36th European Modeling & Simulation Symposium, 004
21th International Multidisciplinary Modeling & Simulation Multiconference

2724-0029 © 2024 The Authors.
doi: 10.46354/i3m.2024.emss.004

Simulation of smoke optical density in road tunnel by two tunnel models for FDS

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Abstract

The ability of computer simulation to simulate the movement of smoke during a tunnel fire is an important prerequisite for effective fire safety measures and strategies. This study investigates test smoke spread in the medium-length Polana tunnel in Slovakia using Fire Dynamics Simulator (FDS). The tested scenario represents a car fire near a tunnel portal, while the fire smoke is represented by a special non-destructive aerosol (test smoke). Optical density development on seven smoke detectors is determined by simulation and compared with the results of smoke tests in the tunnel in 2017. The test smoke was used during the tests to prevent damage to the tunnel equipment. Two models of the tunnel based on different assumptions are used in the simulations and compared. The activation times of four of the five affected detectors were determined with an accuracy of less than 10%. The simulation also correctly determined, albeit with a certain time shift, the increases and decreases in the optical density of the smoke that occurred as a result of the changing flow rate. The results of this study may contribute to the possibility of simulating tunnel fire scenarios and to fire safety in tunnels.

Keywords: Tunnel fire simulation; smoke spread; smoke modelling; longitudinal ventilation; FDS

1. Introduction

Threat of significant damage that could occur in case of tunnel fire requires a great emphasis on effective fire safety measures in the tunnel. Longitudinal ventilation provided by jet fans inducing air movement inside the tunnel has become very frequent solution of emergency ventilation in currently built tunnels. In double track tunnels, the ventilation strategy is often focused on achieving and maintaining smoke stratification (Klote and Milke 1992). Smoke layer should remain stratified below the ceiling above people to ensure tenable conditions for human lives until a safe evacuation can be carried out. It is assumed that smoke stratification can be achieved by maintaining air flow velocity in a narrow interval around the specific target velocity.

A specific feature of this approach is that the smoke is not removed from the tunnel but remains in the vicinity of people. In order to find the location of emergency exits the people need sufficient visibility and thus the reasonably low smoke optical density. The ability to determine the optical density under the given conditions and adapt the ventilation strategy and other rescue operation to it is therefore an important prerequisite for the effectiveness of safety measures.

Individual tunnel fire scenarios are currently thoroughly tested by CFD (Computational Fluid Dynamics) methods ensuring low cost and easy repeatability. Well known FDS code (Fire Dynamics Simulator) (McGrattan et al, 2017) is a widely used for many fire safety applications, both practical and research. FDS is a code for modelling fire and fire-driven fluid flows developed by the National Institute of Standards and Technology (NIST), USA in cooperation with the VTT Technical Research Centre of Finland. FDS numerically solves a form of conservation equations for low-speed thermally-driven flows with an emphasis on the smoke and heat transport from fire. The core algorithm is a very efficient explicit predictor-corrector scheme, second order accurate in space and time. FDS also includes models of fire related processes such as turbulence, thermal radiation, pyrolysis, combustion of the pyrolysis products, conductive heat transfer, etc.

Simulation inputs in text format include the rectangular geometry of the scenario, i.e., dimensions of computational domain, compartments, locations and dimensions of all relevant objects as well as material properties of object surfaces (ignition temperature, thermal conductivity, specific heat, density, emissivity, heat of evaporation, heat release rate, etc.) and other parameters.

The FDS applications include airflows and smoke movement simulations (Valasek, 2013; Weng, Yu, Liu and Nielsen, 2014), evacuation (Glasa and Valasek, 2014) and design of smoke handling systems in buildings and various compartments. Currently, FDS is increasingly used for fire simulations in tunnels. Despite the limitations given by its rectangular geometry, the FDS has also proven itself in the simulation of many aspects of fires in tunnels, which are typically curved in shape. Nevertheless, validation studies of fires in tunnels are still rare and demanded in the literature. Studies investigating the optical density during a fire in a tunnel are relatively rare, as the research often focuses on other quantities.

