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Full-Scale Experimental Study on Influence of Smoke on Pedestrian Movement During Evacuation in Road Tunnel

Natalia Schmidt-Polończyk

Faculty of Civil Engineering and Resource Management, AGH University of Krakow, 30-059 Krakow, Poland; nschmidt@agh.edu.pl

Abstract: The article presents the results of experimental studies of evacuation of 50 people from a road tunnel in various smoke conditions. Calculations of total evacuation times, pre-movement times and movement speeds were carried out and the impact of smoke on the speed of movement was analyzed. The pre-movement times, the alarm realization and response times for the subsequent experiments (1, 2 and 3) were 36, 7 and 5 s, respectively. The total evacuation times for 3 experiments were 340, 301 and 215 s. It has been shown that the speed of movement in smoke depends not only on the density of smoke, but also on the very attitude of the experiment participants and knowledge of the tunnel. It has also been shown that the adverse impact of low visibility on the evacuation time and movement speed is as important as the motivation of the evacuees and the effect of learning. In order to collect the observations of the participants, as well as assess potential aspects which might have influenced the process of evacuation, a survey was conducted after both experiments. The answers show that the two main reasons that prompted the evacuation were smoke in the tunnel and the fire drill.

Keywords: evacuation; real scale experiment; road tunnel fire; safety

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1. Introduction

Road transport dominates freight transport activity in Europe and this trend is expected to continue in the coming decades as the transport of goods by truck appears to offer a significant degree of flexibility, which offsets the higher costs of road transport compared to rail [1]. Increased transit traffic, load on routes and increasingly crowded cities contribute to the need to create new communication solutions, including road tunnels. Tunnel facilities significantly improve transport connections and influence the level of operation of transport enterprises, and road accidents strongly correlate with the level of operation and management of these enterprises [2].

While transporting through road tunnels, users are exposed to many threats to their health and even lives. From the point of view of the scale of the threat, fire is the greatest risk and the most dangerous event that can happen in a tunnel. This is all the more so because tunnels are contained; hence, it is obvious that smoke generated by the fire will pose a serious threat to the evacuation of people. The behavior of people during evacuation from a road tunnel in the event of a fire will be different than in an ordinary building [3].

In the event of a fire in a road tunnel, the priority is to evacuate people at risk in the shortest time possible. The evacuation process is a complex issue, depending on many factors determining the success of the withdrawal of people from the endangered place [4]. The disastrous consequences of various tunnel fires have prompted researchers to make investigations focusing on different aspects of the evacuation [5–9].

Safety aspects in road tunnels are the subject of many studies but experiments conducted on a real-life scale in smoke are carried out relatively rarely. Selected previous studies and analyses have focused mainly on the decision to start evacuation by drivers [3], the speed of movement in smoke [10–12], the marking of emergency exits [13,14] and individual behaviors in thick smoke [15,16].

Accidents involving buses are very dangerous in tunnels. Firstly, passengers have to leave the bus and, secondly, they have to leave the tunnel. Over a few recent years such accidents were reported: for example, the bus fire in the Taojiakuang tunnel in Weihai (Shandong Province, China, 9 May 2017, 12 fatalities), the school bus fire in Jack Lynch Tunnel in Cork (Ireland, 4 June 2013), the accident in the Dullin tunnel (France, 18 January 2004) or the bus fire in the Homer tunnel (New Zealand, 3 November 2002) [17].

