Final smoke spread simulations for Tunnel traffic & operation simulator

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Abstract. Road and highway tunnels have become an essential part and an important element of the road network. In terms of general transportation and transit of goods they have also transnational significance. Tunnels located on the trans-European road network with a length of more than 500 m must also comply with the requirements of European Directive 2004/54 /EC. That directive imposes an obligation on investors and management organizations to pay particular attention to the fire safety of tunnels. This paper describes final smoke spread simulations of road tunnel fires which were created as outputs of the project entitled “Models of formation and spread of fire to increase safety of road tunnels”.

1. Introduction
This paper smoothly follows up to the articles [1], [2] and [3]. In these contributions were described the whole process of solution of mentioned project. Starting with the preparation and performance of the test and in situ measurements. Following the analysis of measurements and the creation of the first simulation models and their calibration. So in this paper we focus on fire smoke spread simulations prepared for our Tunnel Traffic & Operation Simulator (Simulator) as final outputs of the project.

2. Simulator
At the beginning some basic information about the Simulator (figure 1) are required to understand the philosophy and technical part of control processes of virtual or real road tunnels. This Simulator at University of Žilina was created as the result of one research project in 2013. Therefore, the technology equipment of virtual road tunnel, the visualization of Central control system (CCS) and the mode of operation/control is in accordance with Slovak legislation valid at that time. So we are able to simulate incidents which are rare in the real tunnel operation with the aim of verification of correctness and philosophy of the tunnel operation. The correct choice of traffic-operation state and consistent the optimal managing of emergency event are a key element to achieve successful solution of any emergency event. Visualizations of CCS, the tunnel traffic and technology management, is the same as on the real operator workplace of a two-tube tunnel. Our virtual tunnel is unidirectional highway tunnel with length of 1 km. It is possible to control the virtual tunnel by two independent operators (for traffic and technology) and their work is changeable, so it means that single operator can control entire tunnel from his/her workstation. In contrast to real traffic, simulation of video surveillance shows a virtual traffic in the tunnel tubes and in front of them [4]. Smoke spread of any fire in the virtual tunnel is simulated according to the current speed and direction of air flow in the tunnel.
2.1. Simulation of fire
There is possibility to simulate formation of fire after some predefined emergency events (figure 2):

- Slowly moving vehicle - subsequent traffic accident with another vehicle – fire.
- Stopped heavy good vehicle (HGV) with dangerous goods (DG) - fire.
- Lost of cargo – fire.
- Lost of cargo – subsequent traffic accident with other vehicle – fire.
- Leakage of the chemical (subject matter) – fire.
- traffic accident of two vehicles – fire.

The above mentioned events can be randomly simulated in individual thirds of each tunnel tube. The exact location of the event is random. After a fire occurs, this event is detected in one or more ways by (figure 3):

- Video-detection system of video-surveillance.
- Fire alarm button in SOS cabin activated by tunnel user or someone else.
- Fiber laser cable.
- Smoke detector.
- Measurement of opacity.
- CO level measurement.

Figure 3. Fire detection systems in virtual road tunnel.

Then, in case of the fire, the tunnel tubes (both) are closed according to pre-programmed traffic-operation state No. 8.3 (Emergency closure of the tunnel), which is not always same, but depends on emergency event location. In relation to the ventilation system, this means that the startup sequence of the individual fans depends on the fire zone in which fire was detected/activated. Each tunnel tube of our virtual 1 km long unidirectional tunnel is divided into 7 fire zones. The first fire zone at the beginning of the tunnel tube is specific, in case of fire, the air flow caused by the ventilation system blows against the direction of traffic. In case of fire in all other fire zones the air flow from ventilation system is set in accordance with the direction of traffic. In all cases, the air flow in the unaffected tunnel tube is set in a direction consistent with the affected tunnel tube. This is to prevent the smoke coming out of the affected tunnel tube from being sucked into the unaffected tunnel tube. Fans located in the zone of fire always remain turned off due to the possibility of disruption of smoke stratification. All other fans are running at full capacity [5]. This older method of ventilation is applied not only in some Slovak road tunnels but also in many of them around the world. A newer, more efficient and based on research, the safer ventilation system is based on maintaining max. critical air flow velocity in the tunnel to avoid disruption of the smoke stratification in any part of the tunnel tube. Therefore, the ventilation system is based on measuring the current speed of the air flow in the tunnel and automatic control the speed of the fans [6].