Our previous research dealt with simulation of airflows in tunnel induced by jet fans in the case without fire. Two models of medium-length Polana tunnel were created for FDS environment and compared with measurements carried out during ventilation tests. Such studies are rare, as they require the shutdown of the tunnel and associated costs. The aim of this study is to apply the tunnel models to investigate their applicability to the simulation of the smoke optical density of smoke in the tunnel. The simulations results are compared with the values measured during ventilation tests in the Polana tunnel in 2017 in which a special non-destructive test smoke was used to represent smoke. The use of the models to simulate the course of optical density could be beneficial for the field of computer simulation of fires in tunnels.

The article is structured as follows. Section 2 describes the state of the art in the field of computer simulation of tunnel fires and smoke movement. Section 3 describes the smoke tests the Polana tunnel in Slovakia in 2017. Two models of the tunnel are presented as well and their simulation settings are determined. In Section 4, the simulation results are compared with experimental data and the accuracy of models is discussed. Finally, conclusions are drawn in Section 5.

2. State of the art

Full-scale experiments with real fire in tunnels are financially demanding and would lead to significant damage to the tunnel equipment, which is the reason for their relative rarity. Although it can be partially compensated by experiments on a small scale, full-scale experiments are inevitable for computer simulation validation. An important place in fire research has a full-scale fire experiment conducted as part of the Massachusetts Highway Department Memorial Tunnel Fire Ventilation Test Program (McGrattan et al, 2016), which led to the first validation study related to the FDS simulation of tunnel ventilation. A single-point supply of fresh air through a 28 m^2 opening in a 135 m tunnel was investigated.

Various other aspects of tunnel fires have already been investigated. In (Alvarez-Coedo, Ayala, Cantizano and Wegrzynski, 2022), a coupled hybrid (1D/3D-CFD) modeling methodology using the FDS 6 was validated by full-scale fire tests in the 1600 m long Runehamar tunnel with focus on temperature profiles, centerline velocity and back-layering lengths upstream and downstream from the fire source. In (Weng, Yu, Liu and Nielsen, 2014), a series of full-scale experiments with 1.35, 3 and 3.8 MW fires conducted in a short metro tunnel with mechanical ventilation system was described and temperatures were simulated by FDS. In (Wang, Wang, Carvel and Wang, 2007) numerical simulation of critical ventilation velocity and smoke movement for fires in different transverse positions in curved tunnels was presented. An important area of tunnel smoke research using FDS is the numerical simulation of smoke back-layering and the creation of models determining the back-layering length (Du, Li, Wei, and Yang, 2022; Kong et al, 2021; Zhang et al, 2017; Zhang, Lin, Shi, and Zhang, 2022).

Smoke optical density research is more specific and rare. (Ingason and Persson, 2000) presented theoretical models for determining optical density in smoke with CFD simulations and found a good correlation with experimental data. (Yoon, Hadjisophocleous and Kashef, 2009) modelled temperature and optical density in the early stage of a fire using CFD techniques and compared with data obtained from field tests conducted in an operating roadway tunnel in Montreal, Canada.

Studies dealing with simulations of tunnel fires typically do not examine the ability of used models to describe tunnel airflow induced by tunnel ventilation in the absence of fire. Studies focused on the latter problem are rare (Krol and Krol, 2021; Ang, Rein, Peiro and Harrison, 2016). Nevertheless, the accurate description of tunnel airflows may be very beneficial for proper modeling of smoke spread in the case of fire.

In our previous research we created a model of airflows in the Polana highway tunnel (Weisenpacher and Valasek, 2021) for FDS environment. The influence of curved concrete tunnel walls, S-shape tunnel geometry as well as of the tunnel equipment which is not directly modelled, as its dimensions are too small in comparison with the mesh resolution is represented by ROUGHNESS parameter within FDS rectangular geometry. The parameter specifies velocity boundary conditions at rough solid surfaces using log law (Pope, 2000) and its value was determined to 70 mm for the Polana tunnel. (Glasa, Valasek, Weisenpacher and Kubisova, 2023) further contributed to the development of the model. In (Weisenpacher, 2023), an alternative approach was presented in which the influence of above mentioned factors is represented by a system of cuboids under the tunnel ceiling. Both models achieve comparable accuracy when simulating data measured during ventilation tests.

The aim of this study is to apply the models that have given good results for simulating flow in a tunnel without the presence of a fire, to simulate the movement of test smoke. Such research can contribute to the validation of these models as well as to exploring the possibility of their use for the simulation of smoke movement for fire safety purposes.