The situation may be more complicated if there is an accident in the tunnel with a vehicle carrying hazardous materials, as happened in the Mont Blanc tunnel in 1999. A Belgian Volvo refrigerated truck, traveling from France to Italy, caught fire and stopped approximately 7 km from the French portal. The cause of the fire was a glowing cigarette butt that got into the car's air filter. The fire quickly developed due to the presence and quantity of flammable materials in the truck, including materials hazardous for transport: 550 L of diesel fuel in the truck's fuel tank, 9 tons of margarine and 12 tons of flour in the refrigerator. The fire spread quickly, the temperature reached up to 1000 °C. Smoke was filling subsequent sections of the tunnel every minute, limiting visibility and making it impossible to observe the event by cameras. In a tunnel on the French side, 38 people in 25 vehicles were trapped behind a burning truck. The resulting jam included 14 trucks, 10 passenger cars (including 1 van) and 1 motorcycle. Most drivers, instead of evacuating, stayed inside or near their vehicles after the fire broke out. People who tried to escape covered 100–150 m before they lost consciousness due to the smoke and toxicity of gases and fire fumes. A total of 39 people died—38 trapped behind the Belgian truck and one firefighter [18].

This article presents results of the experimental studies on evacuation from a bus on a real-life scale, carried out in the Emilia road-tunnel in Laliki with different levels of smoke conditions. In each of the three experiments, pedestrians were gathered in a bus, the bus was stopped in a tunnel and then the tunnel was filled with artificial smoke and the pedestrians had to evacuate. The human factor plays an indispensable role in ensuring process safety during a fire hazard [19].

The pre-movement time was estimated, the flow and movement velocities were compared and slowdowns were analyzed for different levels of visibility, as determined by the range of the extinction coefficient, Cs.

The article also presents results of the post-experimental surveys conducted in order to assess the individual perception of the participants. The survey consisted of questions that aimed to collect data regarding the observations of the evacuees during experiments, as well as verify certain aspects which might have influenced the decision-making processes.

The aim of safety management is to eliminate, and if this is not possible, limit the extent of damage that may be caused by transport incidents in road tunnels. Valuable for the development of science are empirical studies conducted at a real scale, as they provide knowledge about phenomena and processes closest to real situations or events. However, the organization of such tests is not an easy task due to the need for ensuring safety of participants, high costs and the necessary support from various services, such as a fire brigade or ambulance. In any case, experimental results are essential both for better understanding of the behaviors of evacuees and for the calibration and validation of computerized evacuation models or risk assessment.

2. Materials and Methods

The evacuation experiment was carried out in the Emilia tunnel in Laliki, consisting of a two-lane, two-way road tunnel (main tunnel) and a parallel evacuation tunnel for pedestrian traffic. The tunnel is 678 m long, has a horseshoe shape cross-section and the following dimensions: tunnel width 11.2 m, two lanes' width 7.0 m, tunnel height 6.55 m, cross-section area 83.1 m^2. The tunnel has 4 transverse passages connecting the road tunnel with the evacuation tunnel, located every 150 m, through which people can evacuate from the endangered place. The door to the evacuation tunnel was 1m of width, the evacuation tunnel width was 3.9 m and the bus door width was 0.9 m.

In the experiment, 50 students of the AGH University of Science and Technology in Krakow, 34 women and 16 men, undertook the evacuation exercise. The mean age of the participants was 21.32, the standard deviation (SD), σ, 1.477, min. 19, max. 24 years. Details of the height, weight and shoulder width of the participants are collected Table 1.

Table 1. Selected parameters of the experiment participants.

Parameter	Min.	Max.	Mean	SD
Age (years)	19	24	21.32	1.477
Height (cm)	160	188	177	7.113
Weight (kg)	53	95	69.22	9.248
Shoulder width (cm)	38	56	48.2	4.669

Non-toxic cold smoke was used during the test. In addition, to ensure safe conditions, the experiment was carried out with the participation of the Police, Fire Brigade and rescue services.

During the 1st experiment, the participants did not receive any information about the the purpose of the event, the rules of behavior, the presence of smoke, the infrastructure of the tunnel (the presence and location of emergency exits) or the place of stopping the bus. The bus, riding straight from Krakow, entered the tunnel without previously stopping in order to obtain an element of surprise among the participants of the experiment. During each experiment the driver stopped in the middle of the tunnel.

