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SIMULATION OF THE EVACUATION OF PEOPLE IN A ROAD TUNNEL IN THE EVENT OF FIRE – CASE STUDY

This paper provides an analysis of the evacuation process in a road tunnel in the event of a fire, using the example of the tunnel under the Luboń Mały mountain currently being constructed on Expressway S7's Lubień – Rabka-Zdrój section. As fires are the largest and most dangerous events occurring in road tunnels, it is important to predict the evacuation process as early as at the design stage. The study described here used numerical modelling to simulate evacuation, which made it possible to determine the required safe evacuation time of all tunnel users in a fire.

On the basis of the parameters of the tunnel under Luboń Mały, numerical studies were performed for four different fire scenarios, three of which assumed various fire locations with the currently designed two traffic lanes. The fourth variant accounted for the planned extension of the roadway to include three traffic lanes. Eventually, four numerical models were developed involving various fire ignition locations and numbers of potential tunnel users. The values of initial-boundary conditions used in the simulation, such as movement speed during evacuation, shoulder breadth and pre-movement time, were specified on the basis of experimental data for an evacuation performed in smoke conditions in the Emilia tunnel in Laliki.

The results lead to the conclusion that if the time of reaching critical conditions in the tunnel is not shorter than 5 minutes 40 seconds for the current design state and 5 minutes 47 seconds for three lanes, the distribution of evacuation exits in the tunnel under Luboń Mały will ensure safe evacuation.

Keywords: safety, simulation, evacuation, road tunnels

1. Introduction

Recent years have seen an increased interest in the construction of tunnels both in road and rail transport. Aspects such as the country's economic development has led to the rising number

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of road users and, consequently, higher demand for new transport networks and the development of the existing routes.

Road tunnels are complex structures and an enormous amount of planning and resources is required to design and construct them. Many countries in the world, including Western European countries, have a long tradition and considerable experience of constructing them. Bearing in mind that an increasing number of tunnel construction projects are expected to be implemented in Poland in the near future, it seems important to focus on the safety-related aspects. Despite the clear advantages of building roads underground, there are a number of negative factors coming into play during their use. These primarily include the risks present in tunnels, particularly of heavy fires and accidents. A rigorous analysis of safety in road tunnels, both at the design stage and during use, is extremely important in the context of ensuring the safety of drivers and passengers travelling in tunnels.

The purpose of this paper is to conduct an analysis of the process of fire evacuation of potential drivers and passengers from the tunnel under Luboń Mały. For this purpose, numerical methods were used to model the analysed engineering structure, adopting the initial-boundary conditions corresponding to four fire scenarios. The study makes it possible to estimate the time needed to evacuate all tunnel users in a fire, taking into account the actual geometric parameters of the structure and behaviour during evacuation adopted on the basis of experimental studies in one of the completed road tunnels in Poland.

2. Risks for road tunnel users

The use of road tunnels involves risks to the health or life of users, e.g. elevated concentrations of harmful solid and gaseous pollutants, vehicle collisions, toxic substance leakage, etc. In terms of the scale of risks, fires are by far the largest and most dangerous events potentially occurring in tunnels. According to statistics, they are not very common, but their consequences in the partly-enclosed area of a tunnel might be much more serious than when they occur at open transport routes [1]. Unlike fires in the open, a fire in a space partly-enclosed, such as a road tunnel, can develop in a sudden and rapid manner. There is an added possibility of the fire spreading to other vehicles, increasing the fire intensity, such as in 2001 in the St. Gotthard tunnel [2]. 86 fatalities, 68 injured people, and 100 damaged vehicles are the total casualty figures for just four road tunnel fires: Mont Blanc, St. Gotthard, Tauren and Wuxi Lihu. These data demonstrate the grave danger of such events and much higher risk levels associated with them than with transport accidents in the open [3].

A tunnel fire may continue for several days and cause tremendous losses not only in material goods and tunnel structure, but also in the surrounding area, greatly diminishing its transport and tourist potential, such as after the Mont Blanc Tunnel fire of 1999. It took more than 50 hours to extinguish the blaze and it was three years later that the tunnel was finally reopened. The most dramatic loss, however, was the death of 39 people [2].

In the context of potential fires in road tunnels, ensuring safe evacuation is a priority. By definition, this process should involve the organised movement of people to a safe place in the event of a fire or other hazard. To be successful, evacuation must be performed as fast as possible. Due to the specific nature of road tunnels, the very first moments after the fire starts are the most important, as the conditions inside the tunnel still allow safe evacuation. When the conditions become critical and at least one of the parameters specified in British Standard (visibility, air temperature, temperature of fire gases, heat flux density and oxygen content) is exceeded, danger to the health and life of evacuees increases [4].

Predicting human behaviour during escape from the tunnel is difficult, as there is a large number of possible evacuation scenarios. They depend on the geometrical parameters of the structure, the number of people inside, the location where the danger occurs, the ventilation system, the method of alerting and the nature of the threat. This makes computer simulation techniques based on numerical methods very valuable, as they make it possible to study the evacuation process at the design stage [5,6].

