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FIRE DETECTION IN TuSim BY FibroLaser

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Abstract: Road tunnels are important part of traffic infrastructure not only for shortening the paths in mountainous regions or in towns but also they increase economical effectiveness. Occurrence of traffic accidents in the tunnel is less common, but consequences can be more serious. The contribution shows the simulation of fire in a road tunnel through programmable logic controller (PLC) based simulator. Fire detection in the tunnel model is realized by FibroLaser. Influence of the pressure difference for various fire scenarios, types of vehicle on the air speed, etc. is counted by evaluation of the average temperature in the fire section.
Keywords: Simulation, application programming interface, programmable logic devices, fire, FibroLaser

INTRODUCTION

Road tunnels are important part of traffic infrastructure not only for shortening the paths in mountainous regions or in towns but also they increase economical effectiveness. Occurrence of traffic accidents in the tunnel is less common, but consequences can be more serious. A lot of technological equipment is necessary to provide the tunnel system safe in any circumstances. There are not many chances to simulate malfunctions of selected components in real 24-hour operation to see all consequences. Therefore, Tunnel simulator (TuSim) has been developed to simulate the technological equipment of the tunnel. Models can be used to simulate expected process behaviour with a proposed control system.

TuSim

TuSIM is PLC based system running on the B&R Automation industrial PC (PLC) with uninterruptible power supply (UPS) unit. TuSIM hardware is displayed on Figure1 from top to bottom: Masterview Liquid-crystal-display (LCD) switch, Bernecker and Rainer (B&R) industrial PC on the bottom right part of the figure, visualization server and UPS unit on the bottom left part of the figure.

Figure 1. TuSim Hardware

All devices of the tunnel technological equipment are simulated by the software inside the PLC [1]. Equipment of three tunnels is implemented: City tunnel, Motorway 2 tubes and Motorway 1 tube tunnel. TuSim supports in addition to the simulation of the technological equipment also the control of the traffic sequences. Each tunnel tube can operate in following traffic sequences: tunnel tube open, left lane closed, right lane closed, speed limit 60 km/h, adaptation lighting failure, tunnel tube closed. Switching from one sequence to another follows the time requirements which allow all vehicles to adapt to the new conditions. TuSim supports several simulated responses of the control system to unexpected events in the tunnel like complete or partial power failure, fire, traffic alarm or pre-alarm, lighting malfunction, SOS button activation, physical measurements alarm or pre-alarm [1]. We implemented models important for simulation of unexpected events analysis into the current version of the software. Whole source code concept from the PLC software to the visualization screens is open for enhancements so models important for the basic functionality e.g. traffic model, evacuation model have been already implemented. There are many graphical screens to visualize the state of each subsystem of the technological equipment – at least one for each subsystem. Handling of the screens and separate connections to the simulator is realized by visualization server and two client PCs with human-machine interface (HMI)/ (SCADA) CIMPLICITY software, which uses client/server architecture. Server is responsible for collection and distribution of the data from the PLC; clients allow interacting with the data distributed by the server and perform control actions.

SIMULATION OF FIRE

— Fire curves

Development of vehicle tunnel fires depends on number of factors: interior material, vehicle cargo, size and location of the fire and ventilation. The time behaviour of fire consists of incipient phase, growth phase, fully developed phase and decay phase [2].

First two phases are most important for simulation of fire detection by technological devices, second and third phases are important for evacuation simulation. Decay phase can be ignored in our case. Fire growth curve can be mathematically counted by linear growth, quadratic growth, or exponential growth [2]. Most common is quadratic growth and exponential decay, so we have selected them for the simulation.

$$Q(t) = \alpha \cdot t^2 \text{ for } 0 < t < t_{max}$$
$$Q(t) = Q_{max} \text{ for } \ t_{max} < t < t_{decay}$$
$$Q(t) = Q_{max} \cdot e^{-b \cdot (t - t_{decay})} \text{ for } t > t_{decay}$$

Figure 2 shows the growth of fire, where ultrafast rate is defined like α = 0.1876 kW/s2, fast is α = 0.0469 kW/s2 medium is α = 0.01172 kW/s2 , and slow rate is α = 0.00293 kW/s2 [2].

