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COMPUTER MODELING OF A FIRE HAZARD AND EVACUATION OF TRANSPORTATION TUNNELS WITH LONGITUDINAL VENTILATION SYSTEM

1. Introduction

Despite the fact that different safety systems are employed in communication tunnels, there is still a constant state of the potential fire hazard. According to data presented in Table 1, it is not difficult to imagine that the outbreak of a fire is one of the most considerable hazards during tunnel operation.

TABLE 1

Typical fires and their presented effects in long communication tunnels [1]

Year	Tunnel name	Tunnel length, [m]	Country	Vehicle in which the fire was noticed	Probable cause of the fire	Duration of the fire	Consequences in people	Tunnel tubing and installations
1994	Huguenot	3 914	South Africa	coach with 45 passengers	short circuit in electrical installation and the fire	1 h	1 fatality 28 injured	serious tunnel damage
1999	Mont Blanc	11 600	France – Italy	truck with liquid margarine	oil spill from the engine and the fire	–	39 fatalities	serious damage tunnel reopened 22.12.2001
2000	Eurotunnel	50 000	Great Britain – France	truck	oil spill from the engine and the fire	7 h	–	interruption of traffic for 7 hours
2001	St. Gotthard	16 918	A2 Switzerland	truck	head-on collision of two trucks and the fire	2 days	11 fatalities	serious damage; tunnel closed for two months

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A series of these fires, as in the Mont Blanc road tunnel in 1999 (Fig. 1) where 39 people were killed, demonstrates the necessity to reconsider the philosophy of fire safety for these structures.

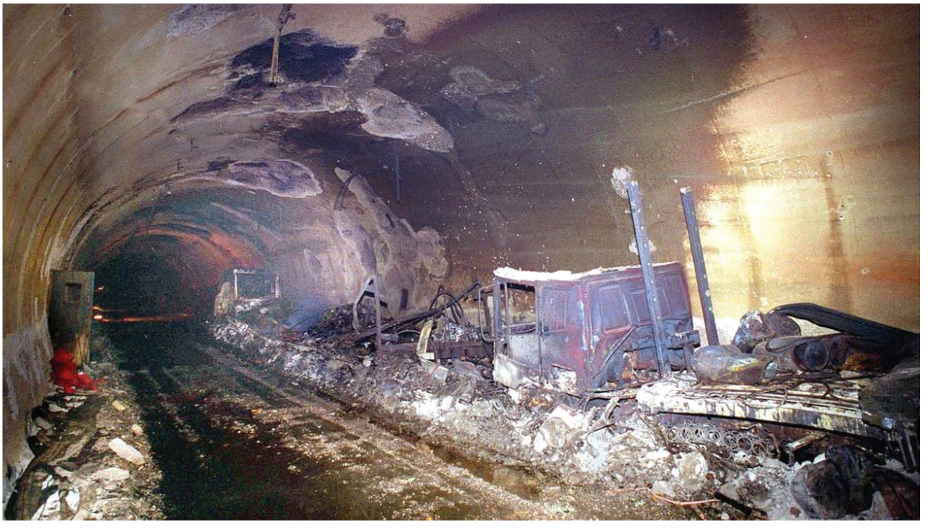

Fig. 1. Result of the fire in the Mont Blanc road tunnel [2]

The most common causes of fires in a road tunnels are traffic incidents, electrical failures (cars) and the overheating of brakes (trucks) [3].

The paper presents an analysis and assessment of the evacuation of the people from a road tunnel using various methods.

1.1. Longitudinal ventilation during fire hazard

Longitudinal ventilation of road tunnels in the case of the fire occurrence should ensure:

- reduction of the concentration of harmful gas, dust and smoke,
- appropriate visibility,
- control of the air flow rate and temperature,
- possibility of safe evacuation of the users from the tunnels,
- efficient fire extinguishing.

The main purpose of the ventilation system during a fire in a tunnel is to allow for the safe evacuation of tunnel users and to allow for the intervention of emergency services.

It is essential that toxic gases and smoke from a fire is kept close to the tunnel ceiling if a fire starts. It should also be remembered, that ventilation system air flow rate has great impact on the course of the fire. If the velocity is too high it will cause the air heat release rate to increase, then consequently increase the volume of the fire and harmful concentration of smokes and gases [1].