3. Case study

The driver safety analyses during a fire were performed for the tunnel Luboń Mały being under construction with a specification of the evacuation time for its potential users. Predicting the duration of self-rescue actions is an essential part of the actions aimed at ensuring safety in emergency situations. However, it is a complex problem affected by a number of interdependent factors. The evacuation process is considered safe when the so-called safe escape time criterion is met [4], i.e. when the available safe escape time (T_{ASET}) is bigger or equal the required safe escape time (T_{RSET}). Numerical modelling was used to determine the time from fire initiation to the moment in which the set number of people in the tunnel manages to evacuate to safety (the required safe evacuation time T_{RSET}). This time should be shorter than the time after which the conditions inside the structure or its part become dangerous to its users [4]. Identifying the time when environmental conditions that pose a risk to the health and life of people appear (T_{ASET}) is a separate research subject that is outside the scope of this paper, however to pre-verify the safe escape time criterion, the value of T_{RSET} was calculated from the plane equation determined on the basis of the results form numerical studies [7]. The required safe evacuation time is the sum of detection time, alarm time, alarm recognition time by the tunnel users (pre-decision), response time (decision and selection of evacuation route) and the travel time along the evacuation route to a safe place [8].

The highly unpredictable factor of human behaviour in crisis situations which can affect the final value of T_{RSET} is also important. Behaviour of people during an evacuation in a road tunnels in case of fire was the scope of various studies focusing on different aspects [9,10], [11]. Different critical incidents in road tunnels, including situation with smoke when people stayed in their cars surrounded by smoke were described in [12]. Fridolf et al. analysed correlations between walking speed and visibility coefficients measured in the real tunnels [13]. During the evacuation studies conducted in the Polish tunnel Emilia in Laliki it was observed that in dangerous situations (fire) people have the tendency to stay in their initial roles (e.g. of a passenger) until they become aware of the serious nature of the situation and receive clear information on how to proceed [14]. Similar behaviour was observed during fires in such tunnels as the King's Cross Tunnel [15], in the Zürich Metro [16] or in the Mont Blanc Tunnel [2]. Such behaviour might delay evacuation and is difficult to predict.

Choosing the right method to simulate the evacuation process requires paying attention to a number of parameters of individual tools. Thanks to the research of specialists dealing with the issues of modelling human behaviour during evacuation, it is possible to choose one of the best rated methods. It was decided to use the Pathfinder program, because this tool is one of the three best-rated numerical modelling tools [5,6].

The research objective was approached using the Pathfinder software, which was used to calculate evacuation times. This advanced crowd behaviour simulator based on numerical methods employs artificial intelligence algorithms in its calculations. Numerical calculations were performed using Pathfinder's steering mode. In this mode, occupants (agents) moving in the model use a steering system to maintain an appropriate speed and distance in relation to others, treating each other as obstacles. This mode does not allow agents to interpenetrate and takes into account the interactions and collisions between occupants during egress. This facilitates the simulation of complex human behaviour, allowing the user to create a model with similar parameters as the actual evacuation process. A detailed description of the software is provided in its technical documentation [17,18].

3.1. Parameters of the tunnel under Luboń Mały

The tunnel under Luboń Mały lies along expressway S7's Lubień – Rabka-Zdrój section. This engineering structure is planned to be constructed directly under the Luboń Mały massif. The need to bore a tunnel for a section of expressway S7 results from the presence of considerable elevation differences. The steep slope of the Luboń Mały massif would require drastic speed reductions for vehicles if the road were to run on the surface.

The road tunnel will feature two parallel tubes housing one-way carriageways of expressway S7. Each carriageway will consist of two 3.5 m-wide lanes, 2.5 and 3 m-wide hard shoulders and lay-byes in the middle of the tunnel's length. It is planned to widen the carriageway to include three traffic lanes 3.5 m-wide each in the future. The two tunnel tubes will be connected by 11 cross passages at distances of 172.5 m, which will be used as evacuation exits. Each cross passage will be 15 m of length and dimensions of the evacuation exits will provide to keep inside them extreme of 2.5 m of the height and the width. In addition, fire signalling, alarm and emergency call niches will be placed every 172.5 m in the outer walls of the naves. Evacuation exits will be equipped with double fire-rated doors. The width of each leaf will be 1.2 m and height 2.2 m. One leaf will be opened towards the evacuation exit and the other towards the tunnel tube. This will allow evacuation in each direction depending on the location of the fire. In an emergency situation the tunnel users will evacuate to the nearest emergency exit leading to the other tube or directly outside through the tunnel portal, depending on the location of the source of danger or situation. The evacuation exits will be appropriately lit and marked to facilitate egress. In the case of a fire in one tunnel tube, the other tube will serve as the evacuation tunnel and access road for rescue and firefighting vehicles. The emergency vehicle passage constructed in the central part of the tunnel (in the middle of the tunnel, ~1 km of tunnel length) will enable the rescue and fire services to reach the fire location from the unaffected tunnel tube. The gate will consist of two leaves with a total width of 3.5 m and height of 3.3 m. The gate will also feature doors with parameters identical to the ones used in emergency passages. The total width of the section in the opening of the final casing will be 14.9 m. The cross-section of the tunnel under Luboń Mały, which takes into account the dimensions of the individual carriageway elements, is presented in Fig. 1 [19].

The road grade line in the tunnel runs at an even longitudinal downward slope of 0.5% from north to south. The total length of the road tunnel will be approx. 2058 m. The road tunnel under Luboń Mały will be ventilated using a transversial ventilation system, which will ensure appropriate environmental conditions inside the structure during its operation.

