

Article

Evacuation in an Underground Space: A Real-Time Investigation of Occupants' Travel Speed in Clear and Smoked Environments

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Abstract: In order to achieve a comprehensive study regarding evacuation efficiency in underground space, globally accepted regulations and standards include, among other parameters, the maximum unimpeded travel speed of occupants in case of emergency evacuation. Researchers attempt to investigate the variation of travel speed using different approaches. The aim of this paper is to study occupants' travel speed during evacuation procedures in an underground space. Underground spaces have special requirements as they differentiate from a typical building regarding the absence of physical lighting, the fact that exit route paths are always ascending and the limited orientation awareness of their users. A total of 40 volunteers participated in a large-scale experiment that involved the evacuation of the underground space in real time. Two distinct evacuation drills took place, the first one in a smoke-free environment and the second simulated fire conditions via the presence of dense artificial smoke. During each trial, the required evacuation time as well as the walking speed of each occupant were monitored, with the aid of digital cameras positioned in appropriate spots inside the underground space. The evacuation speed resulted from the experiments is compared to those of international regulations (e.g., NFPA 130) regarding horizontal travelling, as well as travelling on an upward staircase. The effect of the presence of smoke on evacuation speed is discussed. The importance of direct and constant guidance to the occupants of an underground space is highlighted during evacuation in a smoked environment and its contribution to safety improvement. Finally, the effect of the egress route type of an underground space on occupants' speed is discussed and how this may affect the decision making during the design of an underground infrastructure, in order to achieve a safe environment.

Keywords: travel speed; evacuation behavior; underground spaces; upward evacuation; evacuation in smoked environment

1. Introduction

In recent decades, the use of computer agent models in managing evacuation procedures and crowd movement is on the rise, as it is considered as the most efficient way to accurately simulate the effects of evacuation in all types of structures and assess occupants' safety. Human behavior in evacuation procedures is the most unpredictable and therefore difficult aspect to predict and simulate, as people's characteristics, such as psychology and companionship, do not follow a standard pattern. Evacuation simulation software have adopted some basic human parameters including, size, walking speed, behavior, assistance and more in order to mimic human behavior during emergency events.

Globally accepted regulations and standards include, among other parameters, the maximum unimpeded travel speed of occupants in case of emergency evacuation.

The Society of Fire Protection Engineers (SFPE) has adopted a relation between people's density and walking speed as well as a maximum travel speed [1] that is used widely

in conventional and computer modeling evacuation simulations in order to calculate the evacuation time.

A very useful data collection for movement speed during a fire drill evacuation in a high-rise building has been achieved by Peacock et al. with the collected data by the National Institute of Standards and Technology (NIST) [2]. The study shows that the average movement speed along the whole building is equal to 0.48 ± 0.16 m/s which is quite similar to the range of literature values. However, the local movement speed as occupants traverse down the stairwell seem to vary widely within a given stairwell, ranging from 0.056 m/s to 1.7 m/s. Thus, using a distribution of movement speed rather than a single value should provide more realistic representation of movement speed in stairwells.

In order to investigate human movement in emergency situations and crowded areas, Kiyono and Mori [3] compared simulations of the evacuation behavior using elliptic elements with real pedestrian flows. The simulation results showed a good agreement with the actual phenomena.

Moreover, Kobes et al. [4] studied the ability of virtual reality in studying human behavior in fires and attempted to determine the walking speed by measuring the (approximate) walking distance and divide it by the movement time. They used the ADMS—BART, a pre tested simulation platform by emergency training organizations.

Xie et al. [5] indicated that the body mass index (BMI) has a significant effect on ascending evacuation speed and proposed an evacuation model to predict the best evacuation path in fire stairways. The effect of occupant characteristics on crawling speed in evacuations has been studied by Kady and Davis [6], who showed that the mean crawling speed is 0.77 m/s, significantly higher than other studies which propose a crawling speed of around 0.3 m/s [7,8]. This finding is vital in order to improve the reliability of evacuation models. Even more, the effect of trim and heel angle of a ship corridor on walking speed during an extreme-conditions evacuation has been studied in a ship corridor simulator and showed that average individual walking speed could be greatly attenuated [9].