1.2. Evacuation of users from a tunnel during a fire

The first minutes after a fire starts are vital for tunnel users trying to escape, when the visibility and concentration of toxic gases still allow for efficient evacuation.

There are many factors which affect evacuation time:
- characteristics of the object including its function, geometry, number of emergency exits, exit signs etc.,
- detection and alarm system (smoke and heat detectors etc.),
- behavioral factors (number of people, the knowledge of an object, activity, age and physical efficiency etc.),
- means and method of transportation.

From the point of view of the legislation acts, safe evacuation is determined by a few parameters, the values of which shouldn't be exceeded.

In case of a fire on an escape route, conditions will be deemed life-threatening and dangerous to human health, as a result of exceeding one of the following parameters:
- air temperature above 60°C at a height of less than or equal to 1.8 m from the level of the evacuation route,
- thermal radiation flux density of 2.5 kW/m^2 for the duration of exposure longer than 30 s,
- temperature of hot fire gases above 200°C at an altitude of more than 2.5 m from the evacuation route,
- visibility of less than 10 m at a height of less than or equal to 1.8 m from the level of the evacuation route,
- oxygen content below 15% [3].

To examine the possibility of escape from the tunnel, the calculations were conducted using:
- European Guideline: Available Safe Escape Time (ASET) – time available for occupants to reach a safe place [4],
- European Guideline: Required Safe Escape Time (RSET) – time that occupants take to reach a safe place [4],
- Pathfinder simulator.

2. Computer modeling of a fire hazard in a tunnel and the evacuation process

To determine the effects of fire dynamics, including the movement of gases and smoke, on the evacuation process from tunnel, Computational Fluid Dynamics method were used to help obtain information on the spread of the fire. Data was also taken for the physico-chemical parameters of gases, visibility and radiation etc. For this purpose the program PyroSim was implemented, with its graphical interface of Fire Dynamics Simulator (FDS) application.

Model tests were conducted for a tunnel with a length of 1378 m, which was equipped with seven emergency exits to safety zones (Fig. 2), spaced from 115 m to 175 m. Cross-section (selected by German design guidelines RABT) of the tunnel was 63 m^2 (Fig. 3).

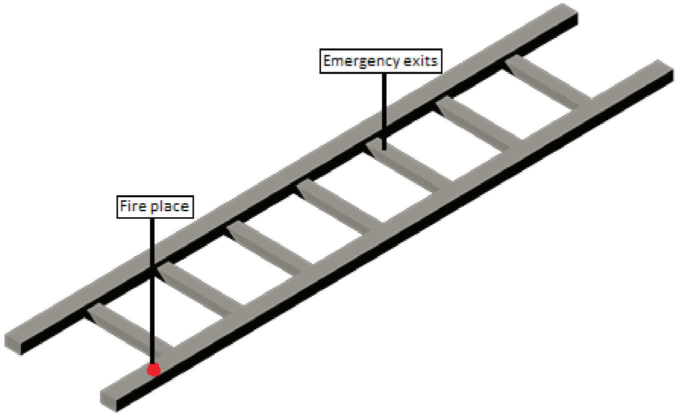

Fig. 2. Scheme of the investigated tunnel

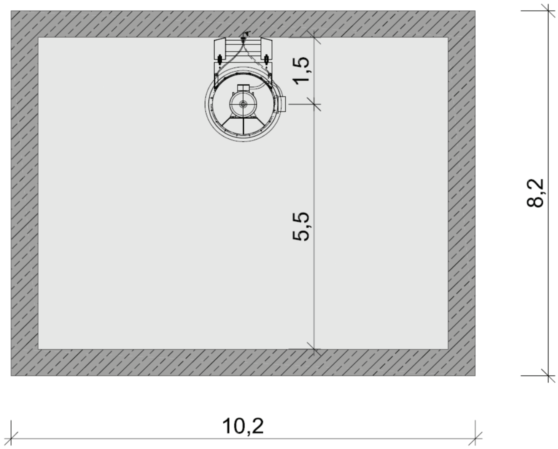

Fig. 3. Tunnel cross-section

The tunnel fire ventilation system consisted of 11 jet fans (each of capacity 30 m^3/s), spaced at the 95 m.

