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3. RISK ANALYSIS FOR USERS OF URBAN ROAD TUNNELS

3.1. Introduction

Urban road tunnels play an increasing role in the urban transport network. Until recently, tunnels facilitated communication mainly in mountain regions. Currently, they are more and more often built in cities and are used to organize transit traffic and run under densely built-up areas. Urban tunnels can also improve river crossing by connecting parts of the city separated by it. Transferring the city traffic to the tunnel allows for reorganizing the urban space, making it more inhabitants-friendly. Thus, since modern cities cannot do without traffic, and it is even expected to intensify, it should be at least partially hidden underground.

Safety considerations are also important as the serious risks to tunnel users are directly related to the nature of the tunnels. These threats are mainly caused by limited space, difficult access and difficulties in evacuation. Additionally, the nature of the road traffic must be taken into account, the main feature of which is a large number of independent drivers and passengers. Their behavior and detailed decisions, although governed by traffic regulations, are generally unpredictable.

Road incidents in road tunnels are less frequent than in other parts of the transport network because the tunnel itself calms the traffic[3]. There are no intersections in the

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[3]Amundsen F.H., Engebretsen A.: Studies on Norwegian Road Tunnels II. An Analysis on Traffic Accidents in Road Tunnels 2001–2006. Statens Vegvesen, Oslo, Norway: Vegdirektoratet, Roads and Traffic Department, Traffic Safety Section, 2009, Raport no: TS4-2009.
Lu J.J., Xing Y., Wang C., Cai X.: Risk factors affecting the severity of traffic accidents at Shanghai river-crossing tunnel, Traffic Injury Prevention, 2015, Vol. 17, No. 2, pp. 176–180.

tunnels, no pedestrians, often speed limits are applied, and the influence of weather conditions is negligible. All of this moderates traffic and reduces the likelihood of an accident. However, if an accident does occur, its consequences are more severe than elsewhere[4].

Many road tunnel systems ensure the comfort of use and the safety of users, but the worst situation in which an accident occurs and, above all, a fire breaks out, cannot be ruled out. Then not only the people directly involved in the accident are at risk, but also all people in the tunnel. Even if a fire is not fully developed, a large part of the tunnel is filled with toxic and hot fire gases. The smoke reduces visibility and causes confusion. It also contains poisonous components that can quickly cause unconsciousness[5]. This zone, dangerous for human health and life, is growing rapidly, and in a few minutes it covers subsequent parts of the tunnel[6]. Therefore, it is extremely important that people trapped in the tunnel undertake self-evacuation in the initial stage of fire development. For this to happen, all tunnel safety systems must operate properly and support self-rescue[7].

When a fire breaks out in a road tunnel, the tasks of the safety systems include fire detection, precise locating, announcing a fire alarm, closing the tunnel entrance and switching the ventilation system to fire mode[8]. Currently, the basic element of the fire detection system is usually a fibro-laser sensor, which is a line detector spanning the entire length of the tunnel. Such a sensor detects either a temperature rise above a certain threshold or an unusual rate of temperature rise[9]. The reaction time of fire detection

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[9] Siemens Switzerland Ltd.: FibroLaser III, Zug Switzerland, 2010.

systems should not exceed 60 s[10], but there are reports in the literature of cases where a fire developed latently for several minutes and the detection took place only after a few minutes[11].

As urban road traffic is characterized by high traffic density and frequent congestion, a large number of people can be expected to be at risk in the case of a fire in the urban road tunnel. Estimating this number and examining the course of the evacuation is a very complex task, because the actual evacuation experiment in the conditions of even a simulated fire is very dangerous for its participants. For this reason, as a rule, only partial experiments are carried out on selected aspects of the considered issues. For example, evacuation experiments are conducted in artificial smoke or darkened rooms[12]. High costs and organizational difficulties make it impossible to freely study many real configurations of the fire development process in a road tunnel, hence it seems natural to use numerical simulations to investigate this problem.

Actually, it consists of three sub-problems:

Depending on the traffic intensity a number of vehicles move through a tunnel. It is possible that a congestion has been formed just due to the specifics of the urban traffic.