The signal to start the evacuation for the participants of the experiment was identical, as it would be in the event of the outbreak of a real fire. Smoke appeared in the tunnel and the fire procedure was started (the fire lighting, voice messages and fire alarm went on). It should be noted that the organizers of the experiment did not give any signal to start the evacuation and the bus driver (who knew the plan of the experiment) was asked to stay in place and do nothing (such as giving instructions to the participants or revealing the plan of the experiment) except opening the door in the bus after hearing the fire alarm. During the first experiment, when there was slight smoke in the tunnel (Cs approx. 0.1–0.2 m^{-1}), the task for the participants was not clearly explained. The next two experiments were carried out in a similar way but with some changes. During the 2nd experiment, with medium smoke (Cs approx. 0.4–0.5 m^{-1}), the participants were tasked to evacuate. During the 3rd experiment, with thick smoke (Cs approx. 0.8–0.9 m^{-1}), the participants were asked to leave the tunnel as soon as possible. The density of smoke was increased in each subsequent experiment (Figure 1).

Figure 1. An empirical comparison of the representative levels of visibility in experiments 1, 2 and 3.

Before the experiment in the Emilia tunnel in Laliki, the Bioethical Commission at the District Medical Chamber in Krakow was consulted. The Commission had no objections to the experiment and provided a written statement saying that "no special approval of the ethics committee is required".

3. Results

3.1. The Pre-Movement Time

In the first experiment, after the bus stopped and smoke appeared, the participants did not leave the bus. After the alarm signal was triggered, they stayed on their seats (Figure 2). Only the voice message given during the fire procedure encouraged the first participants to leave the vehicle (t = 27 s). At this stage of the experiment, nine people decided to leave the bus. Others followed after another 23 s (t = 50 s).

Figure 2. The moment of making the evacuation decision during experiment 1.

During the first experiment, the pre-movement time (alarm realization time + response time + within the bus movement time) was longest (Figure 3). In this experiment, the first person left the bus after almost 36 s, while in the two remaining ones they left after 7 and 5 s, respectively. However, it is the first experiment that is most representative for the estimation of the pre-movement time, mainly due to the element of surprise. The participants did not know the purpose or the scenario and were unfamiliar with the tunnel infrastructure, so their reactions were most representative of the real-life situation. The subsequent, much shorter times were due to the learning effect. Their participation in the previous experiments and the knowledge gained about the evacuation procedures allowed the participants to respond faster and leave the dangerous area sooner.

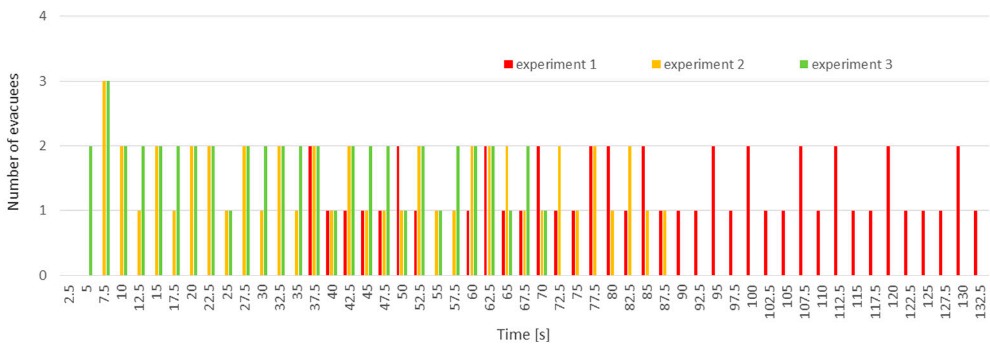

Figure 3. The pre-movement times in experiments 1–3.

3.2. The Speed of Movement

The movement speed velocity was calculated for each experiment, separately for the road tunnel and for the evacuation tunnel, mainly due to the significantly different conditions in both spaces (e.g., no smoke in the evacuation tunnel). The speed was calculated using the modeling method proposed by [10] and the results are shown in Figures 4 and 5 and in Table 2.