For the purpose of the calculation, it was assumed that the jet fan located next to the fire was damaged (Fig. 4).

With this scenario assumed the fire at a distance of 150 m (Fig. 2 and 4) from the entrance to the tunnel was considered to be the most unfavorable situation for several reasons:

- distance of the fire from the tunnel entrance prevented smoke escaping out of the tunnel,
- smoke extract was carried out in the direction of movement of a car (the whole length of the tunnel), which impeded the evacuation,
- all fans were working in "unfavorable" conditions (low density, high temperature etc.).

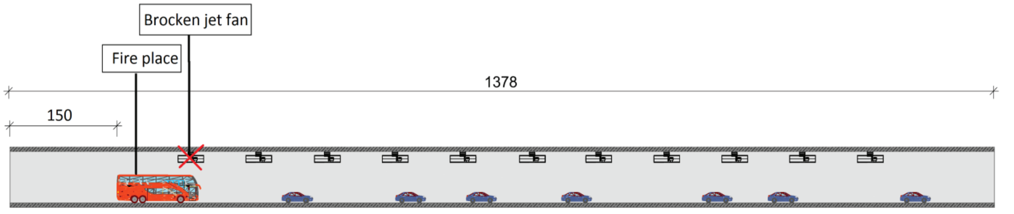

Fig. 4. Fire place in tunnel

According to the EUREKA project, heat release rate (HRR) by the burning bus reached 29 MW peak after 8 min, (from the fire start) and kept it until the end of the calculation [5]. According to PIARC recommendations the approximate bus fire HRR is 20 MW.

In the simulation, the heat release rate was determined by German design guidelines RABT, where the assumed number of the trucks, which was over 4000 per day, gives 50 MW of the heat release rate [6].

Although these calculations correspond to a large bus fire, adding a truck with dozens of wooden pallets, or fire arising during the collision of the bus and 2–3 cars change the situation considerably.

The initial conditions of the simulation were: medium – the atmospheric air, temperature of the air 20°C, acceleration due to gravity 9.81 m/s^2, relative humidity 40%, pressure 1013.25 hPa, HRR 50 MW.

The development of the fire was set by fire curve recommended by the National Fire Protection Association (Fig. 5).

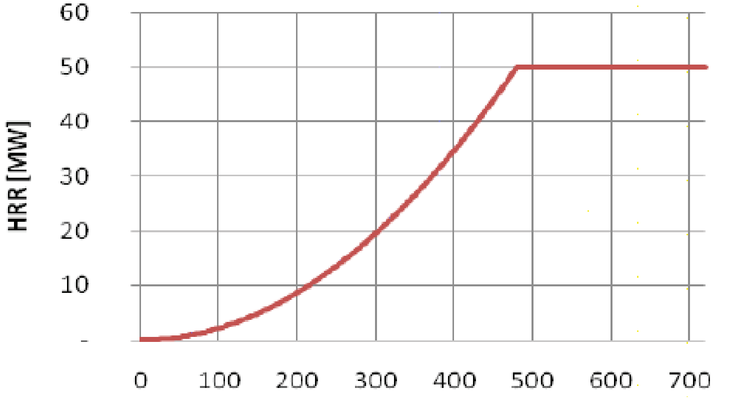

Fig. 5. Fire curve recommended by the National Fire Protection Association [7]

To generate a mesh line for input into Fire Dynamics Simulator (FDS) a Mesh Size Calculator was used. The cell size was determined by using the characteristic fire diameter and cell size ratio, that accurately resolved the fire simulation based on the total heat release rate [8].

2.1. The conditions in the tunnel during a fire – results of simulation

The simulations of temperature distribution in a longitudinal section of the tunnel show that temperature rises relatively slowly but rises to a high value (Fig. 6).