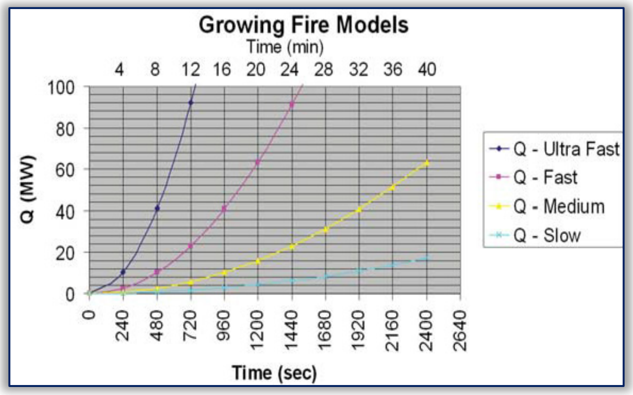


Figure 2. Quadratic fire growth [2]

Our simulations work with following fire scenarios from which everyone has specified Heat Release Rates (HRR) of the fire [3]: Car 5 MW, Van 10 MW, Bus 20 MW, Truck 50MW [3]. Figure 3 shows generated fire curves used for our simulation.

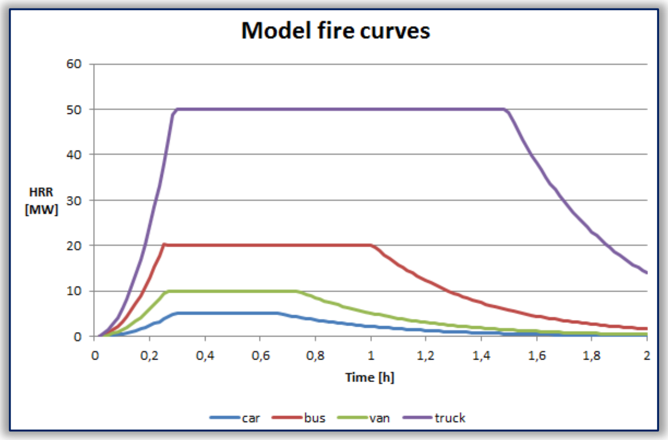


Figure 3. HRR curves for selected scenarios

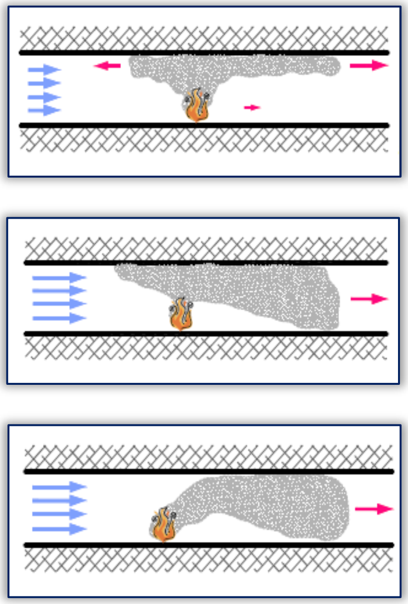
— Air temperatures

TuSim models have been also enhanced for estimation of the safety of people in the tunnels. High temperature and smoke in the tunnel are dangerous for the people because they can block evacuation doors. Following equations have been used for estimation of the air temperature in the place of fire [4][6]:

$$T_f = T_0 + \frac{0.7Q}{v\rho A c_p}$$

where: T_0 - initial temperature in the tunnel [K], v - air speed in the tunnel [m/s], ρ - air density [kg/m^3], cp - air thermal capacity [kJ/kgK], A – tunnel sectional area [m^2], Q – heat release rate [W].

