Impact of Vehicles on Smoke Spread Dynamics in the Case of Fire in Road Tunnel

L Valasek, J Glasa, P Weisenpacher and L Halada
Institute of Informatics, Slovak Academy of Sciences, Dubravska cesta 9, 845 07 Bratislava, Slovakia
E-mail: lukas.valasek@savba.sk

Abstract. In this paper, the impact of vehicles in road tunnel on smoke spread in case of fire is illustrated using the FDS (Fire Dynamics Simulator) system. FDS is a CFD-based fire field model capable to simulate fire in various environments capturing a big variety of physical processes related to fire. A set of simulations of fire in a 300 m long two-lane single directional road tunnel with longitudinal ventilation is described focusing on the impact of vehicles on the smoke spread dynamics in the tunnel.

1. Introduction
Current fire models are capable to describe fire in various environments and incorporate a wide variety of physical phenomena related to fire. They utilize the knowledge of Computational Fluid Dynamics (CFD) and increasing computational power of modern computers. In this paper, smoke spread dynamics in a road tunnel in case of fire is investigated using the FDS (Fire Dynamics Simulator) system. FDS [9] solves numerically a form of Navier-Stokes equations appropriate for low-speed (Ma < 0.3), thermally-driven flow with an emphasis on smoke and heat transport from fire. The core algorithm is an explicit predictor-corrector scheme, second order accurate in space and time. Turbulence is treated by means of Large Eddy Simulation or Direct Numerical Simulation for larger spaces or very fine mesh resolutions, respectively. FDS covers other models for relevant physical and chemical processes related to fire such as pyrolysis, combustion, radiation, heat transport, suppression, etc. FDS allows to model people evacuation in structures and capture the impact of fire on the course of evacuation and people behaviour. Recently, the 6th version of FDS was released; parallel versions of FDS are also available for multi-mesh and multi-processor calculations. FDS has been used for simulation of fires in various structures, for instance in a cinema, supermarket, office building, industrial hall and nuclear power plant (see e.g. [4, 5, 6, 7, 8]). In this paper, we utilize our actual experience with FDS for simulation of fire in short road tunnel in order to study the impact of vehicles in a road tunnel on the smoke spread dynamics in case of fire. In our previous papers [10, 11] and [3, 1, 2], we studied the impact of parallelization of simulation calculation on efficiency and accuracy and various aspects of modelling of people evacuation, respectively.

2. Description of road tunnel and fire scenario
We consider a 10 MW fire in a single-directional 2-lane road tunnel with curved ceiling and longitudi-
nal ventilation. The tunnel is 10 m wide, 300 m long and 7.2 m high with two couples of jet fans which are placed about 1 m under the tunnel ceiling at the distances of 32.6 m and 137.8 m from the left tunnel portal (see figure 1). The fans are placed 3 m far from each other. They have the 0.9 m effective diameter and 5.2 m length. A 2 m wide emergency exit placed 193 m far from the left tunnel portal is considered. The tunnel geometry is represented by 38 OBSTs and 5 VENTs.

![Figure 1. Scheme of road tunnel and fire source and their representation (simulation at the 27th s).](image1)

Table 1. Arrival times (AT) of particular vehicles in the first two scenarios: C1-C24 denote cars; B1 and T1 denotes bus and transporter, respectively.

| Vehicles | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 | C10 | C11 | C12 | C13 | C14 | C15 | C16 | C17 | C18 | C19 | C20 | C21 | C22 | C23 | C24 |
|----------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| AT (s)   | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
| Vehicles | C1 | B1 | C3 | C5 | T1 | C7 | C8 | C9 | C10 | C11 | C12 | C13 | C14 | C15 | C16 | C17 | C18 | C19 | C20 | C21 | C22 | C23 | C24 |
| AT (s)   | 3  | 4  | 5  | 7  | 5  | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 |