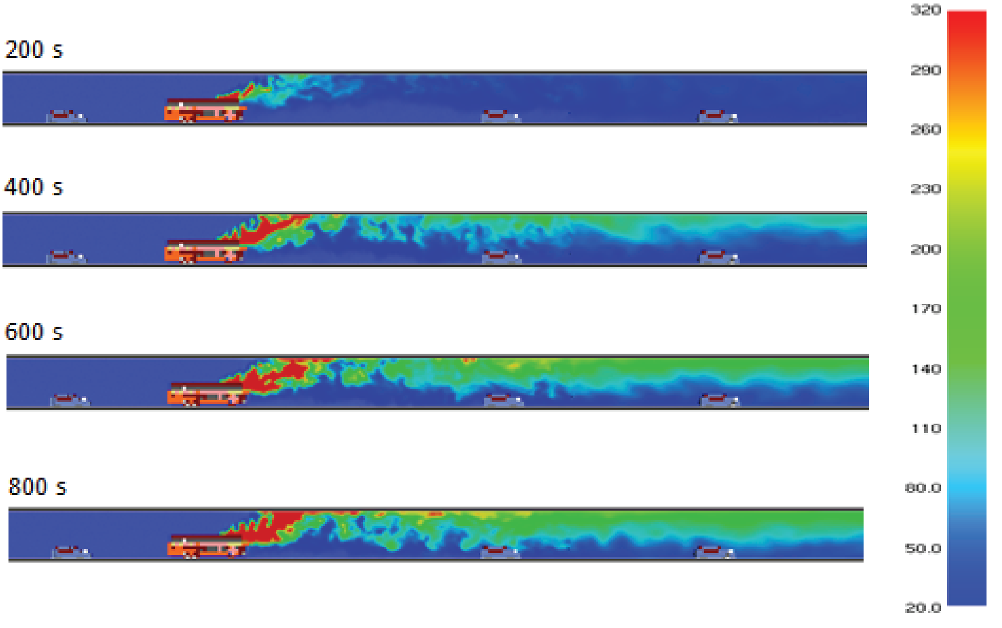

Fig. 6. Temperature distribution in a longitudinal tunnel section at time: 200 s, 400 s, 600 s, 800 s

A few of the parameters that define safe evacuation were analyzed:

— air temperature at a height equal 1.5 m from the level of the evacuation route (Fig. 7),
— visibility at a height equal 1.5 m from the level of the evacuation route (Fig. 8),
— thermal radiation flux density (Fig. 9),
— temperature of hot fire gases an altitude of more than 2.5 m from the – evacuation route (Fig. 10).

The parameters prevailing in the tunnel during the fire which would allow users to safely leave the tunnel:

— air temperature below 60°C at a height 1.5 m from the level of the evacuation route up to 470 s (Fig. 7),
— visibility above than 10 m^{-1} at a height 1.5 m from the level of the evacuation route up to 170 s (Fig. 8),
— thermal radiation flux density below 2.5 kW/m^2 (Fig. 9),
— temperature of hot fire gases below 200°C at an altitude of more than 2.5 m from the evacuation route (Fig. 10).

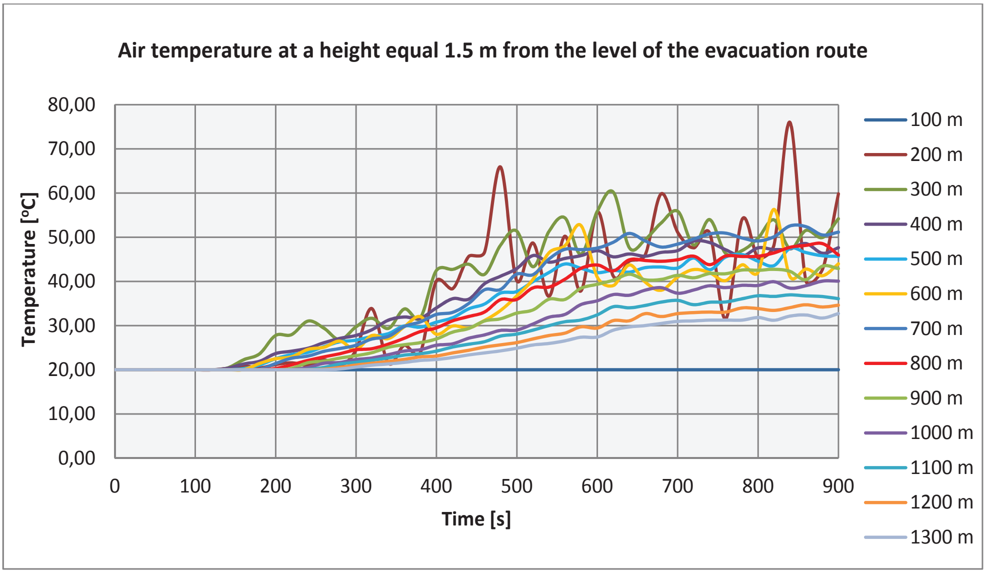

Fig. 7. Air temperature at a height equal 1.5 m from the level of the evacuation route