The HRR of the fire is reduced, since not all heat from the fire is consumed for heating the air, part is also radiated into the wall. Model of the heating is one dimensional, so the value of the temperature obtained from the equation is an average temperature of the temperature cut. Detailed comparison of the temperatures from the model with three dimensional models can be found in [6]. Comparison shows that best results (1% accuracy) are obtained when airspeed is higher or equal to the critical speed. Critical speed of the air during the fire determines the state when back-layering of the smoke occurs. Figure 4 shows how the smoke diffuses depending on the airspeed. Figure 4a) and 4b) the airspeed is lower than critical speed and in the tunnel occurs back-layering of smoke. Fig 4c) the airspeed is higher than critical speed and in the tunnel does not occur back-layering of smoke.



a)

b)

c)

Figure 4. Spreading of smoke depending on the airspeed [7]

Several equations are available for calculation of the critical speed. We have compared calculation according to Kennedy and analytical calculation, which is preferred for our purpose [5]:

$$\left(Fr_{m\cdot} \cdot A \cdot c_p . T \cdot \rho \quad \right) \cdot v_c^3 + (Fr_{m\cdot} \cdot Q) v_c^2 - g \cdot H \cdot Q = 0$$

$$Fr_m = 4.5 \cdot \left(1 + 0.0374 |\min(grade, 0)|^{0.8} \quad \right)^{-3}$$

where: F_{rm} - Froude number, v_c - critical speed in the tunnel [m/s], ρ - air density [kg/m^3], c_p - air thermal capacity [kJ/kgK], g – gravitational acceleration [m/s^2], A – tunnel sectional area [m^2], H – height of the tunnel [m], grade – gradient of the tunnel [%], Q – heat release rate [W].

Figure 5 shows the both mentioned calculations of the critical speed and HRR for model of the tunnel in the TuSim.

FIRE DETECTION

With growing volume of trade and increasing transit cargo transport, the road traffic is taking up a larger part of it in comparison with rail transport, which has unavoidable negative influence on environment, road traffic density and quality of life - particularly in urban areas. If we want to provide protection to the citizens and create suitable conditions for survival in extraordinary situations, it is necessary to know the risks of transporting dangerous goods. The current situation requires creating an electronic system for monitoring of dangerous cargo replacing the insufficient system of today. This system would contribute to increasing security not only of participants of road traffic but also of citizens living in proximity of road communications where dangerous cargo is transported and also protection of the environment.

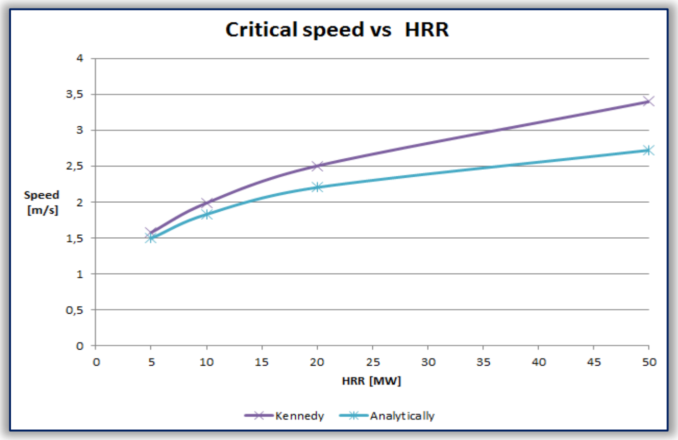


Figure 5. Critical speed vs HRR

— Air speed during the fire

Air speed in the tunnel during the unexpected event is not constant. In case of the tunnel with single directional traffic is air speed at the beginning influenced with "piston effect" – cars move the air in the direction of the traffic. In case of bidirectional traffic is this effect not so significant, it depends on the difference of traffic intensities at each portal of the tunnel. At the moment of the traffic stop, air speed decreases and is influenced until the moment of the start of the ventilation by the temperature, pressure and height differences between the portals. This effect is often called "stack effect". Air flow inside the tunnel can be after simplifications considered as one dimensional flow described by Bernoulli's equation. Tunnel is usually approximated as the circular-profile tube with defined hydraulic diameter. The equation for calculation of the hydraulic diameter is as follows:

$$D_h = \frac{4 \cdot A}{P}$$

where: A – tunnel sectional area [m^2], P – perimeter of the tunnel [m].