3. Simulations of smoke spread
Within the project APVV-15-0340 “Models of formation and spread of fire to increase safety of road tunnels” we have completed the final simulation models of smoke spread for selected emergency events with fire in tunnel. Simulations were developed for 3 locations in the tunnel tube:
- At the beginning under the first pair of fans (S1 and S2).
- In the middle of the tunnel (S3 and S4).
- At the end below the last pair of fans (S5 and S6).

Two simulations were processed for each location. One, based on the older principle of ventilation, which is also applied within the Simulator. And the second, based on the principle of critical air flow velocity in a unidirectional tunnel.
3.1. Simulations based on older method
The preparation of the smoke spread simulations required a large amount of input data based on numerous simulations of an emergency event with a fire at specified locations in the virtual tunnel. Intended development of the emergency event simulation with a fire:

- accident of 2 passenger cars with a fire in the Bôrik tunnel (Slovak 2 tube tunnel, 992 m long with one-way traffic, non-zero slope, used geometric parameters of this tunnel),
- natural air flow 2 m/s in traffic direction,
- closure of the tunnel after 30 s from the occurrence of the accident,
- formation of fire after 2 min from the occurrence of the accident,
- fire source parameters 5 MW,
- start of the ventilation system after 20 s from the occurrence of the fire,
- ventilation: after starting the ventilation system, all fans blow according to the scenario for maximum power (in second tunnel tube consistent air flow direction) except for the fire in the initial zone of the tunnel,
- reversing the direction of air flow in scenario S1 (at the beginning of the tunnel)
- record of measured physical units every 2 s (air flow velocity – figure 4, level of CO, level of opacity),
- record of all tunnel operators activities and actions of CCS (time of fan power on, time of critical values of CO and opacity, time of detected smoke by individual smoke detectors etc.).

![Figure 4](image)
Figure 4. Air flow velocities achieved in the individual scenarios on the simulator. S1-70 s by 6 fans, S3-72 s by 8 fans, S5-74 s by 6 fans in action.

3.2. Simulations based on new method
The process of these smoke spread simulations was based on the same input data until the start of the ventilation system. Then, after the fire alarm, the purpose of the ventilation is to regulate the critical air flow velocity of 1.5 m/s (figure 5). The findings from previous in situ measurements and the physical model of fire and smoke behavior were used.
Figure 5. Achievement of critical air flow velocities in the individual scenarios. S2-90 s by 3 fans, S4-75 s by 1 fan, S5-35 s by 1 fan in action.

3.3. Visualizations of simulations
Five visualizations of simulations were developed for all six scenarios:
- 3D visualizations of smoke spread,
- 2D visualizations of temperature fields,
- 2D visualizations of velocity fields,
- 2D visualizations of visibility,
- 2D visualizations of visibility at the level of the human head (figure 6).

The process of simulation S2 at 120th s using a physical model is shown in the figure 6. Turning the flow direction is dangerous, because the whirled up smoke to the right of the fire after turning is directed at people. In case that to the right of the fire does not create whirled up smoke then the reverse flow will be less dangerous for the assumption of maintaining the smoke stratification. Tenable condition could be maintained to the left of the fire. The problem is how to ensure a relatively low air flow velocity in the initial phase of smoke formation in the event of a rapidly evolving fire.

Figure 6. Visualization of simulation S2 at 120th s of fire.

Legend to figure 6:
- colors for temperature: maximum – minimum,
- colors for velocity: in direction of original flow – in opposite direction,
- colors for visibility: minimum – maximum.

| Scenario | Temperature [°C] | Velocity [m/s] | Visibility [m] |
|----------|------------------|----------------|----------------|
| S1       | 10, 70, 110      | -3, 0, 3       | 0, 10, 30      |
| S2       | 10, 70, 110      | -3, 0, 3       | 0, 10, 30      |
| S3       | 10, 70, 150      | -9, 0, 9       | 0, 10, 30      |
| S4       | 10, 70, 150      | -9, 0, 9       | 0, 10, 30      |
| S5       | 10, 70, 150      | -14, 0, 14     | 0, 10, 30      |
| S6       | 10, 70, 150      | -14, 0, 14     | 0, 10, 30      |

4. Closures
In this paper final smoke spread simulations for Simulator were described. Initial air flow velocities greater than 2 m/s indicate a problem of tenable conditions for road users in case of fire at the beginning of tunnel tube. The relative slow reverse air flow does not guarantee the re-establishment of smoke stratification from whirled up smoke. This situation can be dangerous for accident participants trapped in a vehicle or for other tunnel users with bad or slow reaction on dangerous emergency event.

References
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