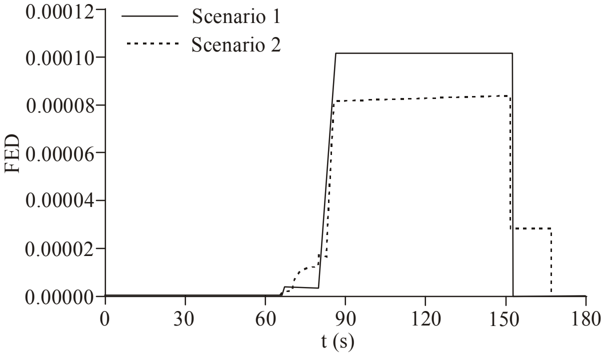


Fig. 24: The maximal value of evacuees' intoxication (FED index)

exit. In Fig. 22, we illustrate a measure of using particular available exit routes in the simulation. The portal was used by more than 56% of the total number of evacuees; the exit was used by less than 44% of the total number of evacuees (95 evacuees).

In Fig. 23 and 24, a time sequence of soot visibility slices at passengers' head level for Scenario 2 (at the same times as in Scenario 1) and comparison of the graphs of maximal evacuees' intoxication by smoke are illustrated, respectively. It can be seen in Fig. 24 that in Scenario 1 the maximal FED index values are higher than in Scenario 2. This was caused by the crowd of evacuees created in Scenario 1 at the place afflicted by toxic smoke. In Scenario 2, the queuing in front of the exit could be dangerous for the evacuees; however, in this scenario the place where the queue originated was not endangered by smoke at that time.

Analysis of real incidents in road tunnels and conducted egress experiments show relatively high variability in human behavior in case of emergency. For instance, variable fire detection and reaction times of individual evacuees, crowd behavior, irrational behavior, panic and groups formation were observed. In this study, evacuees' settings were selected to capture as much uncertainty inherent to human behavior modeling as possible. On the other hand, we try to keep the considered scenarios simple enough to show the impact of higher capacity vehicles on the course of evacuation. FDS+Evac allows to model the uncertainty using its "stochastic mode" utilizing the feature of Evac randomly to assign values of evacuees' settings for different simulations of the same fire scenario. However, such research was not the aim of this study.

Simulation results indicate that occurrence of higher capacity vehicles results in increased number of evacuees; however, it does not always imply increase of the total time of evacuation. In accordance with several papers studying people evacuation in case of tunnel fire, total evacuation time depends significantly on position and accessibility of evacuation exits, location of higher capacity vehicles in tunnel, location of the source of fire, as well as on the fire and smoke spread influenced by ventilation action. Further upgrading, testing and careful validation of available evacuation models and testing their applicability for practical problems in tunnel fire safety is of high importance (McDermott *et al*., 2010; Korhonen and Hostikka, 2009; Ronchi *et al*., 2012; Murray-Smith, 2013). Reliable computer simulation of evacuation scenarios in structures in case of fire can contribute to increase of the structure fire safety and provide a means for analysis and references for existing evacuation plans available in structures in development as well as in operation (Wang, 2013; Zhang, 2013; Yang, 2013).

CONCLUSION

In this study, the FDS+Evac system is used to study the impact of the occurrence of higher capacity vehicles on people evacuation in 180 m long single-directional 2-lane road tunnel with longitudinal ventilation in case of fire. Two traffic situations were described, in which 24 cars of the same type as well as 21 cars, bus and transporter were considered. The used simulation system benefits from the advanced CFD-based fire field model FDS cooperating with the agent-based evacuation model Evac. Evac has a direct access to relevant characteristics of simulated fire obtained by FDS and is able to utilize them to model the impact of fire on the course of evacuation. Application of FDS+Evac on the fire safety problem in road tunnel is illustrated and some important particularities of the current version of the system which must be taken into account to avoid inappropriate inputs representation of the tunnel structure, traffic situation, evacuation scenarios, or emergency exits are briefly discussed. Such misrepresentation can cause distortion of simulation results. Detailed analysis of two simulated scenarios indicates that occurrence of higher capacity vehicles in tunnel in case of fire can cause substantial increase of the risk for passengers and can lead to casualties. However, it was shown that the course of evacuation, behavior of individual evacuees and their groups as well as evacuees' escaping strategies are substantially influenced by the given fire scenario, traffic situation, location and intensity of fire source, placement and action ventilation system components, as well as by individual and crowd psychology and behavior in case of emergency event. Simulation results show that fire and smoke spread can have crucial impact on individual and group behavior of evacuees, on their decisions and choosing of exit routes. Particularly in Scenario 1, it was illustrated that an agent changed his/her previously chosen trajectory to the exit because of smoke and had to escape through the portal; this affected the total evacuation time in this scenario considerably. Evacuation Scenario 2 is a good example that a significant increase of the number of passengers in tunnel needs not to automatically imply risk increase in the tunnel. The simulation results presented and some of included comments and recommendations can be useful for scholars and developers engaged in research, development, testing as well as in the use of FDS+Evac for practical problems of fire safety in road tunnels.

The simulation results indicate the need of some future investigations related to the problem of people evacuation in longer road tunnels in case of fire and impact of fire source, emergency ventilation action, traffic and evacuees' settings on the behavior of individual evacuees and their groups in case of fire.

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