Other studies subject the outdoor human speed in case of emergency, such as the simulation study to observe the walking speed of evacuees in the case of tsunami evacuation in Indonesia [10], in which the results show an average speed of 1.419 m/s. In this real-scale experiment, the volunteers were asked to hurriedly walk from a specified point to a specified point near to shelter and observers were placed at 6 points along the travelling route to observe the time when the volunteers passed their position.

Other studies that include travelling speed under limited visibility such as smoke-filled environments proved that the travel speed may be reduced up to 70% of normal speed with regard to visibility and smoke type (irritant and non-irritant). Among these studies, Jin conducted an experiment in a 20 m-long corridor where a highly irritant white smoke and a less irritant black smoke were produced. He created a graphic relation between extinction coefficient and walking speed for irritant and non-irritant smoke. For example, for an extinction coefficient of 0.5, which corresponds to a visibility of approximately 6 m for irritant and 12 m for non-irritant smoke, the walking speed is 0.3 m/s and 1 m/s, respectively [7,8,11]. In addition, Fridolf et.al reveal that the crucial visibility limit is set to 3 m, and for values below that, speed decreases radically; they also provided a variation of unimpeded walking speed according to population characteristics [7].

As mentioned before, underground spaces have special requirements as they differ from a typical surface building: there is an absence of physical lighting; exit route paths are always ascending and thus cause fatigue to evacuees; and the users have a limited orientation awareness, which affects the travelling speed in contrast to conventional buildings. The National Fire Protection Association suggest that the maximum means of egress travel speed is equal to 0.628 m/s along platforms, corridors, and ramps in more congested areas in contrast to 1.017 m/s in less congested areas and 0.243 m/s for stairs in underground transit systems (in cases of vertical travelling, speed and distance are defined in terms of the vertical change in elevation bridged by the facility), in order to calculate the Request

Safety Egress Time (RSET) in case of emergency [12]. It should be mentioned that these values are meant to be used in the hand calculation method.

Studies concerning underground movement behavior are limited to those on tunnel experiments (both railway and road) [13–15]. In a full-scale experiment in a road tunnel by Seike et al. [16,17], the normal walking speed (“walk in the tunnel as you normally walk”) and emergency evacuation speed (“please decide to evacuate, and do it extremely urgently”) were investigated under different visibility limitations and revealed a variation between 3.55 m/s and 1.1 m/s, respectively. More specifically, the maximum normal speed was observed from 2 m/s to 1 m/s (approximately) and the evacuation speed from 3.55 m/s to 1.41 m/s. In the presence of smoke, the value of maximum speed decreases linearly to 2.53 m/s and the minimum value to 1.24 m/s. Summarizing, evacuation experiments in a smoke-filled tunnel show that the maximum, minimum and mean values of normal walking speed are almost constant regardless of the extinction coefficient, but maximum emergency evacuation speed decreases rapidly as smoke density increases. In addition, the mean emergency evacuation speed is not severely influenced by smoke density.

Finally, concerning evacuation in ascending stairways, Ronchi et al. investigated the effects of fatigue on walking speeds, physiological performance and behaviors in the case of a long ascending evacuation and revealed that physical work capacity affected walking speeds in the case of upwards stairway travelling [18], with the mean value ranging from 0.62 m/s to 0.83 m/s. There are further studies that consider the evacuation in ascending stairways which reveal that a speed variation exists [19–23].

A summary of studied research regarding the occupancy type is presented in Figure 1. Moreover, representative regulations as well as past research concerning walking speed mainly in underground areas (road tunnels and METRO stations), as well as upward evacuation are presented in Table 1.