There are several tools available to simulate the three dimensional air flow through Navier-Stokes equations such as FDS [8], but TuSim simulates the reactions of the control system and has to be able to count the airflow in real-time. We have to consider also the orientation of the air movement, friction term in the equation should have opposite sign to the direction of the air. Same situation occurs in traffic term when vehicle speed is smaller than the air speed. Therefore, expression with absolute value of the speed multiplied by the speed is preferred to the power of the speed. Pressure difference for the wall friction, entry and exit of the tunnel can be described [9]:

$$\Delta P_{friction} = -\frac{1}{2}\rho \cdot v \cdot |v| \cdot \left(\xi_{entry} + \alpha \cdot \frac{L}{D_H} + \xi_{exit} + \xi_{local}\right)$$

where: v – air speed in the tunnel [m/s], ρ – air density [kg/m^3], D_H - hydraulic diameter [m], L – tunnel length [m], ξ_{entry}– loss coefficient tunnel entry, ξ_{exit} – loss coefficient tunnel exit, ξ_{local} – other local losses, λ – friction coefficient.

Pressure difference term for the movement of the vehicles [10][11]:

$$\Delta P_{traffic} = \frac{\rho}{2 \cdot A} \cdot \sum_{i=1}^{N} C_i \cdot |v_i - v| \cdot (v_i - v) \cdot A_i$$

where: v – air speed in the tunnel [m/s], v_i – speed of the i-th vehicle [m/s], ρ – air density [kg/m^3], C_i – drag factor, A – tunnel sectional area [m^2], A_i – front area of the i-th vehicle [m^2].

Pressure difference term for the stack effect [9][11]:

$$\Delta P_{stack} = \left(1 - \frac{T_a}{T_b}\right) \cdot \rho \cdot g \cdot L \cdot \frac{s}{100}$$

where: T_a - ambient temperature [K], T_m - average temperature in the tunnel [K], ρ – air density [kg/m^3], L – tunnel length [m], g – gravitational acceleration [m/s^2], s – tunnel gradient [%].

Pressure difference term for the fans [9]:

$$\Delta P_{fans} = \frac{\eta \cdot I_{fan}}{A} \cdot \left(1 - \frac{v}{v_{fan}}\right)$$

where: η – fan efficiency, I_{fan} - fan power [N], A – tunnel sectional area [m^2], v – air speed in the tunnel [m/s], v_{fan} - fan speed [m/s].

We have several possibilities to include the fire influence on the air movement in the tunnel. The problem is that the fire divides the tunnel in the two sections: section upward the fire and section downward the fire. The average temperature in the section, where most of the smoke remains, is significantly higher than in the other section. We can use table values for temperature differences of each fire type according to [6] such as 25 K for 5 MW fire, 65 K for 30 MW and 90 K for 50 MW fire. Disadvantage is that also length of the fire section is fixed and that's not usable for our simulation, since we simulate different positions of fire in the tunnel. Better attempt is to use the average temperature in the section [6][9]:

$$T_m = T_0 + (T_f - T_0)exp(-\frac{hP}{v\rho A c_p}x)$$

where: T_m - initial temperature in the tunnel [K], T_f - average fire temperature [K], v – air speed in the tunnel [m/s], ρ – air density [kg/m^3], c_p - air thermal capacity [kJ/kgK], A – tunnel sectional area [m^2], x – distance from the fire [m], h – heat conduction coefficient [W/m^{2}K].

Problem is that heat conduction coefficient depends on several factors and analytical solution is more complex.

Analytical solution for the average temperature can be found in [9]. We can use fixed suggested value 25 W/m2K or linearized expression from [6]. Average temperature obtained from the equation can be directly used in pressure difference term for the stack effect. Or we can include additional fire pressure difference term for the air speed between in interval 1,5 – 3,5 m/s [12]:

$$\Delta P_{fire} = c \cdot \frac{Q}{v \cdot D_H}$$

where: v – air speed in the tunnel [m/s], D_H - hydraulic diameter [m], Q – heat release rate [W], c – correction coefficient.

Figure 6 shows the comparison of pressure differences counted from all mentioned ways: fixed temperature difference according the tables, own pressure difference term ΔP_{fire}, average temperature Tm in the fire section for different speeds and different lengths of the section.

