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Modelling of impact of fire on safe people evacuation in tunnel

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Abstract. In this paper, the use of Fire Dynamics Simulator (FDS) and its evacuation module, Evac for modelling fire and people evacuation in a road tunnel is illustrated. For given fire scenario and traffic situation in the tunnel, behaviour of individual evacuees as well as groups of evacuees is analyzed in order to demonstrate the impact of fire on people evacuation. Some specific features of the use of FDS+Evac for simulation of people evacuation in case of tunnel fire are also discussed.

1. Introduction
Current fire models and program systems based on the knowledge of CFD (computational fluid dynamics) allow to simulate fire in complex geometries incorporating a wide variety of physical phenomena related to fire and utilizing high computational power of current computers. Such systems are capable to simulate the fire spread and evaluate fire consequences on tunnel structure, facilities and people in tunnel. In this paper, Fire Dynamics Simulator (FDS, version 5.5.3, svn 7031) [5] and its evacuation module, Evac [2] are used for simulation of fire and evacuation in a short road tunnel. Several other systems for people egress simulation are available; however, most of them are able to model the impact of fire on evacuation only partially [6, 7] and only a few papers focus on the interaction of fire and evacuation simulations. In this paper, for a given traffic situation the impact of fire on behaviour of individual passengers and groups of passengers escaping from cars is illustrated in order to demonstrate some specific features of the use of FDS+Evac for simulation of evacuation in case of tunnel fire. In [8], we studied the impact of occurrence of higher capacity vehicles on the course of evacuation in tunnel. In this paper, we focus on the impact of fire on behaviour of evacuees in case of tunnel fire.

2. FDS+Evac
FDS (Fire Dynamics Simulator) [5] is a CFD-based field fire model capable to simulate complex physical and chemical phenomena associated with fire such as heat transfer, pyrolysis, combustion, radiation, turbulence, fluid dynamics and suppression. It was developed by NIST (National Institute of Standards and Technology, USA) in cooperation with VTT Technical Research Centre of Finland. FDS allows visualization of 3D smoke and flames spread as well as of other parameters characterizing fire in the form of 2D slices, tables, graphs and pictures. Since the first validation study elaborated by the U.S. NRC (Nuclear Regulatory Commission) [1], systematic verification and validation of FDS continue until now (see e.g. [3, 4]). Evac [2] is an evacuation module of FDS capable to utilize fire suppression and other auxiliary means for evacuation.

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parameters for modelling the impact of fire on evacuees’ movement, behaviour and escape strategies. Each evacuee is treated as an independent entity (agent) with own personal properties and escape strategies. As the shape of human body is approximated by combination of three overlapping circles, motion equations of each agent include rotational movement. The model behind the movement algorithm is the social force model taking into account motive and physical forces exerted by the environment and by other agents (for more details about representation of social, motive, contact, attraction and repulsion forces, see [2]). Agents are guided to exits by a vector field of preferred walking directions calculated by FDS. Simple collision avoidance strategy is also included. The exit selection algorithm solves an optimization problem minimizing the evacuation time taking into account agent’s walking time and queuing. The agents’ decision making and individual and group escape strategies are influenced by familiarity with exits, visibility of exits and effects of smoke and obstacles. The interaction between fire and evacuation models and direct access of Evac to the fire information are the main strongpoints of FDS+Evac. It combines 3D fire simulation (calculated on 3D computational meshes) with 2D evacuation simulation (calculated on a single 2D computational mesh). FDS+Evac computes a form of the Purser’s FED (fractional effective dose) index and the agents’ intoxication and incapacitation. The impact of smoke on the agents’ walking speed, exit selection and fire detection is modelled.

3. Fire and evacuation scenario
Let us consider a single-directional 2-lane 180 m long road tunnel with curved ceiling [8] (see figure 1). Two couples of jet fans placed by about 3 m far from each other are located about 1 m under the ceiling. Their effective diameter and length is 0.9 m and 5.2 m, respectively. Initial air flow supposed in the tunnel is modelled by fans blowing at 6.25 m/s velocity during the first 60 s of simulation providing a quasi-steady air flow with approximately 2 m/s velocity under the ceiling. The fire source is represented by 2 m x 3 m surface producing heat at 1666.667 kW/m² heat release rate per unit area. It is placed about 1.1 m above the road. The fire is ignited at the 50th s. It linearly increases achieving 10 MW heat release rate at the 55th s. Since that time, the fire source intensity remains unchanged until the end of simulation (at the 180th s). Other flammable materials inside the tunnel are not considered. We assume the following ventilation action. At the 60th s, all fans start to work with linearly increasing velocity (from 6.25 m/s) reaching 25 m/s velocity at the 65th s. Since that time, the fans velocity is not changed. We assume 20°C ambient temperature in the tunnel at the beginning of simulation. We consider 24 cars arriving through the left tunnel portal which stop in positions shown in figure 1. Arrival times for particular cars and basic passengers’ settings are also listed there. 65 passengers are considered in the scenario. We assume one 1.5 m wide emergency exit placed by about 73 m far from the left portal represented in simulation by a VENT object to which an evacuation mesh and a point lying above the middle of the exit are assigned. In FDS+Evac, the point is used to determine visibility of exit. The left tunnel portal is represented by 3 individual exits rather than by single exit. The triple of exits is selected to minimize the area from which the portal is not visible. Simulation experiments performed indicate that the portal representation as single exit would lead to the portal misrepresentation and non-realistic movement of evacuees (the problem is related to “low obstacles” implementation in the current version of FDS+Evac; for more details, see [8]). We assume that all passengers “know” (are familiar with) the left tunnel portal. Passengers escaping from cars C1-C7 know both the left portal and exit. Note that some simplifications must be adopted (for instance shortened reaction times of evacuees and alarm system in regard to times observed in real situations) to keep fire and evacuation scenarios as simple as possible and the total calculation time reasonable.

