CFD-based fire spread visualization for improvement of road tunnel safety

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Abstract Teaching and training of operators of road and highway tunnels are necessary to increase their preparedness for incidents accompanied by fire and ensure safe tunnel operation. For such purposes Tunnel Traffic & Operation Simulator (TTOS) is used in Slovakia. TTOS is capable to simulate various types of emergency situations in 1 km long twin tube virtual highway tunnel with longitudinal ventilation including scenarios of car accidents accompanied by fire. However, TTOS does not provide information about the fire dynamics and smoke stratification. In this paper, the use of the well-known CFD-based Fire Dynamics Simulator for creating a series of didactic videos is illustrated. The videos demonstrate the smoke propagation and time evolution of temperature, air flow velocity and visibility for selected fire scenarios. They have been implemented into the TTOS environment and became available for tunnel operators.

1. Introduction

Road tunnels are specific underground structures constructed in order to shorten transport routes and improve environment and road safety. They help solving critical traffic problems caused by enormous increase of the number of vehicles on roads and growing demands for passenger transport and cargo traffic capacity. Fires belong to the most dangerous and devastating incidents in road tunnels. They produce large amount of toxic smoke and cause enormous increase of temperatures resulting in huge damages.

For assurance of safe tunnel operation, teaching and training of road tunnel operators is necessary to increase their preparedness for potential incidents including those accompanied by fire. According to European legislation this task is fully in competence of tunnel safety officer and tunnel administrator. In Slovakia, teaching and training of existing and new tunnel operators have been organized with annual periodicity using Tunnel Traffic & Operation Simulator (TTOS) since 2013 [1]. In TTOS various types of emergency situations in tunnel are implemented including scenarios of car accidents accompanied by fire. The system simulates reaction of Central Control System (CCS) of the tunnel and allows verifying operator’s actions. Models of fire spread and smoke propagation implemented in TTOS are very fast but they do not provide information about the fire dynamics and smoke stratification.

In this paper, we describe the use of the CFD-based Fire Dynamics Simulator (FDS) for the development of a series of didactic videos demonstrating the fire behaviour and dynamics. These

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visualizations have been implemented into the TTOS environment as a didactic tool available for tunnel operators.

2. Tunnel Traffic & Operation Simulator
TTOS is a simplified version of operator control centre of 1 km long twin-tube virtual highway tunnel with unidirectional traffic and longitudinal ventilation (Fig. 1) [1, 2]. The system is designed for two operators operating the tunnel. One operator is responsible for the tunnel technology and the other operator is responsible for the tunnel traffic management. The jobs can be merged, that means that the only operator can control the entire tunnel and handle all technological equipment (ventilation, lighting, variable traffic signs, power supply, etc.). All alarms, faults, detections of incidents, warnings, responses and interventions of CCS and operators are recorded. The technological equipment implemented in TTOS is in accordance with national and European regulations and technical directives.

![TTOS tunnel control centre](image)

Fig. 1 Scheme and real photo the TTOS tunnel control centre [1, 2]

3. CFD-based fire dynamics simulation
Advances in fire research have led to the development of fire models and simulation systems capable to simulate fires in various environments. Such systems are able to model complex physical and chemical processes related to fire such as pyrolysis, combustion, low-speed thermally driven flows, turbulence, thermal radiation, thermal transport, flame spread, smoke propagation, etc. They benefit from the progress in CFD (Computational Fluid Dynamics) and from high computing power of current computers.

FDS [3, 4] is the well-known CFD-based fire simulator. The mathematical model of fire implemented in FDS is based on solving partial differential equations representing the conservation laws of mass, momentum, energy and species and the equation of state. After non-trivial modification and simplification, the equations are discretized in time and space and numerically solved on 3D regular orthogonal meshes using second-order accurate finite differences methods. FDS numerically solves the equations for low-speed fire-induced flows with the emphasis on smoke propagation and heat transfer from fire. Turbulence is modelled using the Smagorinsky form of Large Eddy Simulation. Modelling of combustion is based on the mixture fraction concept. Radiative heat transport is modelled solving the radiation transport equation for a grey gas using Finite Volumes Method. FDS supports several parallel computing models utilizing advantages of computer platform available [3, 5-7]. The applicability of FDS for simulation of tunnel fires has been studied extensively [8-13].

4. CFD-based visualizations for TTOS
Fire scenarios implemented in TTOS do not provide any information about the fire dynamics. In order to illustrate smoke stratification and some relevant fire parameters, a set of car incidents accompanied by fire were selected, studied and visualized using FDS. The set of visualizations was then integrated
into TTOS in the form of videos to be available for tunnel operators as a didactic tool. Each video consists of 5 visualizations which demonstrate the smoke spread and time evolution of selected physical quantities describing the fire dynamics; namely the temperature, air flow velocity and visibility. In the videos, 300 m long part of the TTOS tunnel including the fire source and 15 couples of passenger cars are visualized (Figs. 2-3).