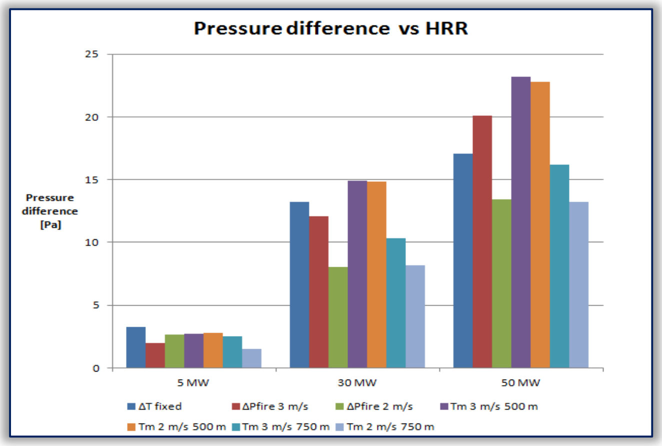


Figure 6. Comparison of fire pressure differences

Most of the pressure terms influence the final equation with similar pressure differences, ΔP fire outputs higher pressure with lower air speed. The effect of the air speed is not so significant with average temperature Tm. Average temperature term demonstrates also the differences between the different length of fire sections. We decided to use the average temperature term in the fire section, because it can consider both air speed and length of fire section. Final differential equation for the air speed in the tunnel [13]:

$$\frac{dv}{dt} = \frac{\sum_{i=1}^{N} \Delta P_i}{L \cdot \rho}$$

where: v – air speed in the tunnel [m/s], ρ – air density [kg/m3], L – tunnel length [m], ΔPi - pressure difference term [Pa].

We have solved the equation for the air speed in the simulator numerically with Euler method and time step one second. We have used following data for the simulation experiment: traffic intensity 1000 veh/h, traffic stop (fire) in the fifth minute of the simulation. We assumed that both lanes with single direction traffic stopped in the same time and traffic congestion occurred immediately. Other cases for example stop of the vehicles only in one lane were not simulated. Tunnel model used for the simulation was 1000 m long; fire section was 500 m long, gradient was 1 %, hydraulic diameter equal to 7.83 m, sectional area 57.26 m2, perimeter 29.22 m. Fans were turned on in the tenth minute (five minutes after the fire) of the simulation of every fire scenario. This does not correspond to the reality, since control system of the tunnel should react dynamically to the conditions, which depend on the vehicle fire type. Therefore, we should include also fire detection time estimation into our simulation.

— FibroLaser detection of fire

Video detection is the only technological subsystem today that can give immediate response to unexpected event in the tunnel. The disadvantage of video detection subsystem is that it is used as multi-purpose: automatic stop detection, low/high speed warning, traffic flow analysis, wrong vehicle direction, smoke detection. Fire detection is only one of the tasks of the subsystem and it can trigger false alarms because of combustion products, light reflections, fog and wet road. Vehicle stop detection can trigger alarm immediately but control system should not perform tunnel close traffic sequence in every vehicle stop situation. Therefore, operator should consider individual situation and perform the control action such as close the lane, limit the speed, or close the tunnel. Therefore, fire detection systems without human influence should also be included in the tunnel.

Heat detection subsystem is nowadays in tunnels realized by FibroLasers. They consist of control unit and laser sensor cables. Laser beam is sent into the cable from control unit and light reflection is obtained and analysed. Light is scattered into “Stokes” and “Anti-Stokes” signals (Raman Effect) [14]. Temperature change in the cable can be detected from the signal strength difference between Stokes and Anti-Stokes signals.