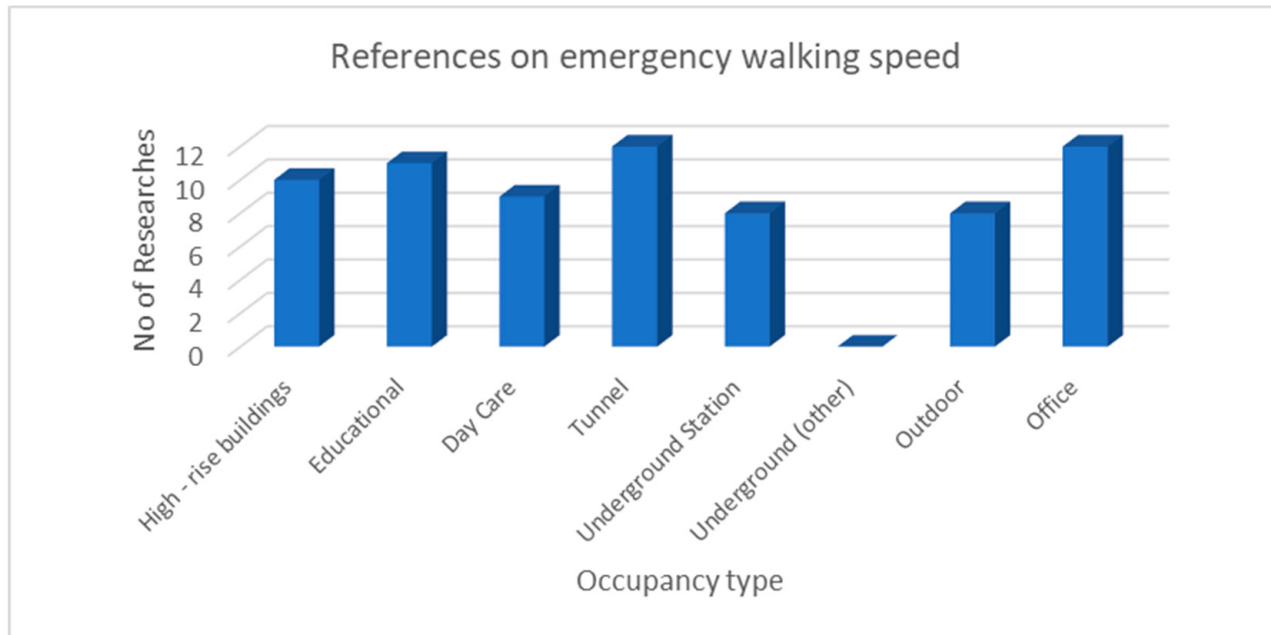


Figure 1. Number of research studies by occupancy type.

As seen from the Table above, regarding the evacuation speed of occupants, there is a variation concerning the type of occupants, building type, visibility conditions, human psychology and more.

Table 1. Walking speed (m/s) during unimpeded travelling.

Reference	Horizontal Surface			Upward Staircase		
	Mean	Min	Max	Mean	Min	Max
NFPA-130 (platform)	0.63			0.43 ¹		0.43
NFPA-130 (other areas)	1.02					
SFPE [24]	1.25	1.25	1.25			
SFPE (Disabled—no locomotion) [24]	1.25	0.82	1.77	0.70	0.55	0.82
PIARC [25]		1.00	2.00			
CFPA-E [26]		1.20	1.25		0.85	1.10
DAS [27]		1.00	1.30			
Pedestrian and Evacuation Dynamics (PED)—Peacock et al. [2]						
PED—Choi et al. [28]	1.35	1.35	1.35			
PED—Fujiyama and Tyler [29]	1.35	1.18	1.52		0.26 ²	1.11
Ronchi et al.—2015 [18]					0.62	0.83
Kretz et al.—2006 long stairways [19]				0.52	0.27	1.55
Kretz et al. ³ —2006 short stairways [19]				0.78	0.13	1.43
Other Studies ⁴					0.13	1.55

¹ Since NFPE 130 refers to vertical distance, this value is a normalization for a common 70% staircase grade.

² These values are dependent on the staircase grade. ³ In that study, Kertz et.al consider a “short” stairway as one with a height of 15 m and a “long” stairway as one with over 30 m height. ⁴ Studies mentioned in the current paper.

In Table 2 various experiments are presented regarding the estimation of travel speed in smoke. Each experiment had its own particular characteristics. For example in Jin’s experiment people were called to walk in a corridor filled with smoke and their speed value was observed for various values of optical density [8]. SFPE proposes speed values for specific optical density for irritant and non-irritant smoke [30]. Seike et. al. conducted an experiment inside a tunnel where walking speed was measured for values of extinction coefficient below one ($C_s < 1$) [17].

Table 2. Walking speed (m/s) in smoke-filled environment.