3. Materials and Methods

3.1. Polana tunnel

The Polana tunnel (Pospisil and Ockajak, 2016; Danisovic, Sramek, Hodon and Hudik, 2017) is a single tube 898 m long bi-directional highway tunnel in Slovakia (Figures 1 and 2). It has a horseshoe cross-section of 10.8 m (width) × 6.8 m (height). Two emergency lay-bys are located at 373 m (left side) and 635.6 m (right side) from the western tunnel portal, respectively. The lay-by niches are 50 m long and 2.2 m wide. The maximal height of ceiling is 7.8 m. Such tunnel dimensions are frequently used in road tunnels in Slovakia (Danisovic, Sramek, Hodon and Hudik, 2017). The tunnel has 2% ascending slope and the typical S-shape of the tunnel tube. It is equipped with various safety installations and measuring devices. Supporting structures bearing lighting and other installations are located below the tunnel ceiling along the tunnel centerline.

The Polana tunnel is equipped with longitudinal ventilation consisting of four pairs of axial jet fans with 0.8 m fan wheel diameter and 3.7 m length (Figure 2). The pairs of jet fans are located at 101, 201, 716 and 801 m at 5.1m height above the road. The jet fans are able to achieve the maximal volume flow of 19 $m^3.s^{-1}$ (38.5 $m.s^{-1}$ airflow velocity, 850 N thrust)

Seven smoke detectors SD1–SD7 with the ability to measure smoke optical density are located at 15, 153, 303, 453, 603, 753 and 888 m under the tunnel ceiling.

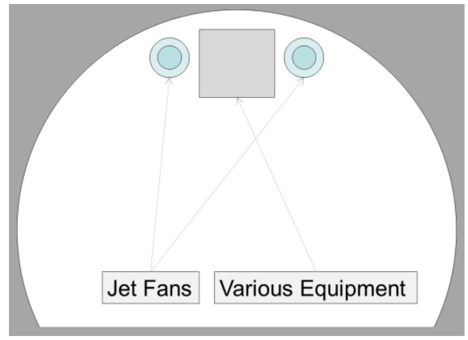

Figure 1. Cross-section of the Polana tunnel.

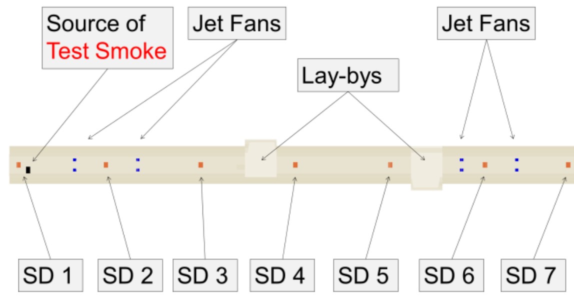

Figure 2. Scheme of the Polana tunnel with locations of 7 smoke detectors (SD).

3.2. Test smoke properties

As part of the development of the highway network in Slovakia, additional tunnels are gradually being put into operation. For each of them, ventilation and smoke tests are required to verify the correct functionality of the emergency ventilation. Instead of smoke from a real fire, a special non-destructive aerosol, a test smoke, is frequently used to represent smoke and visualize it (Bebcak and Bebcak, 2013). The test smoke must meet the following requirements:

- Optical density of the test smoke is similar to that of considered fire smoke
- Heat produced during test smoke generation is sufficient to maintain its stratification
- Opacity sensors and smoke detectors respond to the test smoke correctly
- Heat does not damage the tunnel facilities and test smoke does not cause corrosion
- Test smoke is not toxic.

The test smoke is generated by a chemical reaction of 50 times lower heat release rate (HRR) than the HRR of the corresponding fire. It is assumed that its optical density in a sufficiently long distance from the modelled fire source downstream corresponds to the optical density of real fire smoke (Weisenpacher, Glasa and Valasek, 2018). This way, realistic smoke detectable by tunnel devices and interacting with the tunnel ventilation is created and given fire scenarios can be examined experimentally.

3.3. Smoke tests in the Polana tunnel

In 2017, three smoke tests were performed in the Polana tunnel with the aim of checking the functionality of individual tunnel systems during the automatic response of the tunnel control system to a fire and verifying the effectiveness of emergency ventilation. The non-destructive test smoke was used in all the three cases.

Figure 3. Smoke tests in the Polana tunnel.