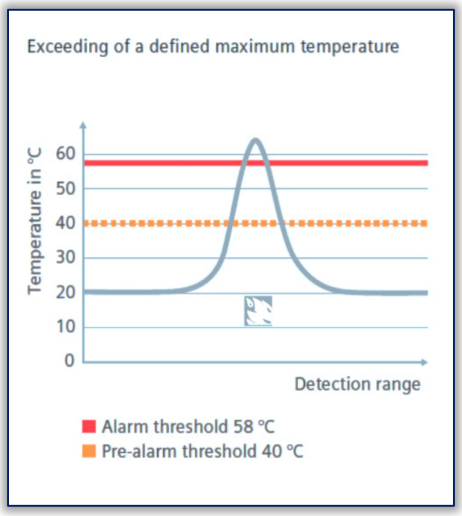


Figure 7. Rule 1 – threshold temperature 40 °C [14]

We decided to implement this subsystem into the simulator according the Siemens FibroLaser datasheet [14]. We implemented and compared all the rules for several fire scenarios. Figure 7 shows the rule 1 for triggering the pre-alarm and alarm in case of exceeding the defined maximum temperature. FibroLaser from Honeywell [15] uses also value 60°C for triggering the alarm. Figure 8 shows the rule 2 for triggering the pre-alarm and alarm in case of exceeding the average temperature. FibroLaser from Honeywell [15] uses also value 15 °C for triggering the alarm.

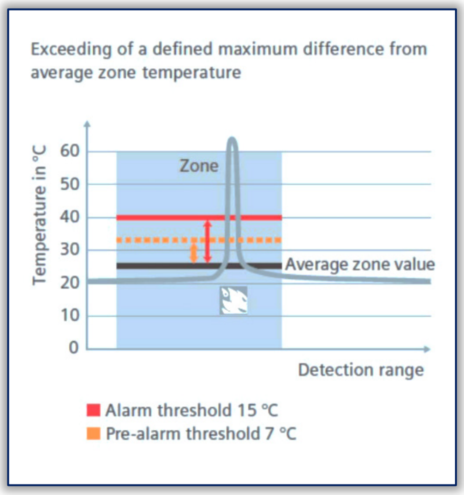


Figure 8. Rule 2 – average temperature 7 °C threshold [14]

Figure 9 shows the rule 3 for triggering the pre-alarm and alarm in case of exceeding the defined temperature gradient. FibroLaser from Honeywell [15] uses value Δ13°C/40 s for triggering the alarm. All FibroLaser rules according the values from the Siemens datasheet were implemented with logical OR statement to trigger the alarm or pre-alarm. We have used standard values from the datasheet and one minute time step for the evaluation of the rules.

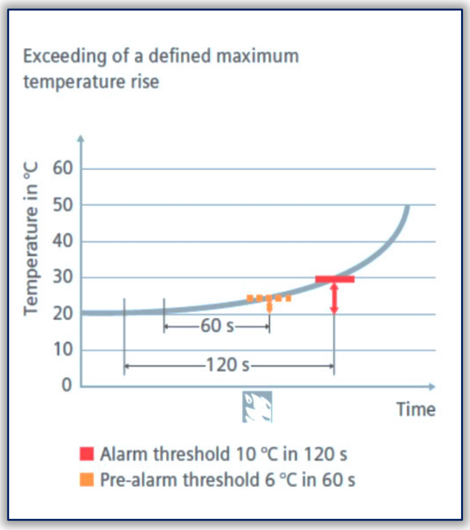


Figure 9. Rule 3 – threshold Δ6° C / 60 s [14]

We cannot use the average air temperature as the input for the FibroLaser detection, since temperature close to the fire is significantly higher and is three-dimensional. We have used calculation for estimation of the heat radiated into the tunnel wall [13]:

$$Q_{wall} = P \cdot L_f \cdot \left[h \cdot \left(T_{SM}^4 - T_{Wall}^4\right) + \epsilon \cdot \sigma \cdot \left(T_{SM}^4 - T_{Wall}^4\right)\right]$$

where: T_{wall} - wall temperature[K], T_{SM} - hot air/smoke temperature [K], h – heat conduction coefficient [W/m^{2}K], ε – emissivity, σ – Stefan-Boltzmann constant [W/m^{2}K^4], P – perimeter of the tunnel [m], Lf - length of fire [m].