Reference	Horizontal Surface		
	Mean	Min	Max
Jin ⁵ [8]		0.55	1.19
Akizuki et al. [11]	1.10	0.90	1.30
Frantzich and Nilsson [11]		0.20	0.80
Fridolf et al. ⁶ [7]		0.80	1.40
Seike et al. (normal walking) [17]	1.40	1.05	1.88
Seike et al. (emergency walking) [17]	2.00	1.40	3.00
SFPE Purser and McAllister [30]	0.30 ⁷		
Ronchi et al. [13]	1.20	0.60	1.80

⁵ Jin provides walking speed with regard to visibility (approximately 10 to 3 m) and smoke type (irritant, non-irritant). ⁶ Fridolf et al. obtained these values from other studies that were conducted that met certain criteria, in order to find a proposed representative value of the people’s speed in smoke. ⁷ This value is respect to visibility of approximately 5 m.

From all the above, it becomes obvious that there is still a high need for further research on evacuation behavior regarding travelling speed, both for the specification of studies by underground structure type, exit path and visibility conditions, as well as for the further development of the computer agent models.

The purpose of this paper is to describe an experiment of real-time evacuation, and present a data-set on walking speed both in a clear and smoke-filled environment. The results are related to horizontal and upward travelling speed, as well as participants' age distribution.

2. Methodology

In order to accomplish the large-scale experiment there are 3 basic parameters that need to be defined:

1. The underground space in which the experiment will take place;
2. The volunteers that will participate in the experiment—drill;
3. The necessary hardware that will control and record the experimental results.

2.1. Analysis of the Selected Underground Area

The experiment took place in the underground hazardous waste repository (UHWR), which was constructed for the hazardous waste management of previous mining activity in Lavrion area. In addition to the storage of the waste, the site can also be used for several research operations. The area of Lavrion is located about 40 km from Athens, the capital of Greece (Figure 2). It was developed almost 40 m below the ground level, following the principles of the room and pillar mining method. Thus, rooms (corridors) 5.5 m wide and approximately 6 m high are developed while the pillars of the host rock that remain in place are rectangular in shape, having widths of 7 m, as presented in Figure 3. The total area of the repository is approximately 2200 m², with an available free space of around 1800 m².



Figure 2. UHWR underground floor plan.

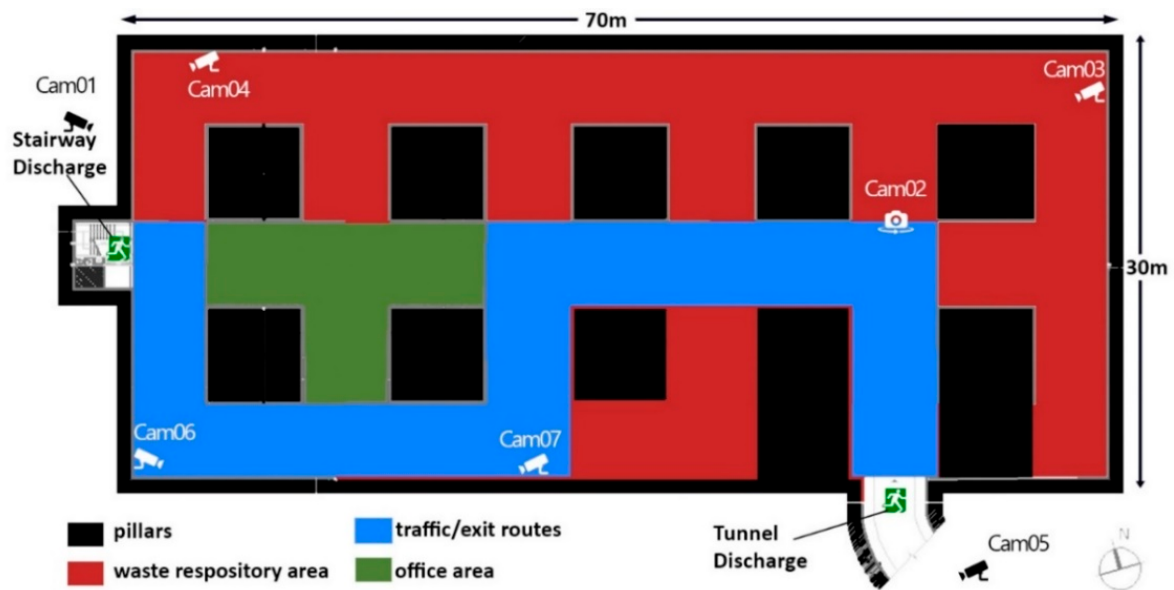


Figure 3. UHWR underground floor plan.