This study focuses on the first experiment, which was supposed to model a stationary car fire near the western (left) tunnel portal (Figures 2 and 3). The optical density values measured during the experiment by tunnel smoke detectors are used for validation of smoke spread simulation presented here.

The duration of the experiment was 25 minutes. The initial natural flow in the tunnel had a velocity of 2.0 m.s^{-1} towards the east, i.e., the smoke was drifting into the tunnel. The source of the fire was located in the right lane, 29.7 m from the western portal and approximately 20 cm above the road level. The internal temperature in the tunnel was 6.5°C, the temperatures at the western and eastern portals were 4.8°C and 10.0°C, respectively.

Figure 4 shows the cumulative power of all jet fans defined as the sum of RPM of all fans normalized by the maximum power of an individual fan (2950 RPM). This value can be considered as the number of active jet fans. Figure 5 shows the flow velocity achieved by ventilation.

The operation of the jet fans had three phases. In the first phase (141–440 s), the ventilation worked with the aim of reducing and maintaining the flow velocity at a value close to the required target velocity of 1.2 ± 0.3 m.s^{-1}. The smoke was drifted into the tunnel during this phase. In the second phase (440–1191 s), the ventilation reversed the flow direction and subsequently maintained the velocity at the value of -1.2 ± 0.3 m.s^{-1}. During this phase, smoke was gradually blown out of the tunnel. In the third phase of the experiment, all fans were operating at full power in order to definitively clean the air in the tunnel.

Detector SD2 was the first to record increased values of optical density, followed by detectors SD3, SD4 and SD5, while SD6 and SD7 did not record relevant optical density increase. After the flow direction was reversed, the detector SD1 located near the western portal detected a significant increase of optical density caused by the smoke blown out of the tunnel.

Figure 6 shows optical density values measured by the smoke detectors. As a result of the gradually decreasing flow velocity at the beginning of the experiment, the density of the smoke formed near the fire source increased. The denser smoke drifting into the tunnel increased the optical density values on the smoke detectors after reaching their position. The densest smoke formed in the interval from 200 to 300s, corresponding to the lowest flow velocity, caused a significant peak on detector SD2 after it reached its position, and subsequently also peaks on the positions of detectors SD3–SD5. Other significant peaks arose after reversing the flow direction as the accumulated smoke passed through the positions of the detectors in opposite direction. Subsequently, the optical density values rapidly decreased to zero after the tunnel air was cleaned.

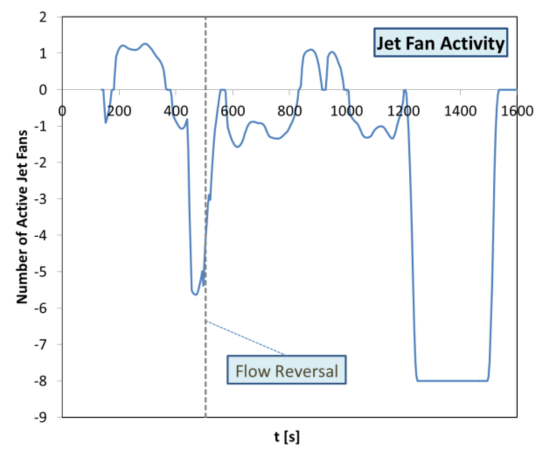

Figure 4. Number of active jet fans during smoke tests in the Polana tunnel.

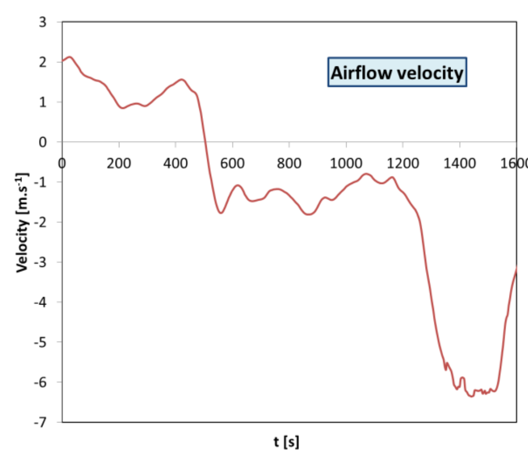

Figure 5. Airflow velocity during smoke tests in the Polana tunnel.

