FDS simulation of smoke backlayering in emergency lay-by of a road tunnel with longitudinal ventilation

P Weisenpacher J Glasa L Valasek T Kubisova
Institute of Informatics, Slovak Academy of Sciences,
Dubravska cesta 9, 84507 Bratislava, Slovakia

E-mail: upsyweis@savba.sk

Abstract. This paper investigates smoke movement and its stratification in a lay-by of a 900 m long road tunnel by computer simulation using Fire Dynamics Simulator. The lay-by is located upstream of the fire in its vicinity. The influence of lay-by geometry on smoke spread is evaluated by comparison with a fictional tunnel without lay-by. Several fire scenarios with various tunnel slopes and heat release rates of fire in the tunnels without and with the lay-by are considered. The most significant breaking of smoke stratification and decrease of visibility in the area of the lay-by can be observed in the case of zero slope tunnel for more intensive fires with significant length of backlayering. Several other features of smoke spread in the lay-by are analysed as well. The parallel calculations were performed on a high-performance computer cluster.

1. Introduction
Ventilation strategy in case of fires in bi-directional road tunnels equipped with longitudinal ventilation utilizes the concept of smoke stratification [1]. The concept can be used for fire safety measures for various types of structures with large dimensions and high compartments, for example in atriums and large corridors [2]. If smoke remains stratified below the ceiling and the smoke layer does not reach the level of human head, tenable conditions for human life can be maintained. Good visibility allows safe evacuation of people even in the case of fire. It is assumed that proper airflow velocity in the tunnel achieved and regulated by jet fans maintains the stratification of smoke layer. Stratification should persist for several minutes to ensure the safe evacuation of people trapped on both sides of fire. If smoke stratification breaks, tenable conditions disappear.

Tunnel geometry configuration may influence smoke stratification, while the niches for emergency lay-bys are some of the most important components of tunnel geometry. Lay-bys allow vehicles to stop inside the tunnel without blocking the carriageway, reducing traffic disruption and decreasing the risk of car accidents. It is easier and safer for passengers to get out of their vehicles there. Lay-bys are located typically every 1000 m in tunnel [3] and they are equipped with various safety installations.

Fire Dynamics Simulator (FDS), version 6 [4, 5] is a well-known CFD code used for heat and smoke spread simulation. In [6] the ability of FDS to simulate the airflows generated by jet fans in a real road tunnel was studied.

In [7] the influence of lay-bys on smoke stratification in a 900 m long road tunnels of the same geometry and equipment but with different slope than in [6] was investigated. Fictional tunnels without lay-bys and realistic tunnels with two lay-bys were considered. Smoke movements were compared for several fire scenarios and the influence of lay-bys on smoke stratification was evaluated.
Visibility at human head level was used as a measure of smoke stratification. Specific location of fire source in the middle between both lay-bys allowed studying mainly the conditions in the lay-by located downstream. The smoke layer does not reach the lay-by located upstream of the fire or it reaches the lay-by without considerable influence. For less intensive passenger car fire the smoke does not reach upstream located lay-by, while for more intensive fire the smoke layer reaches the lay-by, but its influence is not considerable.

In this paper, we study the influence of a fire located in the vicinity of the upstream lay-by. Smoke backlayering is significant enough to reach the area of the lay-by and to influence the conditions for human life.

2. FDS tunnel model
The scheme of the tunnel with two lay-bys is shown in Fig. 1. It is 900 m long with a horseshoe cross section of dimensions 10.8 m (width) and 6.8 m (height). Two lay-bys are located at 373 m (left side) and 635.6 m (right side) from the west tunnel portal, respectively. The niches are 50 m long and 2.2 m wide with the maximal height of vaulted ceiling of 7.8 m. The tunnel dimensions are typical for most Slovak tunnels [8, 9]. The geometry of the tunnel is modelled by rectangular obstructions with material properties of concrete.

The tunnel is equipped with four pairs of jet fans located at 101 m, 201 m, 716 m and 801 m. They are modelled using the HVAC feature included in FDS. Two rectangular vents of dimensions 0.6 m x 0.8 m with a prescribed normal velocity are used to model the inlet and outlet of the jet fan. The length of the jet fan shroud is 3.8 m. The maximal volume flow is 18.62 m$^3$s$^{-1}$. Jet fans performance is modelled via the RAMP feature in FDS. Adaptive algorithm increases or decreases their performance in order to achieve the prescribed target velocity of 1.2 m.s$^{-1}$ required by Slovak regulations [10]. Initial air velocity at the beginning of simulation is of 0 m.s$^{-1}$.