At a moment an accident or a vehicle malfunction happens and the fire outbreaks, then the fire is developing. Eventually all vehicles are forced to stop.

After some time the fire is detected and the fire alarm is triggered, the tunnel entrance is closed and the evacuation begins.

As it can be seen, there are quite different phenomena, which should be taken into account to model reliably the entire sequence of events: road traffic simulation, fire development simulation and evacuation simulation.

3.2. Research description

The coupled numerical research was proposed to cope with this problem. Three different software packages were used sequentially to solve the sub-problems, as is shown in Figure 3.1. There are lots of simulation tools available, but after an inquiry

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[11] Aralt T.T., Nilsen, A.R.: Automatic fire detection in road traffic tunnels, Tunnelling and Underground Space Technology, 2009, Vol. 24, pp. 75–83; Król A., Król M.: Study on hot gases flow in case of fire in a road tunnel, Energies, 2018, Vol. 11, No. 13, pp. 1–16; Kashef A.Z., Viegas J., Mos A., Harvey N.: Proposed idealized design fire curves for road tunnels, in: 14th International Symposium on Aerodynamics and Ventilation of Tunnels, Dundee, Scotland 2011.

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three of them were selected. The results reliability and the relative ease of semi-automatic data processing (which was important for coupling) were into account. The commercial software VISSIM has been chosen for modeling of traffic jam formation[13]. The commonly used FDS (Fire Dynamic Simulator) program[14] was applied to model the fire development and the smoke spread. The evacuation modeling PATHFINDER program[15] was used to track the escape routes of evacuees and to check their touch with harming factors.

The input data for traffic modeling concerning the generic traffic structure were adopted according to the General Traffic Measurement carried out by the Polish General Directorate for National Roads and Motorways in 2015[16]. The assumed fire powers corresponded to typical vehicle fires referred in the literature – they ranged from about 4-6 MW for a passenger car to 70 NW for a HGV with a flammable load[17]. The typical bus fire gives about 24 MW. The vehicles manning was generated randomly to fit the average values obtained in real measurements[18]. The movement speed of the evacuees was described by the normal distribution, which accounted for different fitness of people[19]. It was assumed that direct eye-witnesses of the accident started to escape first, the others had to wait for emergency announcement[20].

As an outcome PATHFINDER provides files with an individual history of each evacuee. Hence there are data on location of each person and conditions at this position available second by second. It allows for determination whether a person was in any touch with harmful factors (somebody was exposed) or the harmful influence exceeded the allowed dose (somebody was endangered)[21]. Hence, the final results of each run of the coupled numerical simulations was the number of exposed or endangered persons.