We have used constant value of heat conduction coefficient; even it depends on the air speed and other parameters, such as Reynolds number. The equation has been solved numerically to obtain estimated wall temperature. We have applied all FibroLaser rules for simulated wall temperature, estimated times for pre-alarm and alarm triggering for each fire scenario were:

- Car: Pre-alarm 3.min, alarm 5.min,
- Van : Pre-alarm 2.min , alarm 3.min,
- Bus : Pre-alarm 2.min, alarm 2.min,
- Truck: Pre-alarm 1.min, alarm 1.min.

Two pairs of jet fans were automatically turned on after triggering the alarm as the reaction of the control system. One pair created the air flow with the speed 3 m/s, which was according the Figure 4 on the edge for safety in all fire scenarios. Figure 10 shows the average temperature in the middle of 500 m fire section. This temperature is used for the simulation of the air speed during the fire in the tunnel. It can be seen that the temperature difference in the car and van scenarios is not so high to influence the air speed significantly.

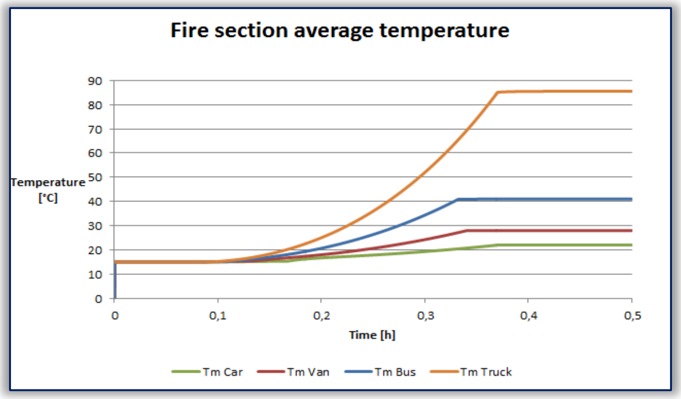


Figure 10. Fire section average temperature

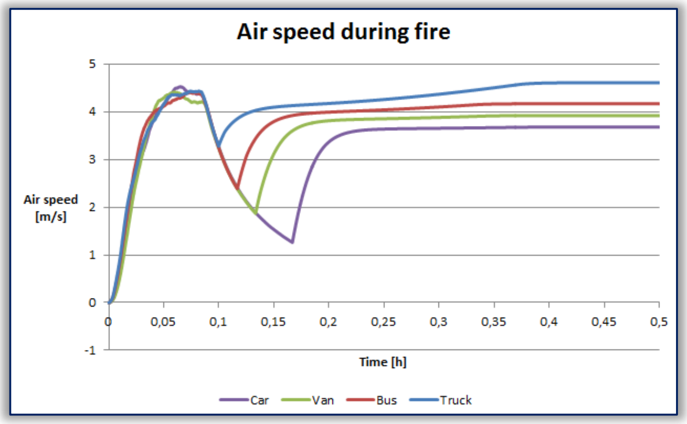


Figure 11. Air speed during fire

Figure 11 shows the air speed in the tunnel with automatic fire detection by the FibroLaser. The average temperature influences most the speed in truck fire scenario. Reaction to the fires with high HRR is faster and therefore reaction of the control system is also faster and raising the air speed in the tunnel can be more prompt.

CONCLUSIONS

We have successfully implemented equation for the air speed with fire influence into the TuSim. We applied FibroLaser detection rules and estimated wall temperature for triggering the fire alarm scenarios and we simulated the reaction of the control system. Therefore we obtained dynamical detection time for each vehicle fire scenario. We haven't considered all fire detection subsystems and all possibilities of traffic situations in the tunnel during the fire. We have specified own HRR curves and we have not used complex fire model with solving of the chemical reactions. FibroLasers are installed on the ceiling of the tunnels so comparison with three dimensional simulation tools would be necessary to use the absolute value of fire detection times. Even alternative principles such as fuzzy models [16] are used to estimate the fire detection time [17] by FibroLasers and smoke sensors. Producers of FibroLasers often provide own software tools for estimation of this time with better knowledge of FibroLaser characteristics. Additional comparison and adjustment of our simulation outputs with estimations based on other principles should also be performed

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