4. Fire Simulation
The fire and evacuation simulation was realized on 6-core PC (Intel i7-3930K, 3.26 GHz, 64 GB RAM). 4 CPU cores were used (3 cores assigned to three 3D computational meshes for fire simulation and one core assigned to single 2D evacuation mesh for evacuation simulation; all meshes had 10 cm density). Total computational time of 3-minute simulation was 95.87 hours.
Cars AT LF RF LB RB
C1  C2  C3  C4  C5  C6  C7  C8  C9  C10  C11  C12  C13  C14  C15  C16  C17  C18  C19  C20  C21  C22  C23  C24
53  54  55  56  57  58  59  60  61  62  63  64  65  66  67  68  69  70  71  72  73  74  75  76  77  78  79  80
A58 A59 M60 F61 A62 M63 A64 M65 M66 M67 M68 M69 M70 M71 E73 M73 M74 M75 F76 M77 M78 M79 E81 M81
RF A58 E60 F60 F61 E63 F65 A66 A68 A69 F70 - E74 F73 A74 A75 - A77 M78 A79 - A81
LB - C60 C60 - M63 E65 - M66 - M68 M69 - - - - E74 M74 M75 - M77 - M79 - M81
RB - - C60 - F63 E65 C65 A66 - C68 - - - - - - - - - - - - - - - -

Notation: AT denote arrival times of cars C1-C24; A, M, F, C and E denote adult, male, female, child and elderly, respectively; and LF, RF, LB and RB denote the left front, right front, left back and right back door, respectively.

**Figure 1.** Scheme of the road tunnel, fire source and cars location, and cars’ and passengers’ settings.

**Figure 2.** Fire and smoke spread at the 56th s.

**Figure 3.** Soot visibility slices in head level at the 65th s and 67th s (first two figures); impact of smoke on evacuation (third figure); and examples of passengers’ behaviour (last triple of figures).
The course of fire was as follows (for more details, see [8]). At first, hot gases spread upwards from the fire source reaching the ceiling at the 53rd s. Then the smoke spread under the ceiling being drifted slightly more towards the right tunnel portal because of the quasi-steady air flow under the tunnel ceiling (see figure 2). Since the 60th s, smoke spread more rapidly towards the right tunnel portal as result of ventilation action. At the 99th s, smoke was completely eliminated from the tunnel at the left of the fire source. The soot visibility slices at head level illustrate the smoke spread and increasing risk of people intoxication in the tunnel (see the first two figures in figure 3).

5. People Evacuation
The third figure in figure 3 illustrates the course of evacuation at the 70th s when 4 (from 36) evacuees were evacuated via the exit, 3 people were intoxicated and none of passengers was incapacitated. Trajectory of passenger from the car C1 who was forced to change escape route because of smoke is highlighted. The next figures in figure 3 illustrate escape strategies of passengers from the car C3; two couples of passengers escaping through two different emergency routes, 4 passengers escaping through the exit (however, they move relatively independently of each other) and 4 passengers behaving as a group escaping through the exit are shown. The cases differ from each other by agents’ settings (familiarity with exits, preferred directions field modification, group force parameter).

6. Conclusion
The use of FDS+Evac for modelling people evacuation in short single-directional road tunnel in case of fire is illustrated. Detailed analysis of passengers’ movement indicates that FDS+Evac is able to realistically capture the main tendencies of evacuees’ behaviour and the influence of smoke on evacuees’ movement, intoxication and decision making. Basic types of individual and group behaviour of evacuees modelled by FDS+Evac are illustrated. However, simulation experiments indicate that the way of implementation of emergency exits visibility must be taken into account to avoid misrepresentation of inputs for FDS+Evac simulation (for more details see also [8]).

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