[13] Ehlert A., Schneck A., Chanchareon N.: Junction parameter calibration for mesoscopic simulation in Vissim, Transp. Res. Procedia. 21, 2017, pp. 216–226.
[14]Cong W., Shi L., Shi Z., Peng M., Yang H., Zhang S., Cheng X.: Effect of train fire location on maximum smoke temperature beneath the subway tunnel ceiling. Tunnelling and Underground Space Technology, 2020, Vol. 97, 103282; Wang X., Fleischmann C., Spearpoint M.: Applying the FDS pyrolysis model to predict heat release rate in small-scale forced ventilation tunnel experiments, Fire Safety Journal, 2020, Vol. 112, 102946.
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[20]Seike, M., Kawabata, N., Hasegawa, M.: Experiments of Evacuation Speed in Tunnel Filled Smoke, Tunnelling and Underground Space Technology, 2016, Vol. 53, pp. 61–67.
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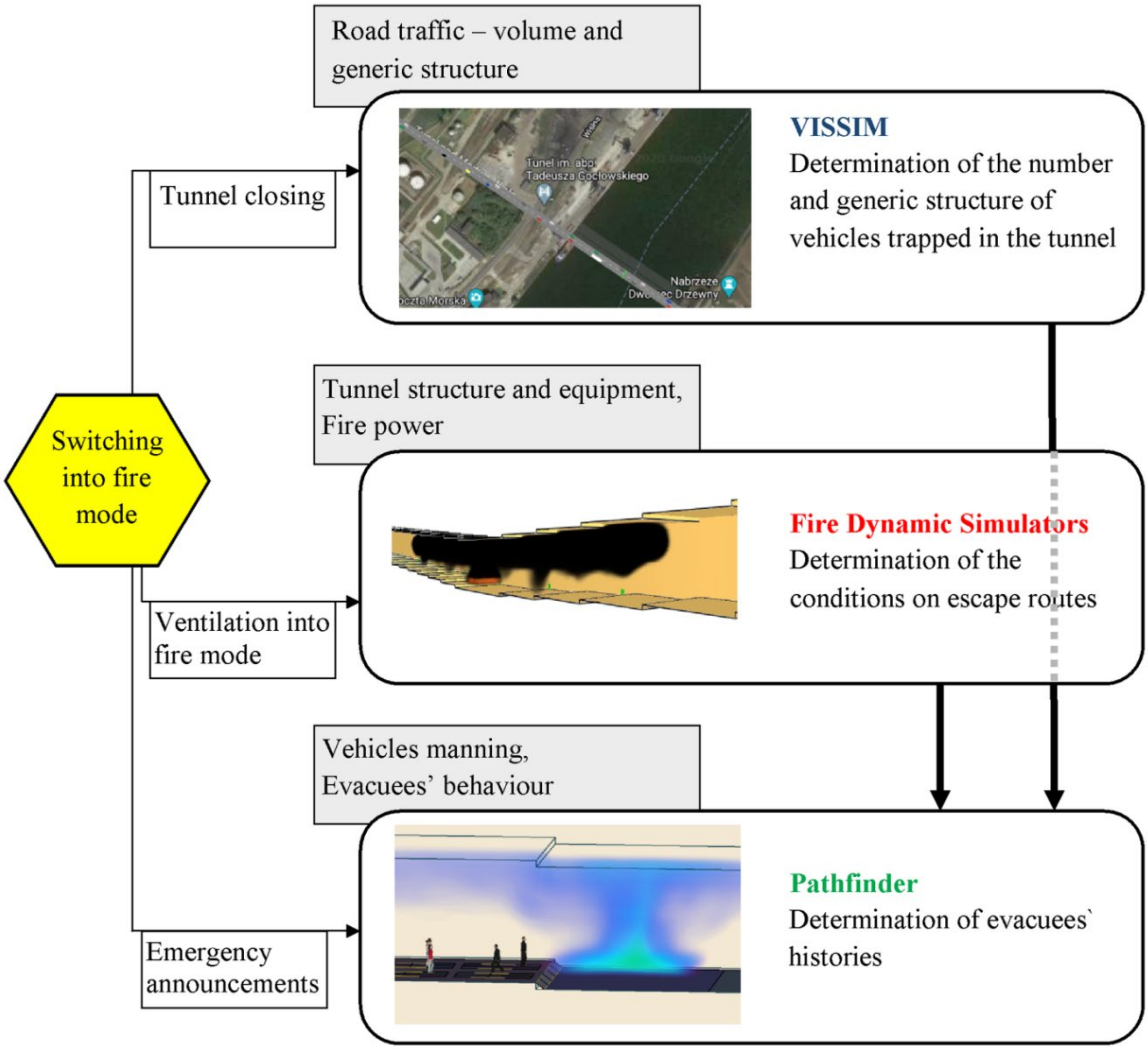

Fig. 3.1. Dataflow diagram of the coupled numerical simulations
Rys. 3.1. Schemat przepływu danych sprzężonych symulacji numerycznych
Source: Król A., Król M.: Numerical investigation on fire accident and evacuation in a urban tunnel for different traffic conditions. Tunnelling and Underground Space Technology, 2021, Vol. 109, 103751.

3.3. Results

The research was carried out in two stages. First, the general influence of different factors on the number of threatened people during a tunnel fire was examined, next a number of fire scenarios were studied for a selected real road tunnel.