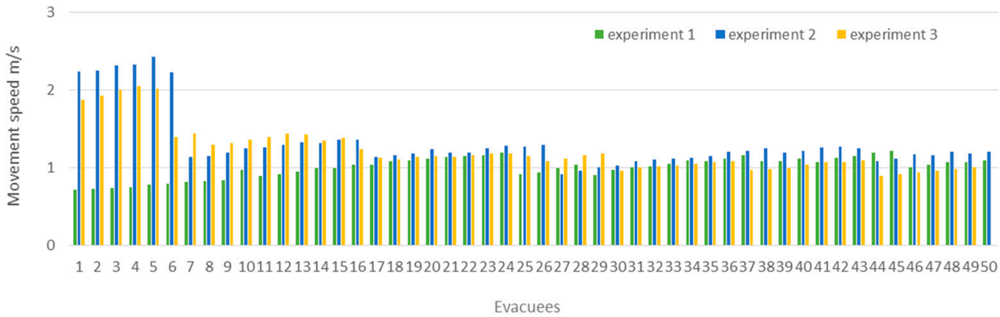

Figure 4. The speed of movement in the main tunnel in the subsequent experiments.

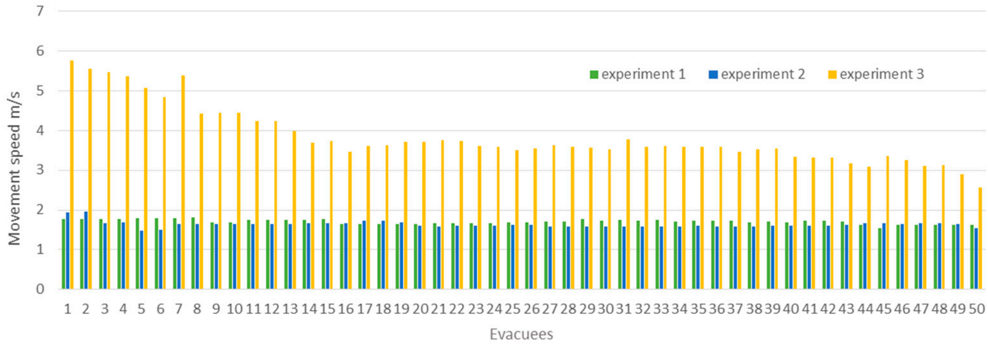

Figure 5. The speed of movement in the evacuation tunnel in the subsequent experiments.

Table 2. The mean speed of movement of people in the main tunnel and in the evacuation tunnel during experiments 1–3.

Experiment (Number) Tunnel (Type)	1 Main	1 Evac.	2 Main	2 Evac.	3 Main	3 Evac.
Mean speed (m/s)	1.056	1.706	1.321	1.653	1.221	3.835
SD	0.083	0.058	0.375	0.081	0.295	0.719

The minimum movement speeds in the main tunnel were similar in all the three experiments (0.895, 0.917 and 0.893 m/s). Although the highest mean speed was expected from experiment 3 (due to the purpose of the test), it occurred in experiment 2 (1.321 m/s). This is probably a result of much denser smoke during the third experiment (Cs approx. 0.8–0.9 m^{-1}) compared to the second experiment (Cs approx. 0.4–0.5 m^{-1}). A similar situation can be observed while analyzing the maximum speeds in the main tunnel: the highest value was recorded for experiment 2 (2.422 m/s), slightly lower for experiment 3 (2.044 m/s) (the poorest visibility) and the lowest for the experiment 1 (1.211 m/s).

In the first two experiments, participants moved within the evacuation tunnel at almost the same speed (Figure 5). The difference is visible in experiment 3, where students were tasked to evacuate as soon as possible. The mean and max. speeds in this case were 3.835 and 5.760 m/s, which demonstrates strong motivation in students during this attempt.