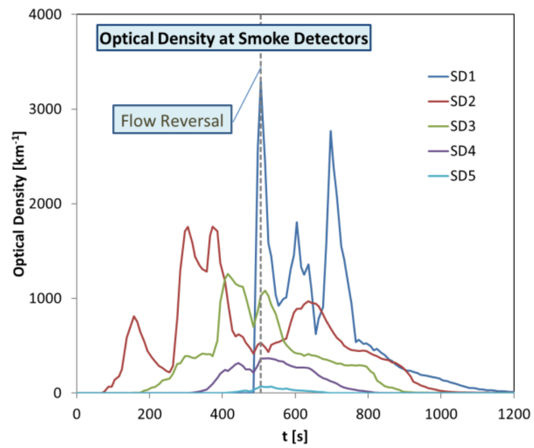

Figure 6. Optical densities measured during smoke tests.

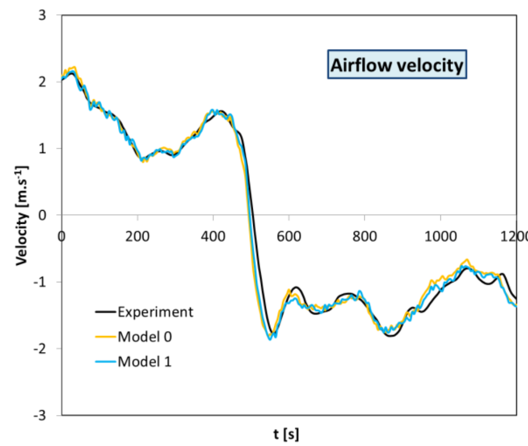

Figure 8. Airflow velocity during smoke tests and in the simulations.

3.4. Simulation settings

Two tunnel modeling approaches within FDS presented in (Weisenpacher and Valasek, 2021) and (Weisenpacher, 2024) were tested to simulate the movement of test smoke in the tunnel. Both contain the geometry of the Polana tunnel and its main equipment within the computational domain of dimensions 900 × 18 × 8.1 m with the 30 cm mesh resolution (Figure 7). However, the models differ in the way in which the influence of those objects is represented in the simulation, which, due to their small dimensions compared to the simulation grid, are not explicitly modeled.

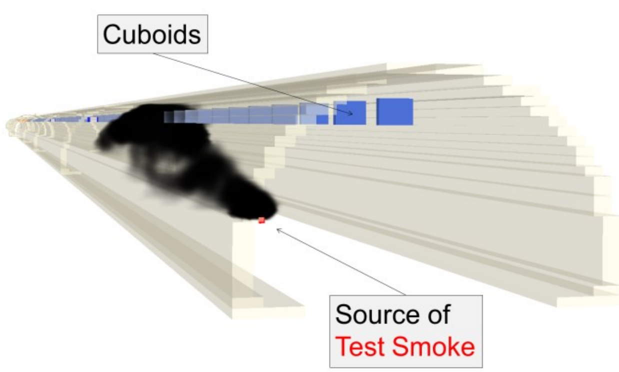

Figure 7. Smoke source and cuboids, a view from the western tunnel portal.

Model 0 represents these effects by increased roughness (70 mm) of the tunnel walls, while in Model 1 (denoted by Model 178 in (Weisenpacher, 2024)) the effect is represented by 178 cuboids of dimensions 1 × 4 × 3 cells located at the height of 5.4 m. The cuboids represent various structures located under the tunnel ceiling.

The operation of 8 jet fans is modelled by the HVAC feature used for modelling of Heating, Ventilation, and Air Conditioning systems in FDS (McGrattan et al, 2017) according to (Weisenpacher and Valasek, 2021). The operation was set in accordance with the records of the tunnel control system (Figure 4). The dynamic pressure values on the portals of the tunnel were not measured, which is an important limitation of this study. However, they were estimated by trial and error so that the simulated airflow velocity matches the measured value as accurate as possible (Figure 8).

Table 1. Parameters of the test smoke source and smoke detectors in simulation

Smoke source x coordinates [m]	(29.7, 30.0)
Smoke source y coordinates [m]	(-1.5, -1.8)
Smoke source dimensions	1 cell (30 cm)
Mass (smoke) flux	9 $g.s^{-1}$
HRR	60 kW
Smoke detectors x coordinates [m]	15, 153, 303, 453, 603, 753 and 888
Smoke detectors y coordinate [m]	0
Smoke detectors z coordinate [m]	6.6

The test smoke source is modelled as an OBSTruction of one cell dimensions placed on the road with the upper VENT representing the source of smoke and heat. Its parameters as well as the parameters of 7 smoke detectors are summarized in Table 1.