A model of a typical tunnel was used in the first stage of the research. It was 680 m long and contained two lanes[22]. It was equipped with longitudinal or semi-transverse ventilation system: two axial fans were optionally supported by a number of fresh air supply vents, which were located just above the road surface (Fig. 3.2). In such system smoke was removed through one of the tunnel portals, the direction of fans' operation was generally in accordance with natural flow in the tunnel. In the semi-transverse configuration the vents supplied certain amounts of fresh air, which prevented the lowering of the smoke layer. The capacity of each fan was assumed as 20 m^3/s and the capacity of each vent was 1.5 m^3/s.

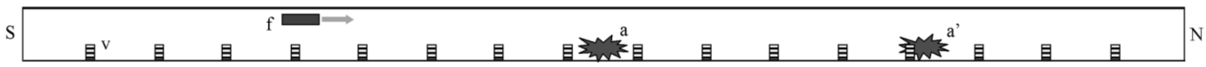

Fig. 3.2. The tunnel model (S and N – portals, f – axial fans, v – air supply vent, a and a' – alternative fire locations).
Rys. 3.2. Model tunelu (S i N – portale, f – wentylatory osiowe, v – otwory napowietrzające, a i a' – alternatywne lokalizacje pożaru.
Source: Król A., Król M.: The factors determining the number of the endangered people in a case of fire in a road tunnel. Fire Safety Journal, 2020, Vol. 111, 102942.

Even simplified analysis would require considering lots of possible configurations of a fire accident and reactions of tunnel systems. Hence, after a preliminary selection 6 variables were taken into account. Since each of them can take a number of states the Taguchi method of experiment design was used to cope with this issue. It was assumed that each factor took two values. Table 3.1 shows the considered factors and their values.

Table 3.1

The examined factors and their values

No	Factor	Acronym	Value 1	Value 2
1	Fire detection time	DT	60 s	120 s
2	Fire location	FL	in the middle	150 m from S portal
3	Ventilation system	VS	longitudinal	semi-transverse
4	Traffic mode	TM	uni-directional	bi-directional
5	Traffic conditions	LS	free traffic	congested
6	Fire power	FP	6 MW	24MW

Source: Król A., Król M.: The factors determining the number of the endangered people in a case of fire in a road tunnel. Fire Safety Journal, 2020, Vol. 111, 102942.

[22] Król A., Król M.: Study on hot gases flow in case of fire in a road tunnel, Energies 11 (13), 2018, pp. 1–16.

Since there were 6 factors taking 2 values, the numerical experiment was carried out according to scheme described by L8 orthogonal table. Due to random nature of the road traffic there were 6 simulations runs of VISSIM applied for each series, then the results were averaged. The detailed review of the results revealed that the main harmful factor was the smoke. The influence of the high temperature was negligible and it was limited to the narrow zone in the close vicinity of the fire. Therefore it might concern just the passengers of the vehicles directly involved in the fire event. Meanwhile the smoke was spreading very quickly and after a relatively short time was able to obscure people far from the fire. The logical scheme of the experiment and the results are shown in Table 3.2.

Table 3.2

The results of the first stage

Series	DT	FL	VS	TM	LS	FP	Total	Exposed	Endagered
1	1	1	1	1	1	1	74±33	5±8	0
2	1	1	1	2	2	2	275±53	79±36	22±14
3	1	2	2	1	1	2	81±30	11±4	0
4	1	2	2	2	2	1	246±63	2±1	1±0
5	2	1	2	1	2	1	231±44	53±30	4±8
6	2	1	2	2	1	2	102±41	76±32	15±4
7	2	2	1	1	2	2	260±38	83±27	31±19
8	2	2	1	2	1	1	116±32	55±43	9±8

Source: Król A., Król M.: The factors determining the number of the endangered people in a case of fire in a road tunnel. Fire Safety Journal, 2020, Vol. 111, 102942.

As it can be seen the values differ significantly from one another, which proves the importance of analyzed factors. A relatively high value of standard deviation suggest also the values are scattered for each series. It resulted mainly from the random structure of the formed congestion. Especially high numbers of exposed or endangered people were caused by the presence of a bus or buses among trapped vehicles. The presented values were further processed according to the Taguchi idea: they were averaged for every factor and for every level to find out the individual contribution of the factors. The results are shown in Figures 3.3 and 3.4 – for each factor the left point corresponds to value no 1, the right one to value no 2.