The whole space is divided into three areas, regarding their usage. The red area is made for the storage the hazardous wastes, the green area is the operation/maintenance office and the blue area is the unblocked corridor that is used as the egress route both for tunnel and staircase exit. For the majority of underground waste repositories, the use of abandoned mines is a common tactic, but the presented underground space has as purpose as hazardous waste storage from prior mining in the immediate area, which imparts a uniqueness in this project and may attract many visitors. Therefore, the appearance of a higher occupant density for educational reasons, besides the normal operation conditions, must be taken into account in the evacuation and safety design.

The area has not begun to operate yet and, therefore, all the rooms and corridors are completely empty. The only means of lighting comes from the ceiling light installation and there are no exit signs installed yet (Figure 4).



Figure 4. Perspective of UHWR underground space.

Before conducting this experiment, structural and technical characteristics of the underground space were taken into account, to make sure that it was safe to complete an evacuation drill. The fact that the site was about 30 m below the surface, combined with the participants' lack of experience in a similar underground evacuation could easily create

a sense of doubt and anxiety among them. Therefore, this experiment was carefully and thoroughly designed to avoid any safety problems during occupants' evacuation.

The tunnel exit consists of a ramp of 175 m length, 6% grade and a final exit door (Figures 5 and 6). The staircase exit consists of a 30 m-height stairwell, which might be considered as a building with 9 levels (Figures 7 and 8).



Figure 5. Underground UHWR tunnel entrance.



Figure 6. Underground UHWR tunnel exit.

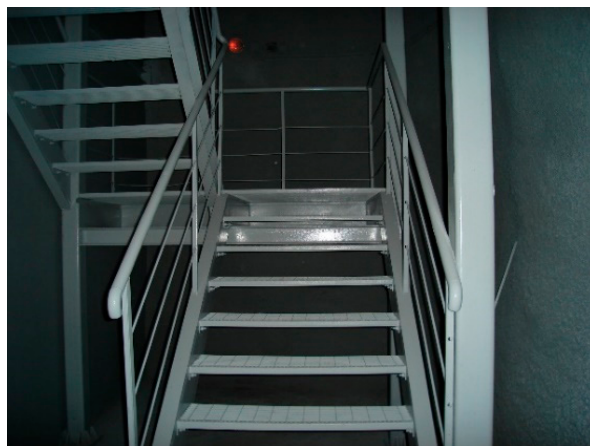


Figure 7. Underground staircase entrance.



Figure 8. Underground staircase exit.

2.2. Participants Description

On the arrival of the participants in the area, information was provided on the evacuation process. The experiment was prohibited for those who felt any anxiety during previous underground visits such as parking areas and metro stations. Subsequently, a guided tour to the underground area was conducted to familiarize participants with the area and to identify egress routes and exits that would be available during evacuation (Figures 5–8). Furthermore, to ensure the safe operation of the experiment, several security managers who had experience in evacuation drills and were familiar with this area, were assigned. The managers wore distinctive vests to be easily recognizable by the participants and were the last to evacuate the area making sure that all the participants were guided safely to the surface (Figure 9).

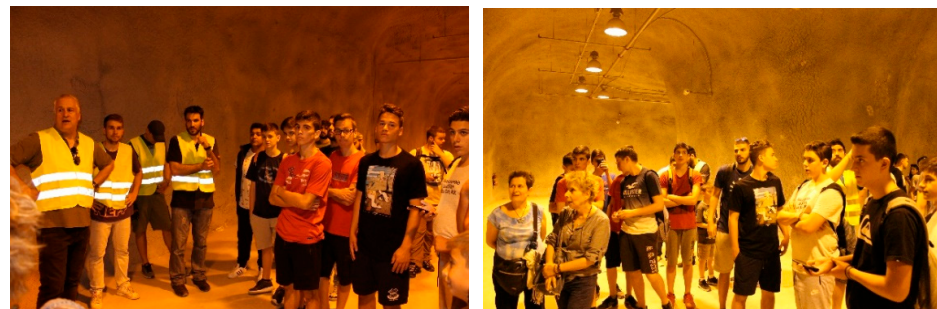


Figure 9. Participant arrival in the underground area.