Fire is located at 453 m. Two different heat release rates (HRR) are considered: 5 MW and 12 MW corresponding to a passenger car fire and truck fire, respectively. The fire HRR increases linearly since the beginning of the simulation, reaching its maximal value after 40 s of the fire. The fire soot yield is 0.2.
For both values of HRR four scenarios are simulated:

- xMW-0: horizontal tunnel (0° slope) without lay-bys
- xMW-0L: horizontal tunnel (0° slope) with two lay-bys
- xMW-2: sloped tunnel (2° slope) without lay-bys
- xMW-2L: sloped tunnel (2° slope) with two lay-bys,

where x = 5, 12.

The computational domain size is 900 m x 18 m x 8 m for all considered tunnels. For the 20 cm mesh resolution, the domain consists of 4,500 x 90 x 40 cells. The total number of cells is 16,200,000. In order to deal with significant computational requirements and to increase the simulations performance, the parallel MPI version 6.5.2 of FDS is used. The computational domain is decomposed into 12 meshes, each of them assigned to one MPI process (one CPU core). The total CPU time strongly depends on specification of each fire scenario. It varies from 256 hours for 5MW-2L scenario to 1018 hours for 12MW-2 scenario.

3. Simulation results

Main tendencies of smoke movement are similar for all tested scenarios (see Fig. 2 for the case of 5 MW fire). Significant backlayering (upstream of the fire) afflicts the area of the lay-by. Movement of smoke downstream is accelerated for higher HRR and in sloped tunnels. However, there are several differences in smoke movement in particular scenarios.

![Figure 2. Smoke movement for four 5 MW fire scenarios after 100 s to the fire](image)

Backlayering increases for greater value of HRR and decreases in sloped tunnels significantly, which is caused by the influence of buoyancy (see Fig. 3). The lay-by only slightly influences the length of backlayering in the case of horizontal tunnel for given HRR (see Fig. 2). For sloped tunnels, the differences are relatively more significant (see Fig. 3). Smoke is contained in the lay-by where its rear vertical wall prevents the smoke movement downstream. Therefore, a larger amount of smoke being cumulated in the lay-by increases the length of backlayering, which is longer than in scenarios without lay-bys.
Visibility at human head level is used as a measure of smoke stratification and is studied in three areas of the tunnel depicted in Fig. 1: in front of the upstream lay-by, in the lay-by and behind it. Visibility is averaged over the whole areas. We obtain three time-dependent quantities describing conditions in the selected areas from the point of view of smoke distribution and tenability of human life. It is assumed [11], that the visibility greater than 10 m is sufficient to allow safe evacuation of people.

The averaged visibility in the area in front of the lay-by is only slightly decreased in case of scenarios for horizontal tunnel with 12 MW fire (see Fig. 4); however, tenability conditions are maintained even in these cases. Visibility drop in the scenario 12MW-0 is slightly more significant than in corresponding scenario with lay-by. There is no decrease in visibility in any other scenario in the area.

The perfect visibility is maintained in the lay-by for all scenarios with sloped tunnel (see Fig. 5). It is obviously due to a significant chimney effect arising in sloped tunnels intensifying the removal of smoke. A slight decrease of averaged visibility occurs in the lay-by in the horizontal tunnel for 5 MW fire, while in the scenario without lay-by no such decrease is observed. The only scenarios in which significant drop of averaged visibility in the lay-by occurs are those with the horizontal tunnel with 12 MW fire. The average visibility drops to 12 m in the lay-by and to 15 m at the same place in the tunnel scenario without lay-by. Although these values are not below the 10 m limit, the visibility can drop under the limit at various places as will be discussed later.
A similar smoke movement can be observed also behind the lay-by (see Fig. 6). The perfect visibility is maintained in all four scenarios including sloped tunnels, as well as in the 5MW-0 scenario. Averaged visibility drop behind the lay-by in the 5MW-0L scenario is more significant than in the lay-by; however, averaged tenable conditions (averaged visibility above 10 m) are maintained. Untenable conditions occur in two scenarios with horizontal tunnels for the case of 12 MW fire. After 350 s to the fire averaged visibility behind the lay-by falls under the limit of 10 m in the 12MW-0L scenario. Visibility decrease in the scenario without lay-by (12MW-0) is less pronounced as untenable conditions occur after 470 s to the fire.
Local distribution of smoke after 400 s to the fire can be seen in Fig. 7. Yellow and red colours denote regions with untenable conditions, green colour denotes tenable conditions and blue colour denotes the regions with almost perfect visibility.

Visibility drop in the lay-by for the 5MW-0L scenario occurs mainly in the lay-by niche. Tenability conditions in the niche are variable. Although they drop locally below the 10 m limit, for most of the time are conditions in the niche allowing safe evacuation of people. Small areas of untenable conditions appear between the lay-by and the fire.