Simulations of the first 1200 s of the smoke tests were performed for both tested models. In the final phase of the tests, from 1200 to 1600 s, a negligible amount of smoke remained in the tunnel; therefore, they are not included in the simulation. Velocity values and optical density at smoke detectors were recorded with 5 s frequency. Main settings of FDS simulations are summarized in Table 2.

Table 2. Simulations settings.

Ambient temperature	6.5°C
Mesh resolution	30 cm
Computational domain	900 × 18 × 8.1 m
Parallelization	Message Passing Interface (MPI)
Mesh decomposition	12 meshes (12 MPI processes/CPU cores)
Turbulence	LES, Deardorff model
Boundary conditions	CONCRETE for tunnel walls and road OPEN for tunnel portals (DYNAMIC_PRESSURE variable)
Time step	Variable, typically 0.006 s for active jet fans
Simulation time	1200 s
Simulation elapsed time	37–40 hours

The simulations were carried out on the Devana cluster (Devana) in Slovakia. Devana is the HPC cluster procured by NSCC/SAS and put into operation in 2023. It consists of 148 compute nodes, totaling 9,472 compute cores, 38 TB RAM and 32 GPGPU accelerators. The system's theoretical peak performance is about 800 TFLOP/s.

4. Results and Discussion

4.1. Optical density behavior

In Figures 9–13, simulated optical densities for Models 0 and 1 are compared with the values measured during the smoke tests. The simulated values reflect some basic tendencies manifested in the experiments; however, certain differences can also be observed.

In general, the decrease in the flow rate causes a local increase of the smoke optical density in the vicinity of the smoke source (and vice versa), which is reflected on the smoke detector with a certain delay after the smoke reaches its location. The simulated curves capture the decreases and increases in optical density caused by the variable flow rate, however, the individual peaks in the simulation are slightly shifted compared to the experimental data.

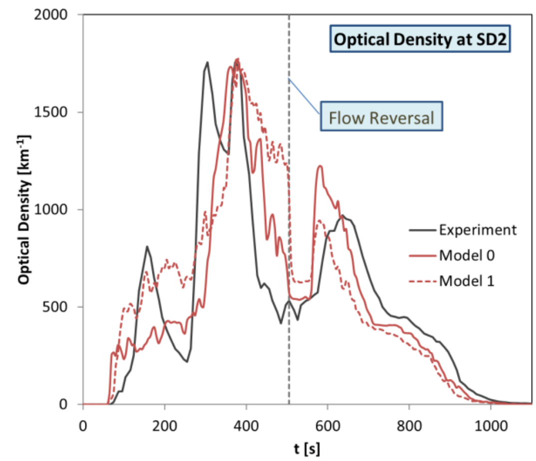

Figure 9. Simulated optical densities at smoke detector SD2.

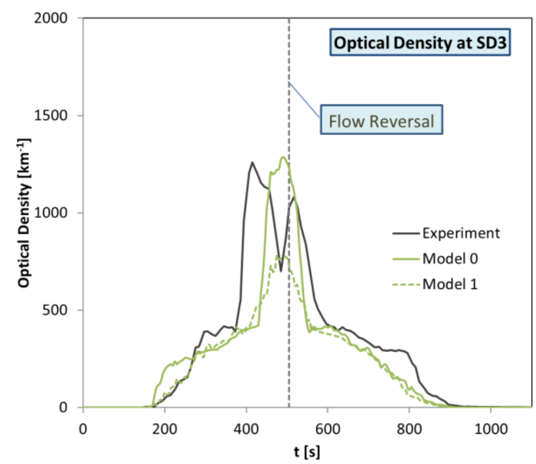

Figure 10. Simulated optical densities at smoke detector SD3.

The initial increase in optical density at detectors SD2 and SD3 occurs sooner and it is more pronounced in the simulation than in the experiment. On the contrary, the second peak for SD2 is delayed by 40 s in the simulation compared to the experiment, which also leads to the acceleration of the onset of the third peak after the flow reversal (Figure 9).