At the beginning, the 1 m/s steady air flow with the left direction is assumed in the tunnel, provided by setting the initial conditions for air flow in the tunnel. The fire source is represented by burning of 2 m x 3 m surface producing heat at 1666.667 kW/m² heat release rate per unit area since the beginning until the end of simulation (at the 240th s). The fire source is placed about 1.1 m above the road 212 m far from the left tunnel portal. We do not consider any flammable materials inside the tunnel. We assume the following ventilation action. At the beginning, all fans work with the 1 m/s velocity; at the 29th s, they start to work with linearly increasing velocity (from 1 m/s) reaching the 2.8 m/s velocity at the 30th s. Since that time, the fans velocity was not changed until the end of simulation. The 2.8 m/s flow velocity is close to the value of critical velocity. We assume 13°C
ambient temperature in the tunnel at the beginning of simulation. We consider three different traffic situations: 24 cars (1\textsuperscript{st} scenario); 21 cars, bus and transporter (2\textsuperscript{nd} scenario); and the situation without any vehicles (3\textsuperscript{rd} scenario), respectively. Vehicles are located in parallel with tunnel direction (figure 2) and arrive through the left tunnel portal at arrival times listed in table 1. At the times they are inserted in the computational domain and start to influence the air flow dynamics. Each car is represented by two OBSTs. The bus and transporter are represented by one OBST.

3. Smoke spread dynamics simulation

The described three fire simulations were realized on 6-core PC (Intel i7-3930K, 3.26 GHz, 64 GB RAM) using 5 CPU cores assigned to five 3D computational meshes of the 10 cm density (the total number of cells was 21600000; 4320000 cells per mesh). Total computational time of 4-minute simulation of the 1\textsuperscript{st}, 2\textsuperscript{nd} and 3\textsuperscript{rd} scenario was 112.23, 113.00 and 110.06 hours, respectively.

| Distance to | C1 | C3 | C5 | C7 | C9 | C11 | C13 | C15 | C17 | C19 | C21 | C23 | Fan2 | Fan1 |
|-------------|----|----|----|----|----|-----|-----|-----|-----|-----|-----|-----|------|------|
| T (s) in Scenario1 | 6.4 | 8.6 | 12.2 | 15.6 | 18.2 | 23.2 | 26.4 | 30.6 | 34.4 | 39.4 | 42.8 | 47.4 | 46.6 | 134.2 |
| T (s) in Scenario2 | 6.8 | 9.8 | 13.4 | 16.4 | 19.6 | 24.0 | 27.0 | 31.8 | 35.8 | 39.8 | 43.6 | 48.0 | 47.0 | 132.4 |
| T (s) in Scenario3 | 8.0 | 10.4 | 13.0 | 15.4 | 18.2 | 21.8 | 25.8 | 29.4 | 33.6 | 37.4 | 41.2 | 45.4 | 40.6 | 133.4 |

**Figure 3.** Smoke dynamics at the 13\textsuperscript{th}, 31\textsuperscript{st}, 45\textsuperscript{th} and 100\textsuperscript{th} s for scenario 1 (side view).

**Figure 4.** Horizontal and vertical slices of flow velocity at head level and at the center of tunnel tube at the 30\textsuperscript{th} s for scenarios 1-3, respectively; color scheme is the same for both cases, the values vary from -3.9 to 4.6 m/s and from -0.8 to 2.1 m/s, respectively.
The course of fire was similar for all three scenarios (see figures 3 and 4, and table 2). At first, hot gases released from the fire source propagated upwards reaching the ceiling at the 3rd s. Then smoke spread under the ceiling in the direction to both portals being drifted slightly more towards the right portal because of the original air flow in the tunnel. The air flow supported later by ventilation blowing with the velocity close to the critical velocity caused that the smoke in upper part of the tunnel propagated to the left with decreased velocity. In lower part of the smoke layer a colder smoke, which was drifted to the right by air flow forced by ventilation, can be observed. Later, local turbulent clouds of smoke started to origin at lower part of the smoke layer. These clouds were induced by eddies caused by circumfluence of vehicles standing in the tunnel (vehicles act as obstructions against laminar air flow in the tunnel tube). The size of vehicles and their location cause small differences in smoke spread (see table 2 and figure 4); however, even these small differences can have significant impact on increase of safety risks for passengers in the tunnel and their intoxication as it was discussed in [1, 2].

3. Conclusion
In this paper, a set of simulations of fire in road tunnel is described. The simulations differ from each other by traffic situations considered. Detailed analysis of simulation results indicates that FDS is able to realistically capture the main features of road tunnel fire and study the influence of vehicles on smoke spread dynamics and increase of safety risks for passengers in tunnel in the case of fire.

4. Acknowledgment
This paper was partially supported by National Science Foundation VEGA (contract No. 2/0184/14).

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