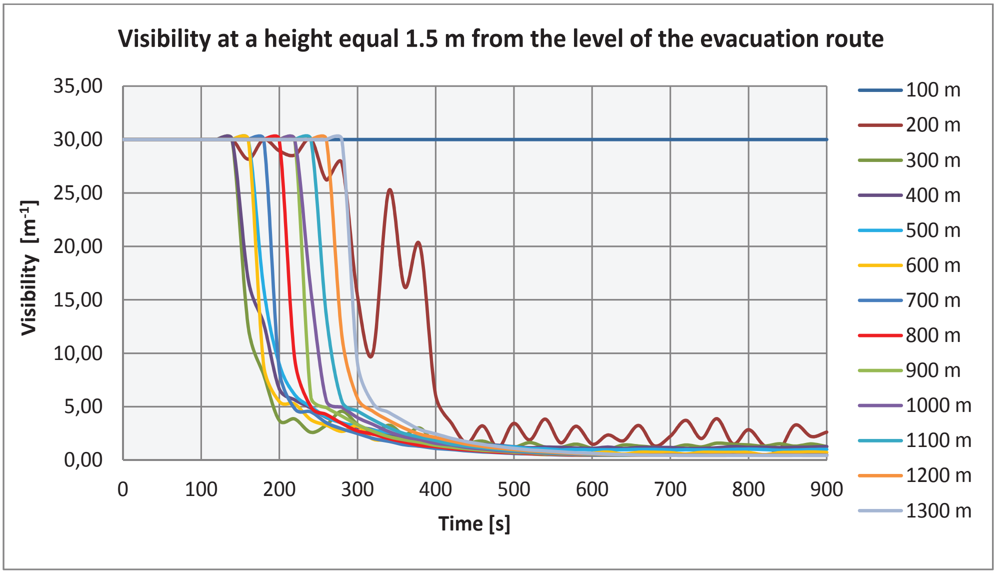

Fig. 8. Visibility at a height equal 1.5 m from the level of the evacuation route