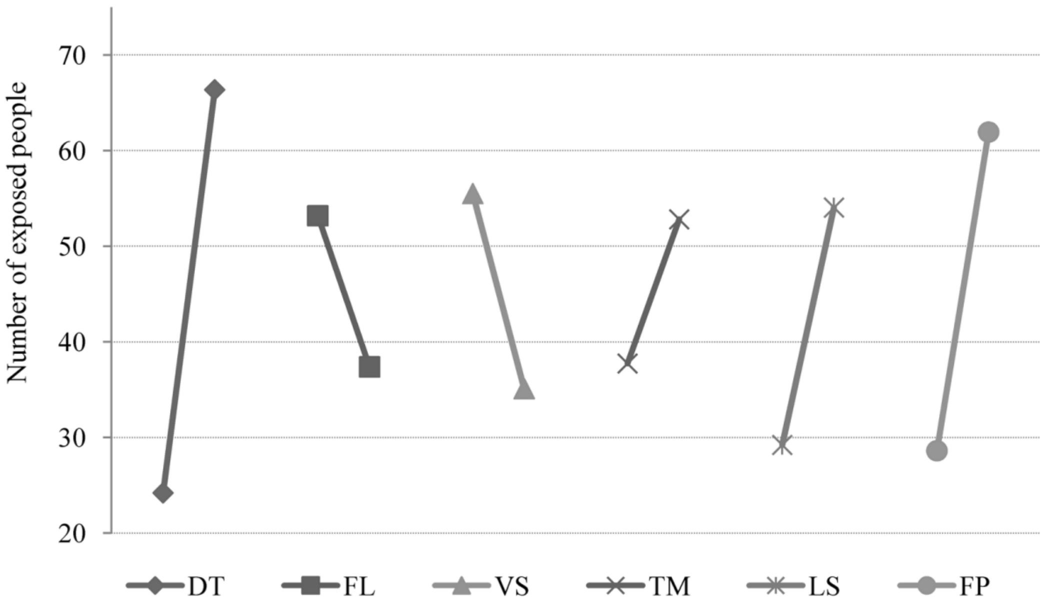

Fig. 3.3. Impact of the examined factors on the number of exposed people
Rys. 3.3. Wpływ badanych czynników na liczbę ludzi narażonych
Source: Król A., Król M.: The factors determining the number of the endangered people in a case of fire in a road tunnel. Fire Safety Journal, 2020, Vol. 111, 102942.