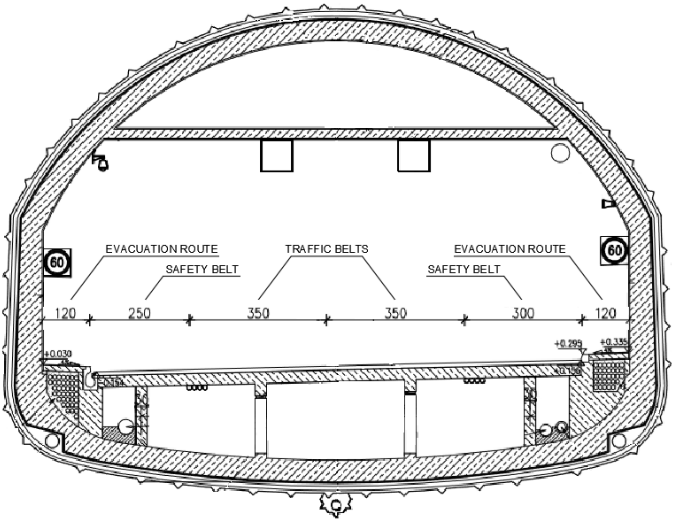

Fig. 1. A schematic showing the cross-section of the tunnel under Luboń Mały [19]

3.2. Fire scenario parameters

Numerical tests were performed for four different scenarios. Three fire scenarios for the current tunnel parameters featuring different fire locations were developed. In addition, scenario IV analysed evacuation for the tunnel with three-lane carriageways, 3.5 m each. This scenario involved the most critical fire location (selected on the basis of simulation results – the longest evacuation time), taking into account a larger number of tunnel users. Eventually, four numerical models were developed involving various fire ignition locations and numbers of potential tunnel users.

3.2.1. Scenario I

The first fire scenario assumes the ignition location 170 m from the tunnel entrance, i.e. beyond the northern portal in the carriageway towards Zakopane. Two detailed fire locations were considered – between the emergency exits and at the level of the exit [7]. Eventually, the more unfavourable fire scenario was chosen – located at the level of one of the emergency exits. In this scenario, the emergency exit gets blocked and persons evacuating from the danger area must proceed to the next nearest emergency exit. According to this the evacuated persons left the danger area through the tunnel portal – Fig. 2. It was assumed that the fire was caused by a technical fault (vehicle overheating) or an accident (collision). The traffic intensity was specified as very high, which resulted in slowed-down traffic. A large number of cars were present in the tunnel. Due to the traffic jam, the distance between the vehicles should not be lower than 5 m pursuant to the Road Traffic Act of 20 June 1997, which is why the numerical model assumed this value of distance as the more unfavourable but possible scenario. The data on the proportion of individual motor vehicle categories in annual average daily traffic on national roads prepared in 2015 by GDDKiA (the General Directorate for National Roads and Motorways), were used to prepare a breakdown by type and average dimensions of motor vehicles and to estimate the number of vehicles in the tunnel, including the approximate number of users for each scenario. Table 1 presents the detailed data. It was also assumed (for each scenario) that cars located beyond the ignition location will leave the tunnel, so the individuals located in those cars are not included in the simulation. Fig. 2 presents an overall schematic of the situation for scenario I.

TABLE 1

Data on the number of users located in the danger area for scenario I

Vehicle	Motorcycle	Passenger car	Heavy goods vehicle	Heavy goods vehicle with trailer	Coach
Percentage share of vehicle type [%]	0.50	80.00	11.50	6.50	1.50
Vehicle length [m]	2	5	10	18	12
Average number of passengers/vehicle	1	3	1	1	50
Estimated number of vehicles in the tunnel	0	23	4	2	0
Estimated number of passengers in the tunnel	0	69	4	2	0
The total estimated number of evacuees				75	

[*Source:* own study]

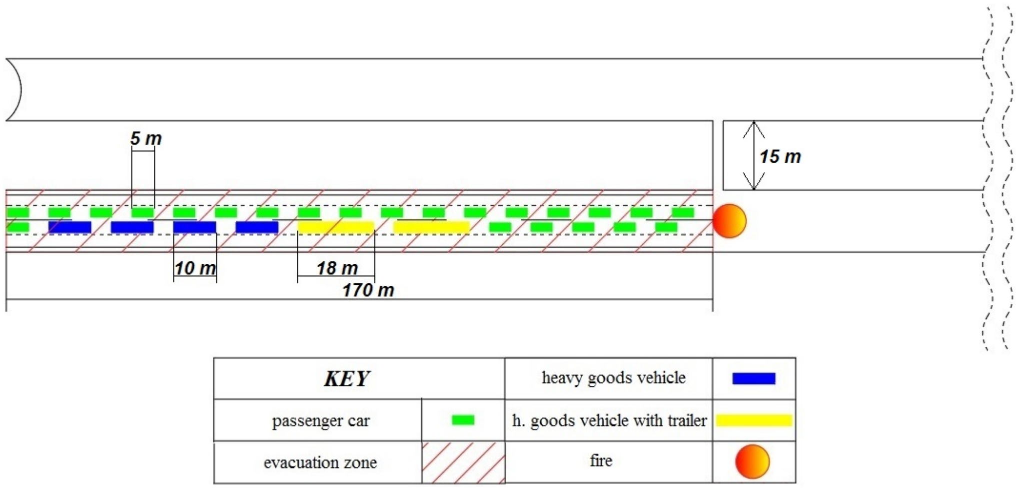

Fig. 2. An overall schematic of the fire situation in the tunnel for scenario I
[*Source:* own study]

3.2.2. Scenario II

The second fire scenario assumes the ignition location 1025 m from the tunnel entrance, i.e. beyond the northern portal in the carriageway towards Zakopane. The location of the fire resulted in the unavailability of one of the emergency exits near the fire – Fig. 3, so users start evacuating through 6 lateral emergency exits leading to the second tunnel tube or directly outside the tunnel through its entrance portal. To calculate number of vehicles and passengers in the tunnel identical parameters were adopted as for scenario I (i.e. the percentage share of vehicle type in tunnels, vehicle length). Table 2 presents the detailed data.