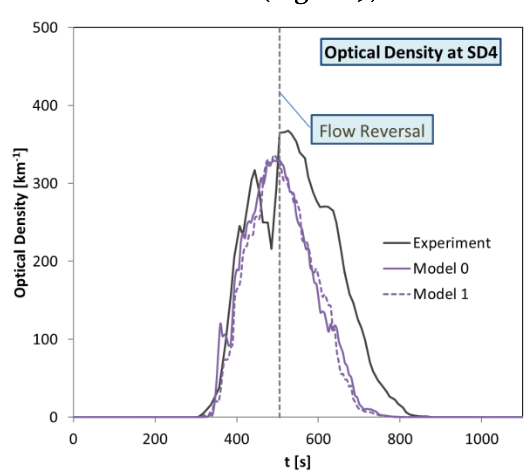

Figure 11. Simulated optical densities at smoke detector SD4.

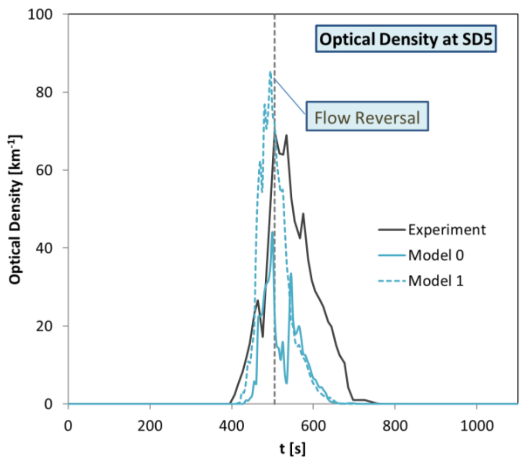

Figure 12. Simulated optical densities at smoke detector SD5.

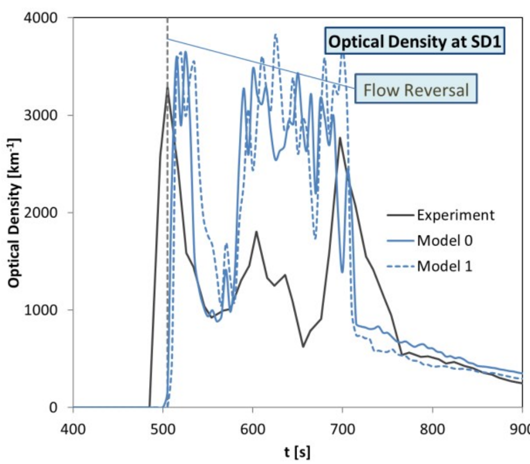

Figure 13. Simulated optical densities at smoke detector SD1.

In the case of the more distant detectors SD4 and SD5, the increase in optical density in the simulation is in better agreement with the experiment (Figures 11 and 12). At all 4 detectors the decrease during the final cleaning of the tunnel occurs slightly earlier in the simulation.

The SD1 detector captures high optical density values of dense smoke spreading in the opposite direction to the western portal after the flow reversal. Simulated values are often overestimated compared to the experimental ones (Figure 13).

In order to be able to compare the complex course of the optical densities recorded by the smoke detectors in the simulation with the experimental values analytically, the norm of the real function f is introduced as follows

$$\|f\|^2 = \int_{t_1}^{t_2} f^2(t)dt.$$

Considering that, the measure of the differences between experimental and simulated curves is the quantity

$$D_f = \frac{\|f - f_{exp}\|}{\|f_{exp}\|}.$$

Table 3 shows the differences D_f of both models for optical density curves on individual 5 smoke detectors as well as for the achieved flow velocity.

Table 3. Differences D_f for curves of flow velocity and optical density at SD1–SD5.

	Velocity	SD1	SD2	SD3	SD4	SD5
Model 0	0.12	0.82	0.39	0.42	0.35	0.70
Model 1	0.09	0.90	0.47	0.43	0.36	0.62

Table 3 confirms that Model 0 achieves a slightly higher accuracy compared to Model 1. The inaccuracy of both models increases with the distance of the detector from the fire source. This is also confirmed by the special case of the SD1 detector, which is located close to the smoke source but is affected primarily by smoke spreading from further area of the tunnel.