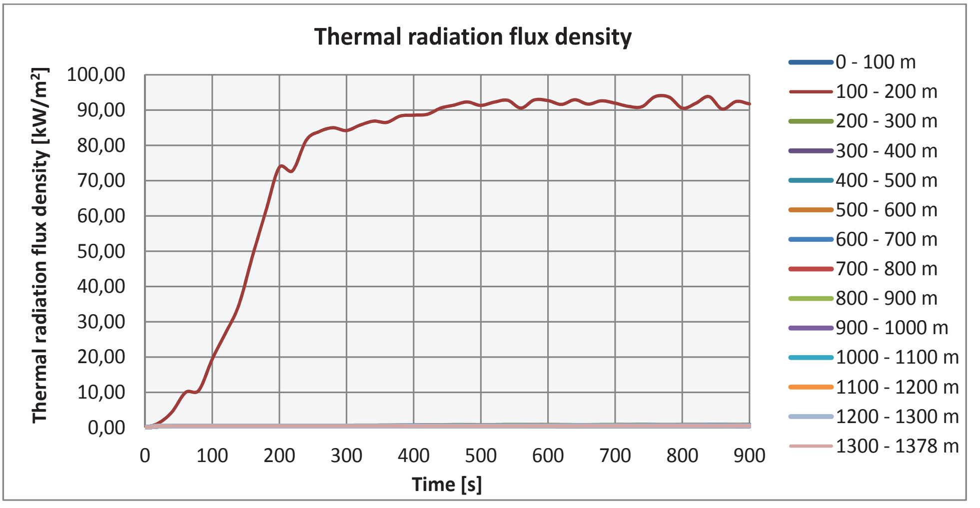

Fig. 9. Thermal radiation flux density

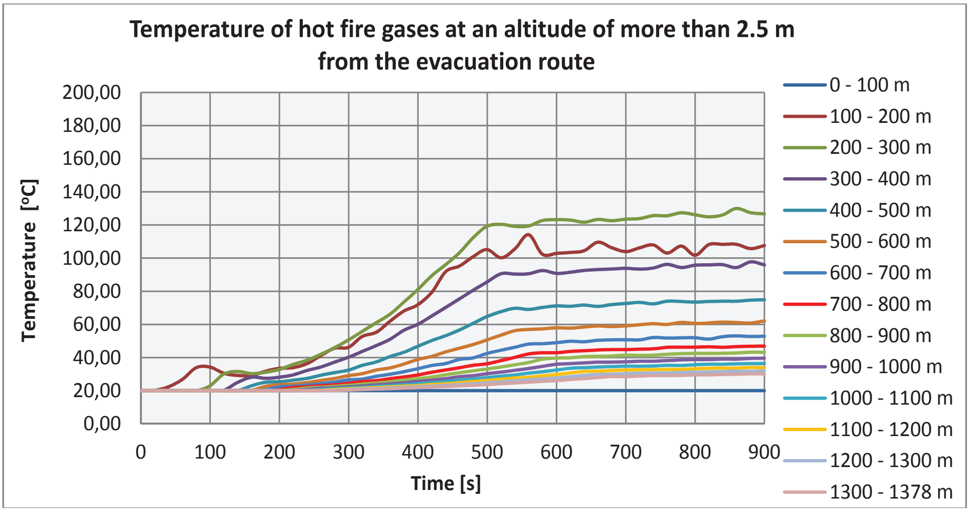

Fig. 10. Temperature of hot fire gases at an altitude of more than 2.5 m from the evacuation route

Simulation results showed that the crucial parameter during the evacuation process was visibility (Fig. 11). Visibility range distribution in a longitudinal section of the tunnel showed a rapid increase to the exit site. This could create a threat to those evacuating by car to the exit site.

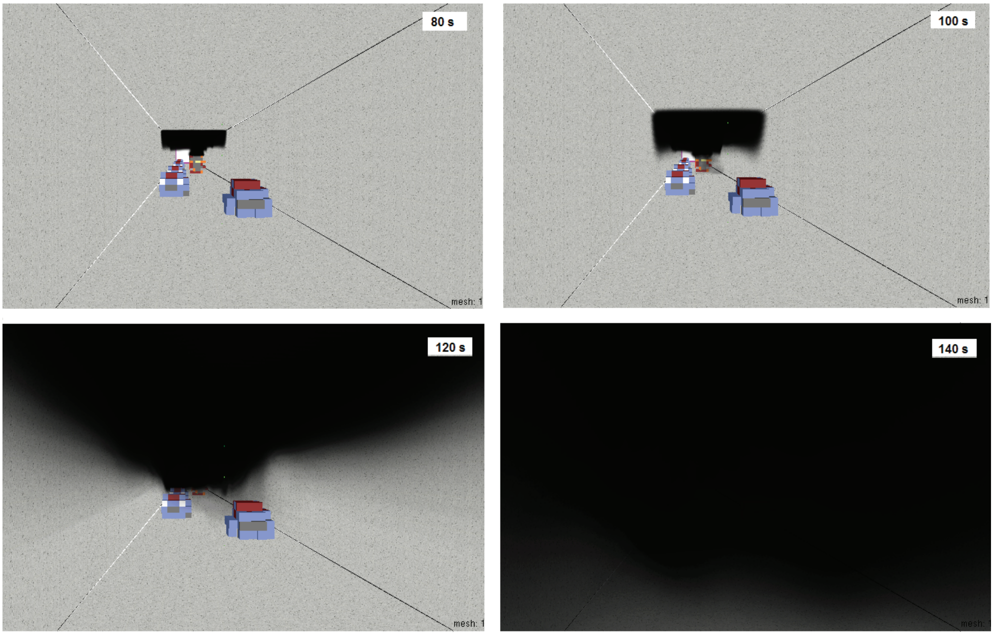

Fig. 11. Visibility range in tunnel in length 130 m from the fire place

Visibility below 10 m^{-1} was presented in Table 2.

TABLE 2

Range of visibility in tunnel

Length, [m]	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300
Time, [s]	–	400	170	190	200	180	200	220	240	250	270	280	300

According to the simulation results, there was no smoke propagation in the entry portal direction. Available Safe Escape Time [4] estimated by the results of computer modeling was 170 s (determined by visibility).