TABLE 2

Data on the number of users located in the danger area for scenario II

Vehicle	Motorcycle	Passenger car	Heavy goods vehicle	Heavy goods vehicle with trailer	Coach
Estimated number of vehicles in the tunnel	1	144	20	11	3
Estimated number of passengers in the tunnel	1	432	20	11	150
The total estimated number of evacuees				614	

[*Source:* own study]

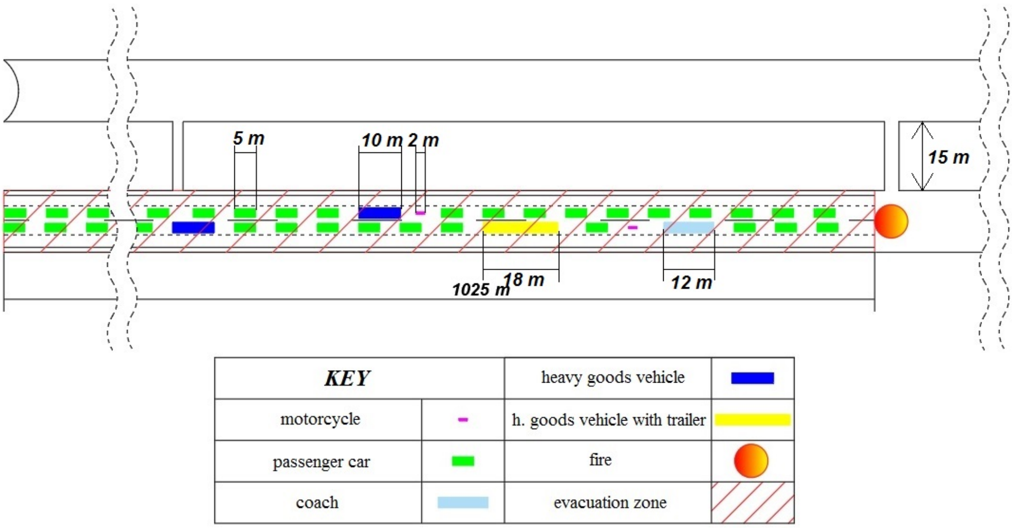

Fig. 3. An overall schematic of the fire situation in the tunnel for scenario II
[*Source:* own study]

3.2.3. Scenario III

The third fire scenario assumes that the fire breaks out 1885 m from the tunnel entrance portal. The location of the fire causes a blockage of one of the emergency exits – Fig. 4. This scenario adopts identical parameters for risks as scenarios I and II. Once again, the number of motor vehicles located in the tunnel with a breakdown by type and the approximate number of users were estimated. Table 3 and Fig. 4 present the detailed data.

TABLE 3

Data on the number of users located in the danger area for scenario III

Vehicle	Motorcycle	Passenger car	Heavy goods vehicle	Heavy goods vehicle with trailer	Coach
Estimated number of vehicles in the tunnel	2	264	38	20	5
Estimated number of passengers in the tunnel	2	792	38	20	250
The total estimated number of evacuees				1102	

[*Source:* own study]

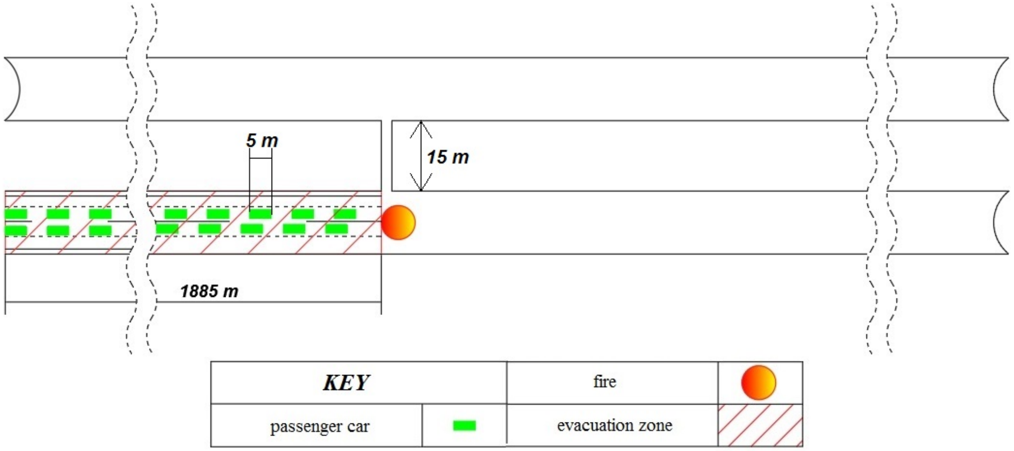

Fig. 4. An overall schematic of the fire situation in the tunnel for scenario III
[*Source:* own study]

Tunnel users started evacuation by proceeding to the nearest emergency exit – one of the 10 lateral emergency exits leading to the second tunnel tube (the 11th exit was blocked by the fire) and directly outside the tunnel through its entrance portal.