3.3. The Effect of Smoke on the Movement Speed

The analyses made it possible to determine the slowing down effect of smoke in the main tunnel. For this purpose, the speed of movement of each participant in the main tunnel was calculated as a percentage of the expected speed, understood as the speed of free movement achieved in the evacuation tunnel. The evacuation tunnel during the tests was smoke-free and wide enough to allow free movement with a speed corresponding to the purpose of each experiment. These values were considered to be representative (achievable) speeds in the main tunnel.

During the first experiment, the mean speed of movement of the participants in the main tunnel was 62.56% of the expected speed (Table 3). Surprisingly, during the second experiment, despite denser smoke, the evacuation speed in the main tunnel accounted for 73.17% of the expected speed. A significantly smaller value was achieved in the third experiment, only 31.46%, as the mean representative speed in this test was relatively high (3.835 m/s).

Table 3. The speed of movement in the main tunnel as a percentage of the representative speed (the free movement speed achieved in the evacuation tunnel).

Experiment	1	2	3
Mean value	62.56%	73.17%	31.46%
SD	6.12%	5.90%	3.12%

3.4. The Duration of Evacuations

The total evacuation times for the three subsequent experiments were 340, 301 and 215 s, respectively. The time of leaving the most dangerous space during the fire (the main tunnel) was the longest in the first experiment (84–163 s) and the shortest in the third experiment (21–102 s) (Figure 6).

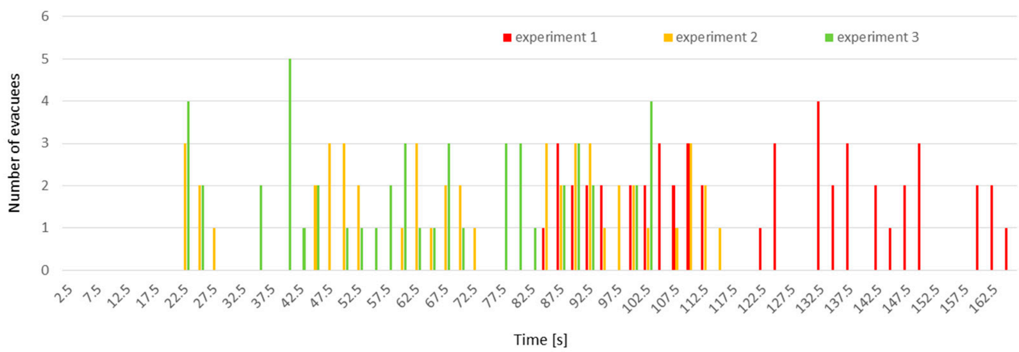

Figure 6. A comparison of the times at the checkpoint in the experiments—the passage between the main and evacuation tunnels.

The rate flow of the participants through the bus door does not change in the experiments. It was not high and did not change much between the experiments (Figure 3). The only significant difference, noted in the first experiment, was due to the longer initial response time.

The actual differences in the flow rates between the experiments occurred only at the exit from the evacuation tunnel (Figure 6). In experiments 1 and 2, the evacuation proceeded in distinct widely spaced groups. In the third experiment, the flow at the exit of the evacuation tunnel was constant and, in addition, no formation of larger groups was observed.

The flow times of the evacuees through the bus door and through the inter-tunnel passage were similar in experiments 2 and 3 (Figures 3 and 6). However, the participants were much faster at the exit from the evacuation tunnel (Figure 7) compared to experiment 2, which is due to their stronger motivation [14]. In addition to smoke, the time to leave the most dangerous area (the main tunnel) depended mainly on the participants' experience and knowledge of the tunnel and the evacuation process.

Figure 7. A comparison of the times at the checkpoint in the experiments—the exit from the evacuation tunnel.