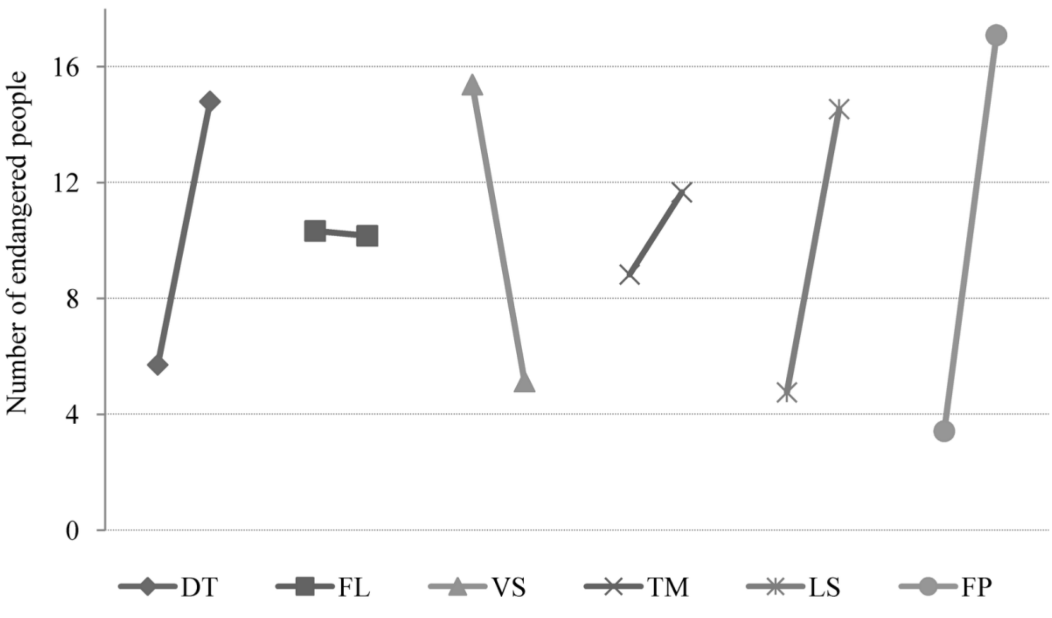

Fig. 3.4. Impact of the examined factors on the number of endangered people
Rys. 3.4. Wpływ badanych czynników na liczbę ludzi zagrożonych
Source: Król A., Król M.: The factors determining the number of the endangered people in a case of fire in a road tunnel. Fire Safety Journal, 2020, Vol. 111, 102942.

Although the values are different, both figures lead to almost the same conclusions. The most important factors are the fire power and the detection time. When just the number of exposed people is considered the detection time prevails, because the quick detection allows most people to avoid any touch with the harmful influence. According to the expectations the traffic intensity is important as well – simply for more intense traffic more people has been trapped inside the tunnel. A bit astonishing is the significant impact of ventilation system applied – the semi-transverse ventilation system is required by regulations only for tunnels longer than 3000 m, meanwhile if applied it drastically decreases the number of endangered people even for a relatively short tunnel. It was because the supplied fresh air kept a larger space free of smoke and thus allowed the evacuees to avoid any touch with it.

At the second stage of the research a number of fire scenarios was considered for a real urban tunnel. The analysis were carried out for the road tunnel located in Gdansk (Poland). It goes under the Vistula river from North-West towards South-East and connects the downtown with the harbor zone. It consists of two tubes of length of 1378 m with two lanes for each tube. The tube cross-section is 7.03 m high and 10.09 m wide. The vertical profile of the tunnel is v-shaped, the longitudinal inclinations are 3% for NW part and 4% for SE part and the deepest point lies 33 m under the river surface. Each tube is equipped with semi-transverse ventilation system, which consists of 11 axial fans placed every 95 m and 22 air supply vents. The thrust of axial fans is 1200 N in the normal direction and 407 N in the reversed mode.

The analysis involved three factors: fire detection time, fire power and traffic state. The fire was assumed to be located at the deepest point, just in the middle of the tunnel. Since it was shown previously that low fire power doesn't usually pose a big threat to the people in tunnel just high and very high fire powers were considered. The detailed list of examined cases is presented in Table 3.3.

Table 3.3

Cases being examined

Code	Fire detection time (s)	Traffic state	Fire power (MW)
ACE	60	Free	29
ACF	60	Free	70
ADE	60	Congested	29
ADF	60	Congested	70
BCE	120	Free	29
BCF	120	Free	70
BDE	120	Congested	29
BDF	120	Congested	70

Source: Król A., Król M.: Study on hot gases flow in case of fire in a road tunnel, Energies 11 (13), 2018, pp. 1–16.

The data on the road traffic concerning its generic structure, intensity and vehicles speed were obtained from tunnel supervising system and were shared for the research by Road and Greenery Management (ZDiZ) Gdansk. As previously six VISSIM simulation were carried out for each case, which allowed for accounting for the random nature of the road traffic. The results in form of the average number of endangered people are shown in Figure 3.5.

Just at first glance one can see, that there are three clear groups. The first group contains cases (ACE, BCE, ACF, ADE) with rather small number of exposed people. This corresponds to favorable accident conditions: lower fire power, quick fire detection or non-congested traffic. For the second group (BDE, ADF, BCF) the number of exposed people is about hundred. Here the impact of two threatening factors makes an unfavorable tangle. The third group consists of only one case (BDF), in which the coincidence of all danger factors have a disastrous influence and results in a huge number of threatened people.