4.2. Activation times of smoke detectors

Table 4 contains experimentally determined activation times achieved by particular tunnel smoke detectors and corresponding simulated values determined by the Models 0 and 1. Smoke detectors in the tunnel are activated after the optical density value of 7.5 km^{-1} is reached and the same rule was applied also for simulated values. Since a total of 5 out of the 7 smoke detectors were activated during the experiment (SD1–SD5), our analysis is limited to them only.

Table 4. Activation times of smoke detectors SD1–SD5 [s].

	SD2	SD3	SD4	SD5	SD1
Experiment	72	176	323	425	486
Model 0	61	169	342	461	501
Difference	-11	-7	19	36	15
Rel. Difference	-15%	-4%	6%	8%	3%
Model 1	62	164	341	437	506
Difference	-10	-12	18	12	20
Rel. Difference	-14%	-7%	6%	3%	4%

As can be seen in Table 4, the activation of the detectors in the simulation occurs earlier than in the experiment in the case of detectors SD2 and SD3, which are the first to be affected by the smoke. In the case of detectors affected by smoke later (SD4, SD5 and SD1), the activation time in the simulation is delayed. The accuracy of the simulated activation times is acceptable, with the exception of the SD2 detector, where it exceeds 10%.

4.3. Discussion

The simulations successfully reproduced the main tendencies of smoke movement as recorded by individual detectors. This applies especially to the activation times of the detectors and increases and decreases of the optical density per individual detector. However, some inaccuracies recorded in the simulations compared to the experiment, such as the activation time of SD2, the course of the increase in optical density after the smoke arrival, and the time shift of individual peaks of optical density require further analysis.

A possible source of inaccuracy can be the parameters of the test smoke, the exact values of which are not published (primarily HRR and mass flux) or the time course of its generation, especially right after the generators are started. It is also necessary to thoroughly examine the influence of the resolution of the computational grid on the accuracy of the simulations, which in the case of finer resolution requires significant computing resources.

Although Model 1 achieves a slightly better or comparable description of the flow velocity profile than Model 0 when simulating the air flow without a fire, it is slightly less accurate when simulating the spread of test smoke. It is necessary to analyze the reasons for this difference and examine the possibilities of a more suitable representation of the cuboids under the tunnel ceiling. Modelling the tunnel geometry requires further research and analysis.

5. Conclusions

Test smoke spread in the Polana tunnel (Slovakia) was examined by the FDS computer simulation using two models of the tunnel created for FDS environment. Model 0 represents the effect of the tunnel geometry on the tunnel flow by increased roughness of its walls, while in Model 1 the effect is modelled by a set of cuboids under the tunnel ceiling. Simulated optical densities were compared against the optical density of test smoke recorded by seven tunnel smoke detectors during smoke tests in 2017.

The scenario of the smoke tests corresponded to the fire of a passenger car located near the western (left) portal of the tunnel. A special non-destructive aerosol, test smoke, which is used during ventilation tests in Czech and Slovak tunnels to represent and visualize fire smoke was used during the tests as well. The test smoke used should achieve the equivalent value of optical density downstream, while the HRR of the related chemical reaction is about 50 times lower.

The simulation determined the activation times of affected smoke detectors with accuracy below 10%, with the exception of the detector closest to the smoke source. The simulation also realistically captured the increases and decreases in smoke optical densities that occured as a result of decreasing and increasing the flow velocity. Model 0 performed slightly better than Model 1.

Some inaccuracies of the simulations are manifested in the more sudden onset of the increase in optical density on the closer detectors, on the time shift of individual peaks of increased optical density and in the higher optical density of swirling smoke after flow reversal.

This study is the first attempt to use the models to simulate test smoke. Its results indicate the possibility of a realistic simulation of the course of the smoke optical density with a significant contribution to the fire safety of tunnels. Further research will focus on the refinement of the simulation parameters, on the investigation of the influence of the resolution of the computational grid as well as on the improvement of the representation of the test smoke and the simulation models.

Funding

This work was supported by the Slovak Scientific Grant Agency VEGA under the contract 2/0096/24. Research results was obtained using the computational resources procured in the national project National competence centre for high performance computing (project code: 311070AKF2) funded by European Regional Development Fund, EU Structural Funds Informatization of society, Operational Program Integrated Infrastructure.

Acknowledgements

The author would like to thank Peter Schmidt (National Motorway Company, Slovakia) for information about technical specifications of road tunnels.

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