3.2.4. Scenario IV

The location of the fire in scenario IV is the same as in scenario III. The current scenario takes into consideration the future plans of extending the tunnel's carriageway to feature a third lane, which will lead to higher vehicle traffic and increase the number of tunnel users. The location of the fire caused the blockage of one of the emergency exits, so users left the tube in the danger area through 10 lateral emergency exits and through the tunnel's entrance portal. Table 4 shows the estimated number of people in the area affected by fire. The remaining parameters and assumptions regarding the progress of the risks are identical as for the previous scenarios.

TABLE 4

Data on the number of users located in the danger area for scenario IV

Vehicle	Motorcycle	Passenger car	Heavy goods vehicle	Heavy goods vehicle with trailer	Coach
Estimated number of vehicles in the tunnel	3	390	57	32	8
Estimated number of passengers in the tunnel	3	1170	57	32	400
The total estimated number of evacuees				1662	

[*Source:* own study]

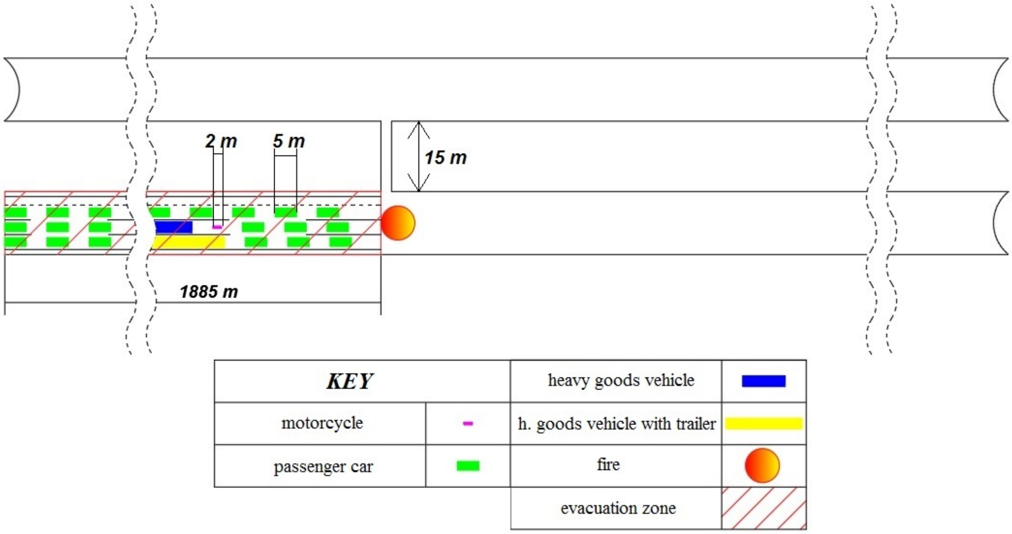

Fig. 5. An overall schematic of the fire situation in the tunnel for scenario IV

3.3. Initial-boundary conditions

The preparation of the numerical model required assigning each "evacuating person" a set of individual parameters such as movement speed, shoulder breadth and pre-movement time. These parameters were assigned on the basis of experimental studies of evacuation from a coach in smoke conditions conducted in the Emilia tunnel in Laliki [14]. The experiment involved 50 participants. It consisted of four tests and the individual properties of agents were assigned on the basis of the first one. During the first test, the participants did not receive any information on the exact purpose of the visit, the course of the study, the rules of conduct in a tunnel, the presence of smoke and tunnel infrastructure (the presence and distribution of emergency exits, the place where the coach stops). The coach running directly from Kraków entered the tunnel to achieve the element of surprise among the participants in the experiment, so the first test was selected as the closest to real-life situations. Table 5 presents the agents' movement speed and shoulder breadth parameters adopted for the numerical model.

TABLE 5

The parameters of movement speed and shoulder breadth of agents adopted for the numerical model [14]

Agent parameters	Minimum value	Maximum value	Mean value	Standard deviation
Movement speed **(m/s)**	0.895	1.211	**1.056**	0.083
Shoulder breadth **(m)**	0,38	0,56	**0,482**	0,04669

Pre-movement time, which is the sum of alarm recognition time by the tunnel users (before making the decision) and their reaction time (making the decision and selecting the evacuation route) was identified on the basis of the first test in the evacuation experiment in Laliki. It should be added that the said evacuation experiments took into account very similar conditions to those of a real fire – there was smoke in the tunnel (cold, non-toxic smoke) and the fire procedure was launched, involving e.g. fire lighting, voice announcements and the alarm signal. When the alarm had been activated the study participants did not take any action related to leaving the coach. The voice announcement issued during the fire procedure probably "encouraged" the first participants to make the decision to leave the vehicle (after 27 seconds). This demonstrates that these individuals recognised and correctly interpreted the fire alarm. However, another 23 seconds were needed for all people to decide to leave the vehicle. On this basis the maximum alarm recognition time was assumed as 50 seconds, which is understood as the time counted from the moment of activating the fire alarm to the moment of reaction, i.e. making the decision to leave the vehicle. After that these individuals left the coach and proceeded in the direction of one of the emergency exits, which is connected with reaction time. The first person needed only 10.5 seconds after recognising the alarm to leave the coach and proceed to the exit, while the last