2.2. Evacuation of tunnel users – results of simulation

In the case of a fire in a road tunnel, the primary concerns of tunnel users are self-rescue operations, the main factor being evacuation is time.

In the calculations it was considered:

- average capacity: 55000 E/day (E – contractual vehicles),
- average traffic speed: 60 km/h,
- 52 cars were in the tunnel during a fire (including 11 trucks or buses),
- 5 cars blocked by fire trucks (from 0 m to 150 m length).

It was also assumed that in the section from 0 m to 150 m in front of the fire, a blockage was created and cars weren't able to drive out of the tunnel. Evacuation in this area had to be carried out on foot in the opposite of the fire. In the area behind the fire, a few moving cars left the tunnel. As a result of congestion, hazardous air conditions and like lack of visibility, others had to evacuate on foot to the nearest emergency exit.

The Required Safe Escape Tim was estimated on the based on: detection and alarm time, reaction time, travel time to the safety places (Fig. 12). These times are strongly influenced by human behavior, for this reason it is not easy to give them an exact value [4].

$$T_{RSET} = \Delta t_{det} + \Delta t_{a} + \Delta t_{r} + \Delta t_{tra}$$

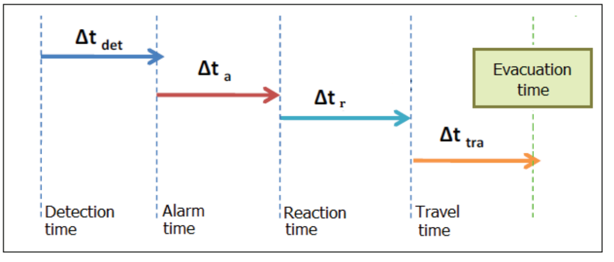

Fig. 12. The total time occupants take to reach a safe users

Detection time for people in the vicinity of the fire was 0 s, for people who were further away from the fire – 60 s. Warning time was included on detection time resulting from an automatic system. Taking into account the average speed of a normal healthy person 1.2 m/s, the maximum distance to the nearest emergency exit, reaction time and density of users the RSET was estimated to be 153 s.

The possibility of tunnel user evacuation from a road tunnel with longitudinal ventilation was also simulated using the Pathfinder simulator (Fig. 13). This method takes into account individual characteristics and decision-making of users, the dynamics of the crowd, the panic and the evacuation process [3].

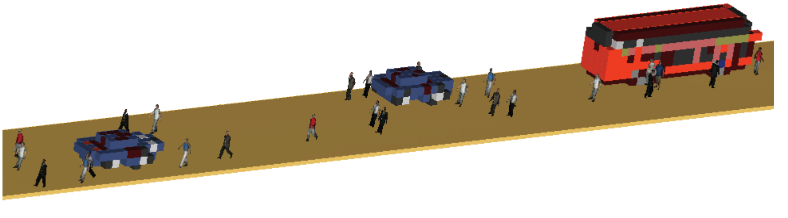

Fig. 13. Print screen of visualization of simulation

The main parameters that define the behavior of the crowd during the evacuation are: speed of movement, shoulder width, reaction time, and distance between people, escape routes and knowledge of the topography or building. Each evacuating person was assigned individual properties selected on the base of [9] by a Gauss normal distribution. This function provided a greater variety of parameters, and thus a more realistic evacuation time.

The result of the simulation showed that tunnel users can be evacuated to safety zones in 163 s (Fig. 14).