It seems interesting to analyze the time differences at the checkpoints, especially the difference between the first and last evacuated person. The exact data for the time comparison are given in Table 4 and in Figure 8.

Table 4. A comparison of the difference in the first and the last persons' passage times obtained at the checkpoints in the subsequent experiments.

Experiment	Bus Door	Main/Evacuation Tunnel Passage	Evacuation Tunnel Exit
1	95.1 s	78.5 s	92.6 s
2	79.6 s	92.9 s	131.5 s
3	64.7 s	80.8 s	143.2 s

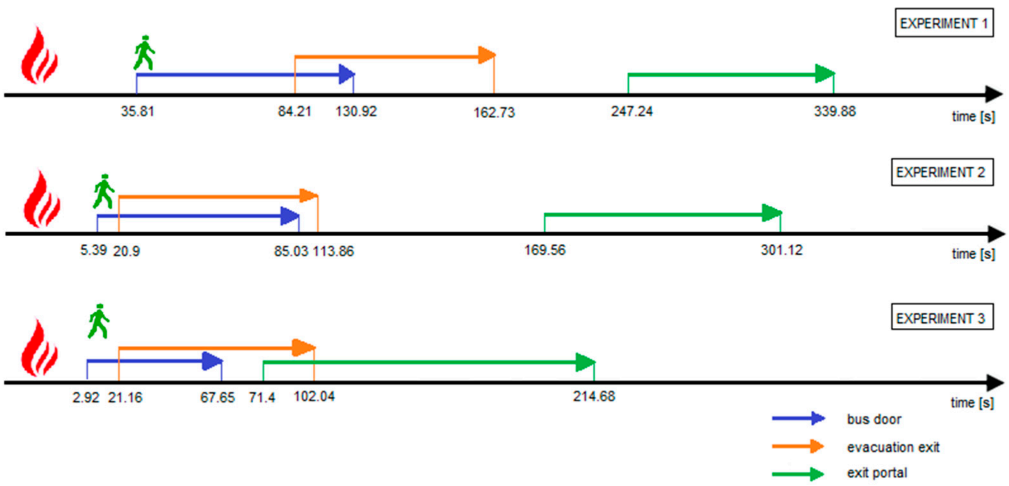

Figure 8. The first and the last persons' passing times recorded at the checkpoints in the subsequent experiments.

It can be seen that the subjects left the bus increasingly more effectively with each attempt: the time difference between the first and the last person to leave decreases. In turn, for the emergency exit, this value is more or less similar (except for a small increase in the second experiment). Unlike for the bus door, the difference in the times of the passage through the exit from the evacuation tunnel (portal) increased in the subsequent experiments. The reason for this may be the fact that during each evacuation the participants had to walk (slightly uphill) a section of 300 m, so the difference in their physical condition and in motivation may be the reason for the increase in the time difference.

Only during the first experiment was the time difference between the first checkpoint (the bus door) and the last one (the exit from the evacuation tunnel) similar. During the next two tests, these times were longer and the reason may be similar to the one mentioned in the above paragraph.

3.5. Decision Making During the Evacuations

After each experiment, all of the 50 participants were asked questions which focused on their individual observations regarding the reasons for deciding to start evacuation (Table 5), and the choice of the evacuation route (Table 6). The main reason clearly pointed to the presence of smoke and the fire drill.

Table 5. Survey results concerning the question about one or two basic decision premises to start evacuation.

	Experiment 1	Experiment 2	Experiment 3
bus stoppage	18.00%	10.00%	13.00%
fire drill	72.00%	72.00%	87.00%
smoke in the tunnel	94.00%	92.00%	89.00%
other people's behavior	6.00%	4.00%	2.00%
other	2.00%	4.00%	2.00%

Table 6. One or two basic reasons to choose a specific evacuation path.