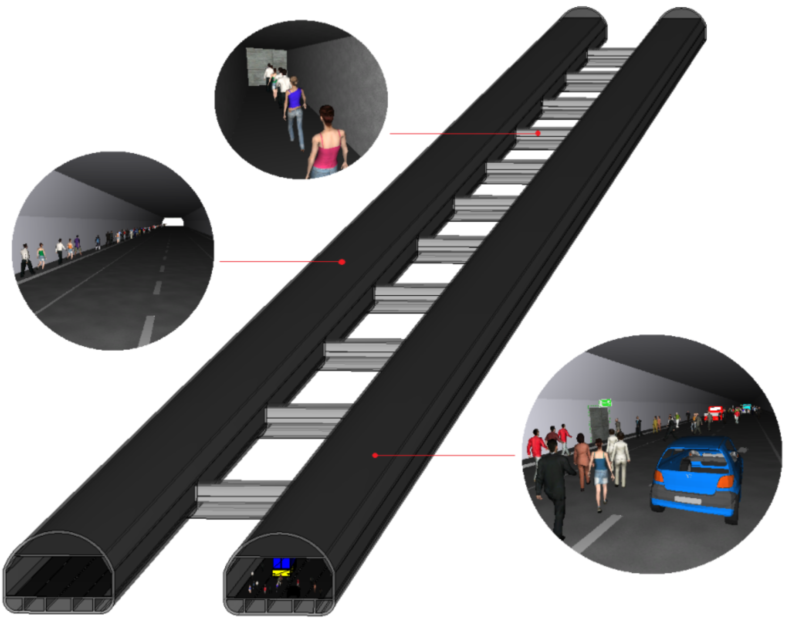

Fig. 6. The geometric model of the road tunnel along with a visualisation of the simulation results [*Source:* own study]

person took 82.5 seconds. For this reason, the total pre-movement time for the numerical model was assumed to be within the range of 37.5 seconds – 132.5 seconds (M = 86.6, SD = 27.92), as observed in the evacuation experiment [14]. Individual parameters and pre-movement times were assigned to agents in the numerical model on the basis of normal distribution.

The next stage involved setting the alarm and fire detection times. The former defines the time interval from ignition to detection by detection systems, the tunnel operator or tunnel user. The latter is the time needed to process the impulse about the event by the signalling system and finally to activate the fire alarm. In accordance with the design parameters, the total fire detection and alarm time of 60 seconds was adopted [19].

In the geometric model, tunnel parameters such as length and width, the distribution and width of emergency exits, the location and width of the passage for rescue services, etc. were adopted in accordance with the existing design state. In addition, the model accounted for vehicles that will be abandoned by tunnel users during the fire, becoming obstacles during evacuation – Fig. 6. As a result, evacuees must go around these vehicles, which also affects evacuation time. In Pathfinder simulation evacuees are moving with the locally shortest possible escape route choosing closest available emergency exit.

3.4. Numerical calculation results analysis

Evacuation times resulting from the calculations performed in Pathfinder software can differ on a case-by-case basis for the same scenario. This difference largely results from the random distribution of users in the geometric model. To obtain a representative value for evacuation time, the simulations were run twenty times for each scenario. A total of 80 computer simulations were performed, each time with a different random distribution of agents in the tunnel.

The simulated average time of evacuation ($T_{Pathfinder}$) resulting from a series of numerical calculations using Pathfinder software for the first fire scenario was 275.2 seconds (SD = 16.3) – Fig. 7. Taking into account the fire detection and alarm times it can be stated that the first person evacuated after 114.4 seconds and the required safe egress time after which all tunnel users managed to leave the danger area was 335.2 seconds. Due to the location of the fire, the users

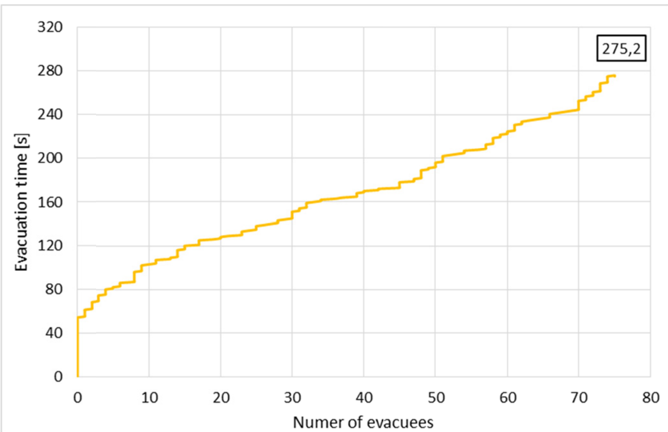

Fig. 7. Evacuation times for scenario I

left the danger area through the tunnel's entrance portal. The flow rate through the available emergency door was 0.34 people/s – table 6.

TABLE 6

Data for the evacuation of people for scenario I

Available exit doors		**North portal**
Evacuees		75
Average flow [per./s]		0.34
Time [s]	first	54.4
	last	275.2

For scenario II, assuming that fire ignition occurred 1025 metres from the tunnel's entrance portal, the average simulated movement time $T_{Pathfinder}$, being the result of a series of numerical calculations, was 277.0 seconds (SD = 10.5) – Fig. 8. The average required safe evacuation time T_{RSET}, after which all tunnel users left the tunnel tube with the danger area was 337.0 seconds (taking into account the fire detection and alarm times). Self-rescue actions involved 6 emergency exits. Table 7 presents detailed data for the evacuation of people through the available exits.