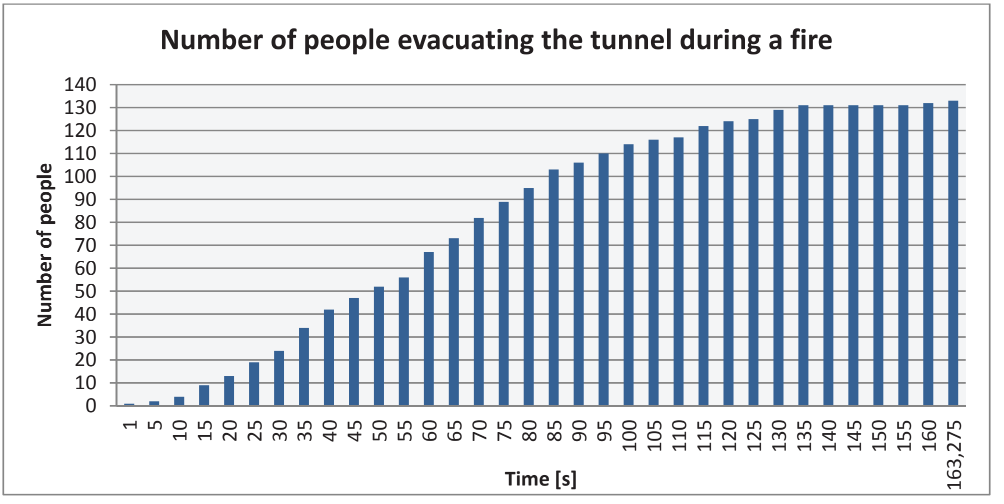

Fig. 14. Number of people evacuating from the tunnel during a fire – Pathfinder simulator

Taking into account the conditions in the tunnel during a fire, the evacuation of users should take place 170 s after the outbreak of a fire, which according to the calculations and simulations would be possible in the presented case.

3. Conclusions

Based on the conducted analysis, the following conclusions can by arrived at:

- fires in the tunnels are a huge potential hazard for tunnel users,
- complex ventilation systems are often the cause of difficulties in fire control, especially in the first moment of fire e.g. like in the Mont Blanc tunnel,
- the biggest danger in the case of fire is the smoke that develops and spreads in the tunnel, and makes it difficult and sometimes impossible to evacuate people from the tunnel and is the cause of intoxication and death,
- in order to establish escape routes and evacuation parameter, a simulation program can be used to help determine the time of evacuation,
- for the safe evacuation of a tunnel, the design of emergency exits taking into account the distance between them, as well as the evacuation time has a crucial importance,
- the choice of the calculation methods for an appropriate evacuation design belongs to the designer, and can rely on various opportunities,
- it should be taken into account that the evacuation time is strongly influenced by human behavior, for this reason it is not easy to estimate an exact value,
- there is a demand for acquiring knowledge about fire safety by conducting experimental research in the real scale, laboratory research and numerical modeling.

REFERENCES

[1] *Nawrat S.*, *Schmidt N.*, *Napieraj S.*: Selected issues concerning protection of road tunnel structures and ventilation systems in relation to fire hazard. Journal of Mining and Geoengineering, Krakow 2012

[2] http://najwiekszepozary.pl/pozar-w-tunelu-w-alpach-mont-blanc.html [online: 05.06.2013]

[3] PD 7974-6:2004: The application of fire safety engineering principles to fire safety deign of buildings. Part 6. Human factors: Life safety strategies – Occupant evacuation, behavior and condition (Sub-system 6), BSi 2004

[4] European Guideline. Fire safety engineering concerning evacuation from buildings, CFPA-E, No. 19:2009

[5] *Ingason H.*, *Lönnermark A.*: Recent achievements regarding essuring of time-heat and time-temperature development in tunnels, 1st International Symposium "Safe & Reliable Tunnels", Prague 2004

[6] RABT (Richtlinien für die Ausstattung und den Betrieb von Straßentunneln), Bonn 2006

[7] NFPA 204. Standard for Smoke and Heat Venting, 2007 Edition

[8] http://www.koverholt.com/fds-mesh-size-calc/ [online: 05.06.2013]

[9] *Smith J.L.*: Agent-Based Simulation of Human Movements During Emergency Evacuations Of Facilities, "Structures congress", Conference Proceeding Paper, Canada 2008, pp. 1–10

[10] *Nawrat S.*, *Schmidt N.*, *Napieraj S.*: Computer modeling of a fire hazard risk assessment and safety in transportation tunnels. Budownictwo Górnicze i Tunelowe, Kraków 2012

[11] *Nawrat S.*, *Napieraj S.*: Wentylacja i bezpieczeństwo w tunelach komunikacyjnych. Uczelniane Wydawnictwa Naukowo-Dydaktyczne AGH, Kraków 2005

[12] *Nocula W.:* Pathfinder – poprawny dobór parametrów i zachowań ludzi w czasie ewakuacji. Materiały Stigo, Kraków 2012

[13] PIARC Committee on Road Tunnels. Fire and smoke control in road tunels