	Experiment 1	Experiment 2	Experiment 3
mimicking other people	28.00%	10.00%	9.00%
evacuation signs	90.00%	86.00%	72.00%
voice alarm messages	34.00%	24.00%	23.00%
intuition	14.00%	6.00%	32.00%
knowledge of evacuation procedures	16.00%	24.00%	19.00%
earlier experiences	2.00%	34.00%	43.00%
other	0.00%	0.00%	2.00%

As per the choice of evacuation route, the participants were chiefly based on the signs in the tunnel; the second most influential reason was voice messages, and the third was the previous experiences of the participants.

Further on, the participants were asked about a possible loss of orientation (Table 7). While the first experiment caused no disorientation among 70% of the evacuees, or mostly none among 27%, during the second experiment the numbers lowered to 53% and 40%. The circumstances during the third experiment triggered the most confusion—43% of the evacuees were disoriented most of the time and 26% during the entire evacuation.

Table 7. Problems with bearing, due to limited visibility.

	Experiment 1	Experiment 2	Experiment 3
no	71.00%	53.00%	9.00%
most of the time no	27.00%	39.00%	22.00%
most of the time yes	2.00%	8.00%	43.00%
yes, during the whole trial	0.00%	0.00%	26.00%

Another question assessed whether the participants decided to begin evacuation individually or in groups (Table 8). The participants of the first experiment almost entirely evacuated along with others (24% in twos, 24% in threes and 48% in bigger groups), and the grouping tendency recurred in the second experiment. On the contrary, during the third experiment, almost half of the participants evacuated on their own.

Table 8. Grouping behavior during experiments.

	Experiment 1	Experiment 2	Experiment 3
no	4.00%	8.00%	45.00%
yes (dyad)	24.00%	33.00%	21.00%
yes (triad)	24.00%	18.00%	15.00%
yes (bigger group)	48.00%	41.00%	19.00%

3.6. Participants' Observations

The highest number of comments (20) regarded the unmarked curbs in the tunnel, which in the poor visibility of heavy smoke conditions hindered the evacuation, causing the participants to trip or collide with others (Figure 9).

Figure 9. Tripping over the curb in the third evacuation experiment.

Eighteen comments complained about the quality of audio messages in the main tunnel, which were at times echoed and reverberated. The alarm messages were reported to be especially difficult to understand inside the bus—an insight that had already emerged in previous studies [15].

The markings of escape routes received negative comments mainly after the third experiment, while the positive comments did mainly after experiments 1 and 2. The negative feedback might be a result of the heavy smoke conditions present in experiment 3, and indicates a need to improve the markings in the tunnel. However, few comments regarded the difficulty in reading evacuation signs—participants described them as unclear, for example, when showing arrows in two opposite directions.

4. Discussion and Conclusions

In this paper, the process of evacuation was analyzed in the context of the most important parameter: the evacuation time. For this purpose, the pre-movement time was estimated, the flow rates and movement speeds were compared, and the movement delays caused by smoke were analyzed—for different levels of visibility determined by the range of the extinction coefficient, Cs.