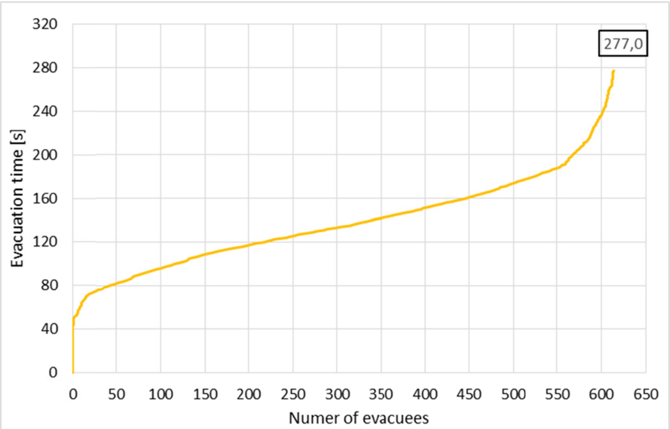

Fig. 8. Evacuation times using the available emergency exits for scenario II

TABLE 7

Data for the evacuation of people for scenario II

Available exit doors		North portal	Exit 1	Exit 2	Exit 3	Exit 4	Exit 5
Evacuees		43	102	107	92	103	167
Average flow [per./s]		0.32	0.63	0.67	0.56	0.66	0.76
Time [s]	first	57.3	50.1	52.3	43.4	52.3	58.9
	last	190.8	211.1	211.8	207.4	208.9	**277.0**

For scenario III, assuming fire ignition 1885 metres from the tunnel's entrance portal, the average simulated movement time $T_{Pathfinder}$ was 281.3 seconds (SD = 12.32). Fig. 9 and table 8

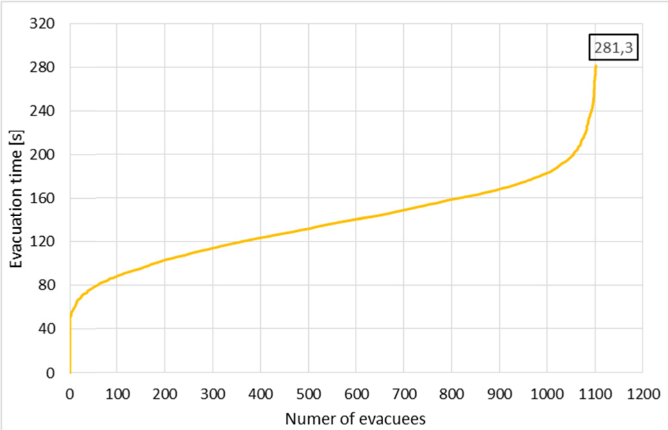

Fig. 9. Evacuation times using the available emergency exits for scenario III

TABLE 8

Data for the evacuation of people for scenario III

Available exit doors		**North portal**	**Exit 1**	**Exit 2**	**Exit 3**	**Exit 4**	**Exit 5**	**Exit 6**	**Exit 7**	**Exit 8**	**Exit 9**	**Exit 10**
Evacuees		48	101	105	116	81	79	121	108	97	113	133
Average flow [per./s]		0.36	0.72	0.83	0.88	0.61	0.53	0.81	0.72	0.62	0.72	0.59
Time [s]	first	60.4	61.6	67.4	72.2	58.8	67.7	68.4	51.8	57.6	51.7	52.8
	last	193.9	202.6	193.6	204.7	192.2	215.8	218.0	201.1	214.4	208.8	**281.3**

presents the detailed simulation results. The average required safe egress time T_{RSET}, after which all tunnel users left the tunnel tube with the danger area was 341.3 seconds.

The required safe egress time for scenario IV was $T_{RSET} = 346.8$ seconds, ($T_{Pathfinder} = 286.8$ seconds, SD = 7.6) – Fig. 10. in which the fire started approx. 172 metres from the tunnel exit, but for the planned future three lanes in the road tunnel. The number of exits available for evacuation is the same as in scenario III. The density of tunnel users increased in comparison to the first scenario (0.04 people/m^2) and reached 0.06 people/m^2. Table 9 presents the detailed evacuation data.

The longest evacuation times for two lanes were obtained for scenario III and this ignition location variant was considered the most unfavourable during evacuation.

The longest egress time for all analysed cases was obtained for scenario IV. The 50% increase in the number of evacuees in scenario IV in comparison to scenario III led to a 5.5-second increase in evacuation time. This relatively small increase is caused by such factors as the distribution of agents along the tunnel for the adopted traffic jam situation and the laminar flow of pedestrians [20].