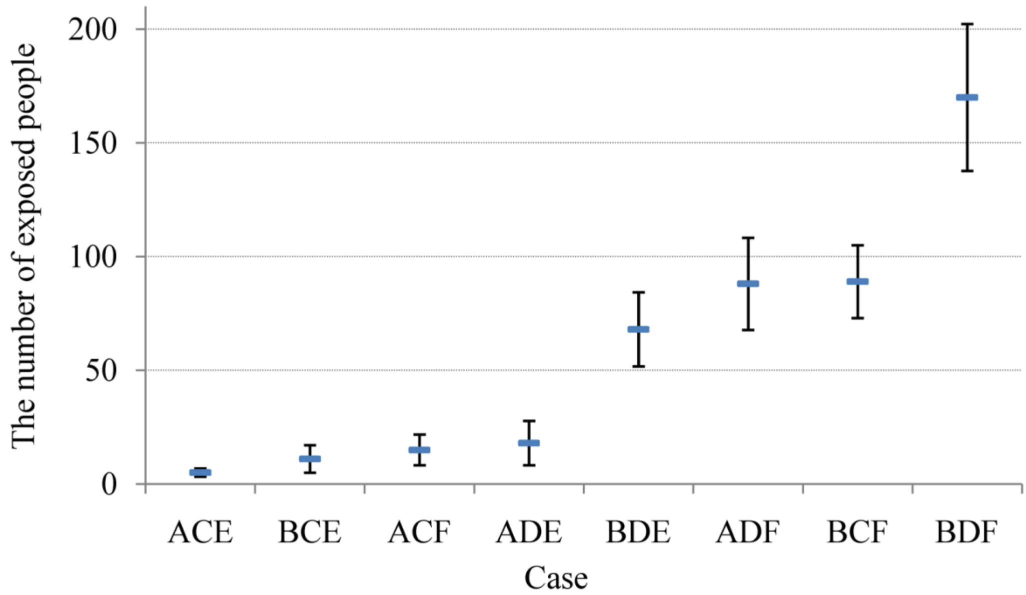

Fig. 3.5. The average number of exposed people for all cases
Rys. 3.5. Średnia liczba ludzi narażonych dla wszystkich przypadków
Source: Król A., Król M.: Study on hot gases flow in case of fire in a road tunnel, Energies 11 (13), 2018, pp. 1–16.

3.4. Conclusions

In large modern cities, traffic is often routed through tunnels. This solution is beneficial to the quality of urban space, but brings specific risks. The chapter presents the numerical research on the safety level of users in urban road tunnels during a fire outbreak. The novelty of the work is to apply the coupled numerical simulation for reliable modeling the entire process. First road traffic simulator VISSIM was used to model the congestion formation, then FDS software modeled the fire development and smoke spread and finally PATHFINDER provided the results in the form of individual histories of all evacuees. This allowed for finding the impact of the selected factors on the number of exposed and endangered people.

Although the results significantly fluctuated due to the random nature of road traffic a number of clear conclusions can be stated:

- A delayed fire detection resulted in an increased number of exposed people – time is the main factor during the evacuation.
- Smoke is the most danger factor – it is spreading quickly and affects people even far from the fire event.
- For congested traffic the number of exposed people may be very high, however just few of them are in a real danger.
- Very high power fires are especially danger because in such cases large amounts of smoke are produced.
- If unfavorable circumstances are entangled the number of endangered people may be very high.
- The fire location in the tunnel is of minor importance.
- If a bus or a number of buses are involved in a fire accident the number of threatened people significantly increases – it is due to the prolonged time needed to leave the bus.

Since the time factor appeared to be crucial, the ability to self-evacuate efficiently plays the most important role in the initial stage of the fire. This requires at least basic knowledge on proper evacuation procedures[23].

[23] Schmidt-Polończyk, N., Wąs, J., & Porzycki, J. (2021). What is the knowledge of evacuation procedures in road tunnels? survey results of users in Poland. Buildings, 11(4), 146.