Figure 2. Five fire visualizations 60 s after the fire start.

Figure 3. Five fire visualizations 100 s after the fire start.
In Figs. 2-3, two frames of such video are shown. The first picture illustrates the smoke propagation. Operators can observe formation of smoke stratification and its break caused by natural and forced tunnel ventilation. Three vertical slices of temperature, air flow velocity and visibility passing through the tunnel centre are shown in the second, third and fourth pictures, respectively. The fifth picture represents a horizontal slice of visibility at human head level. The black colour is reserved for significant values of the considered quantities: 70°C for temperature (the second picture), 0 m/s for air flow velocity (the third picture) and 10 m for visibility (the fourth and fifth pictures). Note that the videos dimensions are modified in the ratio of 3:1 (height : width) to fit the TTOS screen dimensions according to customer’s requirements and provide as much information about the considered scenario as possible. Such visualizations give a good picture about the dynamics of fire and its selected parameters and allow demonstrating possible consequences of operator’s interventions into the tunnel control in the case of fire. One can see a break of smoke stratification downstream of the fire as well as a backlayering formation and breaking the smoke stratification upstream of the fire within the first two minutes after the fire origin (Figs. 2-3).

5. Discussion
There is an extensive discussion about appropriate target air flow velocity which should guarantee proper conditions maintaining smoke stratification during the self-rescue phase of fire. It results in diversity of national tunnel safety legislations in different countries. Some specialists for tunnel ventilation advocate the use of small target velocities. The fire scenario illustrated in Figs. 2-3 shows a situation in which ventilation decreased the air flow velocity from the value of about 2 m/s to 0.5 m/s within 40 s of fire. The visualization shows forming a counter flow in lower part of the tunnel where air moves in opposite direction in regard to the air flow in the upper part of the tunnel. It also indicates that such an air flow can cause acceleration of smoke backlayering leading later to undesired break of smoke stratification or it can cause distortion of air flow velocity measured in the tunnel. In such situation, the upper smoke layer reaches significantly different velocities from the values measured by flow velocity measuring devices installed in the tunnel. The black colour highlighted in the third picture in Fig. 3 represents zero air flow velocity separating two layers of air moving in different directions.

In this context, potential of autonomous vehicles (AV) in tunnels which represent a perspective model of transport development seems to be usable for decision making. During the last decade, great emphasis has been placed on technological development of AV to ensure their safe driving and identify requirements for modifying the road infrastructure. Nowadays, research is focused also on wider aspects (economic, environmental, societal, ethical, etc.) of mass deployment of AV [14-17]. However, little attention has been given to AV as a potential source of information usable by tunnel operators during an incident accompanied by fire. Sharing information from sensors and images processed by AV as well as capability of AV for communication (AV-AV and AV-Infrastructure) could provide missing information applicable for decision-making, accelerate the fire source determination and help to maintain proper conditions for safe self-rescue and evacuation. The second example is to allow tunnel operator to take partial control of AV in emergency situation. In the case of fire, driverless cars could be able to perform simple actions requested by tunnel operator. For instance, at least a small decrease of the minimum allowed distance between safely parked AV could increase the distance between the fire and parked vehicles and thus reduce, slow down or even eliminate the risk of fire spread to adjacent vehicles and prevent greater damages and catastrophic fire development.

6. Conclusion
In this paper, the set of videos, which consists of 5 synchronized visualizations of selected features of fire dynamics, created for Tunnel Traffic & Operation Simulator (TTOS) is discussed. The videos were developed for purposes of teaching and training of operators of road and highway tunnels in Slovakia. TTOS enables to simulate various emergency situations in 1 km long twin tube virtual highway tunnel with longitudinal ventilation. It includes also car fire scenarios. However, it does not
provide any information about smoke stratification and fire dynamics. The set of videos was created using the CFD-based Fire Dynamics Simulator to demonstrate smoke propagation and time evolution of temperature, air flow velocity and visibility in selected fire scenarios. This research benefits from full-scale fire experiments with automobiles as well as from smoke tests in real highway tunnels conducted in Slovakia in 2016-2018 [6, 18-20]; the tested scenarios were then simulated by FDS. The set of videos have been implemented into the TTOS environment for didactic purposes. Some of the visualizations illustrate the critical situations which can appear during the self-rescue and evacuation phase of fire and can lead to break of smoke stratification or distortion of tunnel air flow velocity measurements. Potential of autonomous vehicles for prevention or elimination of safety risk and damages is also indicated.

7. References
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