The pre-movement times, i.e., the alarm realization times and the response times (including the time of movement within the bus), in subsequent experiments were 36, 7 and 5 s, respectively (Figures 3 and 8). The most representative value of this time is the result of the first experiment where there was the element of surprise. Despite the presence of smoke and the triggered fire alarm, the decision to evacuate was not made. It was only after a while, about 36 s, that the evacuation was started. This is because people usually stick to their roles (e.g., as a passenger) in the event of an accident until they realize the seriousness of the situation and/or until they are given clear instructions on what to do. Similar behaviors were observed during the actual tunnel fires [14,18,20]. In the post-experimental survey, the participants pointed to the presence of smoke and the fire drill as main reasons for deciding to begin the evacuation (Table 5). It was probably that that made the first people evacuate and the rest of the participants just follow after another 23 s. The indifference to the alarm signal was also noted during other evacuation experiments [21]. The results also clearly point to the evacuation signs as having the most impact when it came to choosing the evacuation route (Table 6). The second factor was voice messages, and the third was following other evacuees. The speed achieved in the evacuation tunnel (smoke-free) was much higher in the third experiment (the subjects were encouraged to run) (Figure 5), which indicates that the tunnel evacuation efficiency depends also on the attitudes (motivation) of the users. The highest speed of movement in the main tunnel (smoky space) was recorded during the second experiment (1.321 m/s) (Figure 4). Due to the goals of the subsequent experiments, the maximum values were expected from the third one. However, apparently, this parameter depends on the density of smoke and it was thickest in the third experiment (Cs approx. 0.8–0.9 m^{-1}). The actual speed achieved in the main tunnel accounted for 31.46% of the expected speed achievable in the evacuation tunnel (Table 3). This matrix shows how big the impact of smoke can be on the speed of movement. It is worth noting that, although during experiments 1, 2 and 3 the density of smoke was increased, the subjects managed to achieve better speeds of movement (Figure 4). The total evacuation times in the subsequent experiments were 340, 301 and 215 s, respectively. The shortest time to leave was recorded for experiment 3 (80.88 s), despite the fact that during this test the smoke density was the heaviest and the participants in the survey indicated problems with loss of visibility (Table 7). In this experiment, the evacuees were asked to leave the tunnel as soon as possible (competitive behavior) and, therefore, the participants moved independently. In turn, especially in the first experiment, grouping behavior was noticed, which might have stemmed from a new, unknown situation and the unfamiliarity of the tunnel infrastructure (Table 8).

These results clearly indicate that the speed of movement in smoke depends not only on the density of smoke (the visibility determined by the extinction coefficient) but also on the very attitude of the participants and knowledge of the tunnel [22]. In previous studies, the speed of pedestrian movement was often considered as a function of the extinction coefficient alone [10,21]. The foregoing results indicate that both the knowledge of the surrounding environment (experiment 2) and the attitude of the evacuees (experiment 3) also affect the speeds of their movement. As in [16], at low visibility level stoop-walking behavior was noticed. In turn, research [20] has shown that negative emotions impacted slow walking behavior. In the survey, the participants describe their individual perception pointing to unmarked curbs that can be a dangerous obstacle during evacuation in heavy smoke. Several participants tripped over the curb and some stumbled on each other.

The time to leave the most dangerous space during the fire (the main tunnel) was the longest in experiment 1 and the shortest in experiment 3 (Figures 6 and 8). The results indicate that the adverse impact of low visibility on the evacuation time is as important as the motivation of the evacuees and the effect of learning, which was also observed in [3,12]. Many comments in the post-experimental survey gave a positive opinion about the experiment itself, considering it as very useful, realistic and interesting. The role of the learning effect after each subsequent experiment was also emphasized. The study can help to develop movement models for different visibility levels and help determine initial boundary parameters in numerical modeling of evacuation. In addition, the results of research conducted on a real scale allow for a better understanding of the behavior of evacuees and indicate areas for further improvement of the tunnel infrastructure [1].

The results of the experiment clearly indicate the need to increase the educational value, e.g., during driving courses. In the first experiment, the evacuation of all people from the smoke-filled part of the tunnel (main tunnel) took 2 min 42 s. After this time, during the real fire in the Mont Blanc tunnel in 1999, 900 m of the tunnel was filled with dense smoke. So, the delay in evacuation observed in experiment 1 can lead to critical conditions like those created in experiment 4, and in this experiment, the large amount of smoke caused loss of orientation and, as a result, the choice of the evacuation direction towards the fire. This would probably end tragically, as in the Mont Blanc tunnel.

The study's shortcomings include the fact that it did not take into account the impact of toxic fire gases on the evacuation process. However, for safety reasons, this was impossible. This type of research should be continued and repeated. In the future, it is worth paying attention to the psychological aspects explaining how people make decisions under fire.

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