More severe visibility drop occurs in the case of 12 MW fire in horizontal tunnel scenarios. It can be seen in Fig. 7 even in the case of the scenario without lay-by. The decrease of visibility starts in the fire vicinity due to cooled smoke entrained from the bottom part of the smoke layer. It is drifting downstream, descending at head level. Therefore, visibility is the worst in the fire vicinity and is improved with the distance from the fire. However, in the location of the lay-by local tenable conditions are maintained.

The upstream lay-by intensifies the process of visibility deterioration. Smoke spreading upstream of the fire interacts with a vertical wall at the beginning of the lay-by which causes its descent and mixing with cold air. As a consequence, several variable areas with untenable conditions appear near the tunnel walls in the lay-by, especially in the lay-by niche (see Fig. 7). They represent a serious threat for safe evacuation, as they are able to obscure the emergency exits located in the niche. Note that averaged visibility in the lay-by is slightly higher than the 10 m limit all the time. However, areas with untenable conditions grow over time.

4. Conclusions

The paper evaluates the smoke backlayering in emergency lay-by of a 900 m long road tunnel with longitudinal ventilation and its vicinity. The lay-by is located upstream in the fire vicinity. Eight scenarios with various tunnel slopes and HRRs of the fire are under consideration. Almost perfect smoke stratification and visibility are maintained in the case of the tunnel with the slope of 2° due to buoyancy suppressing the length of backlayering. Significant decrease of visibility can be observed in the lay-by in the case of the 12 MW fire (truck fire) in horizontal tunnels. Averaged visibility in the lay-by does not decrease below the limit of 10 m marking untenable conditions; however, significant drop of visibility in the lay-by niche constitutes a serious threat for safe evacuation of people. This is especially in the case of slow evacuation prolonged beyond 7 minutes. Moreover, it can be expected that HRRs higher than 12 MW would deteriorate conditions in the lay-by even more. Untenable conditions occur in the section of the tunnel between the lay-by and the fire. Tenable conditions are maintained for the case of the 5 MW fire (passenger car fire) in horizontal tunnel.

5. References

[1] Boehm M, Fournier L and Truchot B 2008 Smoke stratification stability: presentation of experiments Proc. 4th International Conference on Tunnel Safety and Ventilation (Graz, Austria, 21–23 April 2008) pp 176–182
[2] Klote J and Milke J 1992 Design of smoke management systems American Society of Heating, Refrigerating and Air Conditioning Engineers (Atlanta, Georgia, USA)
[3] Rattei G 2010 Safety installations in road tunnels – are they used in incident cases? Proc. of 5th International Conference on Tunnel Safety and Ventilation (Graz, Austria, 3–4 May) pp 235–241
[4] McGrattan K, Hostikka S, McDermott R, Floyd J, Weinschenk C and Overholt K 2017 Fire Dynamics Simulator, Technical Reference Guide (National Institute of Standards and Technology, Gaithersburg, Maryland, USA, and VTT Technical Research Centre of Finland, Espoo, Finland, sixth edition)
[5] McGrattan K, Hostikka S, McDermott R, Floyd J, Weinschenk C and Overholt K 2017 *Fire Dynamics Simulator, User’s Guide* (National Institute of Standards and Technology, Gaithersburg, Maryland, USA, and VTT Technical Research Centre of Finland, Espoo, Finland, sixth edition)

[6] Weisenpacher P and Valasek L 2021 Computer simulation of airflows generated by jet fans in real road tunnel by parallel version of FDS 6 *Int. J. Vent.* **20** 20–33

[7] Weisenpacher P, Valasek L and Glasa J 2019 Influence of emergency lay-bys on smoke stratification in case of fire in bi-directional tunnel: parallel simulation *Proc. 31st European Modeling & Simulation Symposium (DIME Universita di Genova, Rende, Italy, 2019)* pp 47-53

[8] Danisovic P, Sramek J, Hodon M and Hudik M, 2017 Testing measurements of airflow velocity in road tunnels *MATEC Web of Conferences* **117** 00035

[9] Sirilla M and Schmidt P 2017 D3 Zilina (Strazov) – Zilina (Brodno), Povazsky Chlmec tunnel (in Slovak) *Inzinierske stavby* **65** 6 30–33

[10] TP 2018 *Road tunnels ventilation (in Slovak)* (Ministry of Transport and Construction of the Slovak Republic, Bratislava, Slovakia)

[11] Purser D A 2009 *Assessment of Hazards to Occupants from Smoke, Toxic Gases and Heat* The SFPE Handbook of Fire Protection Engineering, 4th Edition ed P J DiNenno (National Fire Protection Association, Quincy, MA 02269) pp 2/96–2/193

**Acknowledgments**

The authors would like to thank Peter Schmidt (National Motorway Company, Slovakia) for technical specifications of road tunnels. This work was partially supported by the Slovak Science Foundation (project No. VEGA 2/0108/20) and the Slovak Research and Development Agency (project No. APVV-15-0340).