Simulation result analysis did not find any congestions at emergency exits, which was probably due to the density of user distribution in the tunnel. For low densities, the speed of movement remains undisturbed and no congestions are formed at the exits [4]. In addition, when the density of people along evacuation routes is lower than 0.54 people/m^2, the individual

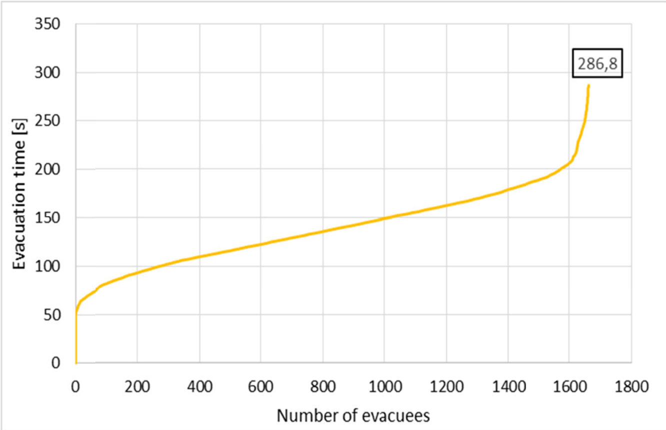

Fig. 10. Evacuation times using the available emergency exits for scenario IV

TABLE 9

Data for the evacuation of people for scenario IV

Available exit doors		North portal	Exit 1	Exit 2	Exit 3	Exit 4	Exit 5	Exit 6	Exit 7	Exit 8	Exit 9	Exit 10
Evacuees		83	142	151	139	154	169	155	137	156	168	208
Average flow [per./s]		0.64	1.07	0.99	1.04	1.01	1.02	0.97	0.91	1.04	1.12	0.94
Time [s]	first	62.2	64.8	53.6	66.9	60.9	50.6	53.7	56.3	55.1	63.0	64.9
	last	191.8	197.1	206.3	201.0	213.5	216.0	213.2	207.4	205.0	213.2	286.8

speed of movement is independent of other people [4], hence the modelling results relating to movement time can be considered reliable. As density increases, people start negatively affecting each other's movement in ways which are difficult to predict with numerical modelling techniques.

4. Conclusions

In the case of a fire occurring inside a road tunnel, it is the priority to evacuate all people in the danger area in the shortest time possible. The authors would like to stress the role of numerical studies in predicting the safety of evacuation from the danger area. Such studies provide valuable knowledge, important material for analysis and conclusions on how to improve tunnel infrastructure safety. They facilitate the analysis of various architectural solutions in buildings in terms of the evacuation process and pedestrian traffic observation. They are also an excellent tool to verify the impact of emergency exit density, the number of evacuees and some of their behaviour on evacuation time. Conducting such studies requires a good knowledge of the tool used for simulation, the geometry of the structure being analysed, specialist knowledge of the evacuation process, tunnel equipment, its infrastructure and the functioning of its safety systems.

Unfortunately, a large number of scenarios cannot be tested due to the limitations of these tools and also because some types of behaviour, such as the herding behaviour during evacuation [14], or double-lines patterns while under heavy smokiness during two-directional motion [21] are very difficult to model. Employing the solutions obtained using CFD models should be verified by way of experiments, which in this case will not be possible until the tunnel is completed and opened.

The results obtained in the simulations made it possible to estimate the approximate value of evacuation time from the tunnel under Luboń Mały. Three ignition location scenarios were studied for the current geometrical parameters of the tunnel and, as a final step, evacuation time was considered for the most critical fire scenario. The analyses were also applied to the planned future extension of the carriageway to three lanes in each tunnel tube, which could increase the number of vehicles inside the tunnel (e.g. during a traffic jam) and the number of people during a fire situation. It should be noted that the values of initial-boundary conditions used in the simulation, such as movement speed during evacuation, shoulder breadth and pre-movement time, were specified on the basis of experimental data for evacuation research performed in smoke conditions [14]. The value of pre-movement time is influenced by the behaviour observed in that time – lack of knowledge about the infrastructure and the situation, indecision about evacuation, lack of confidence, disorientation and a sense of uncertainty.

The estimated evacuation time (T_{RSET}) from the tunnel under Luboń Mały in the event of a fire is ~340 seconds for the current design state and ~347 seconds for three lanes for the least favourable ignition location. Considering the above, it may be concluded that the density of emergency exits in the tunnel under Luboń Mały should be sufficient to ensure safety during evacuation if the time of reaching critical conditions in the tunnel is not shorter than 340 seconds for the current design state and 347 seconds for three lanes.

The time of reaching critical conditions in the tunnel, posing a risk to the health and life of people during evacuation (available safe egress time T_{ASET}), can be determined by numerical research using Computational Fluid Dynamics. In this article the results from CFD modelling research works has been used [7]. T_{ASET} were calculated from the plane equation determined on the basis of the results of this numerical studies. This time depends on fire heat release rate (HRR) and tunnel length (for the coefficient of determination R^2 = 0.77). On this basis, for HRR 30 MW, 50 MW and 100 MW – three of the most recommended HRR for the truck [22] and for the quadratic fire development curves and a fire growth rate of 0.18760 [kW /s^2] the available safe egress times are 373 seconds, 368 seconds, 355 seconds, respectively. However, these results are true for the adopted parameters and initial-boundary conditions, one of which is a longitudinal ventilation system (direction of air flow and smoke are the same as the direction of vehicle movement for each fire scenarios). Hence, if the tunnel under Luboń Mały were equipped with a longitudinal ventilation system, then there would be a basis to state that the tunnel provides safe evacuation conditions for all three fire intensities. Otherwise, on the basis of data presented in this article it can be concluded that the time of reaching dangerous conditions for the tunnel (T_{ASET}) should not be lower than 340 seconds. The issues discussed in this paper should be discussed further by conducting numerical studies of fire development in a tunnel in order to estimate the available safety evacuation time and study the evacuation process in real-scale in smoke conditions.

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