In the experiment, a number of 40 participants took part and their age range was from 15 to 68 both of male and female as presented in Figure 10.

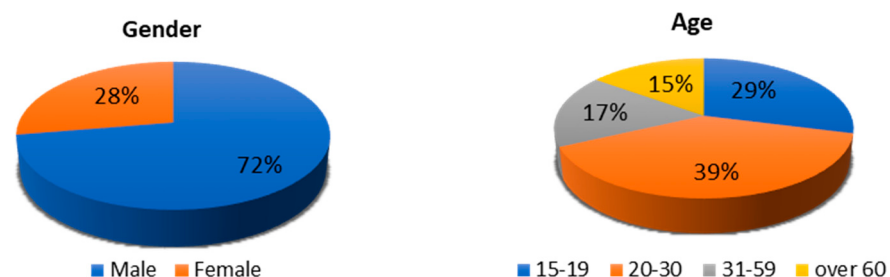


Figure 10. Participants' distribution, gender and age.

2.3. Experiment Conduction Methodology

To record the evacuation time, each participant had a timer that was activated with the evacuation start signal and was deactivated the moment the participant came to the surface exit. Seven cameras were placed to attain the most accurate results, export reliable conclusions and calculate the movement speed of the participants in different areas. Five cameras were located in the interior of the underground storage at 4 m height from the floor, so as to cover the whole space, and two were placed in the final exits at the surface, as presented in Figure 3. The interior cameras' views are shown in Figure 11. To calculate the speed of the participants in the underground storage, a self-adhesive marking tape was placed every 5 m along the entire length of all the corridors (Figure 12) to help optical recognition of each occupants' position and time to pass from one line to another. Therefore, in the post-processing of the experiment, the videos were examined and the evacuation time as well as the walking speed for each participant was calculated. Finally, the participants were given a questionnaire to complete after the experiment in order to assess their experience.

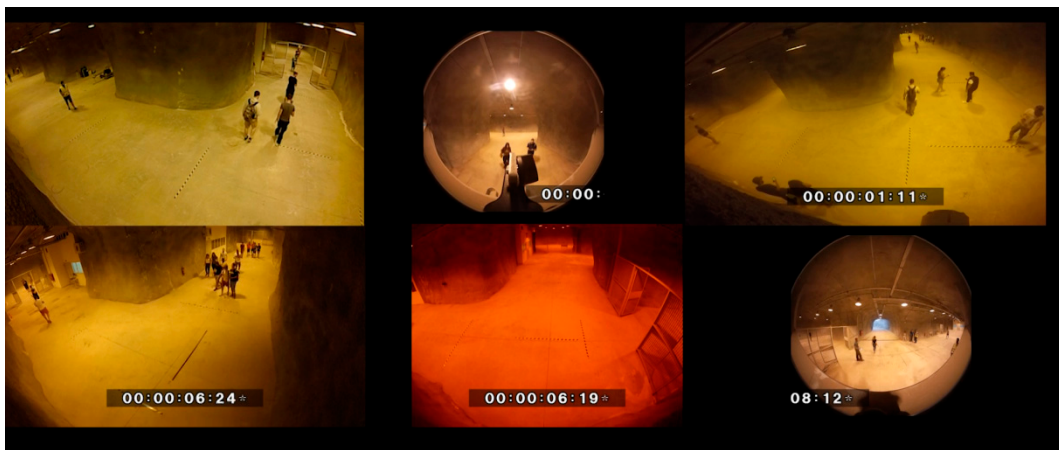


Figure 11. Views of interior cameras.



Figure 12. Self-adhesive tape placement.

3. Examined Scenarios

Two Evacuation Scenarios Were Examined

During the first scenario, the participants were placed in different locations within the underground area, when the evacuation procedure started. No smoke was generated, so the evacuation speed was not affected by visibility conditions. The participants were randomly positioned inside the space and they could choose their evacuation route between the tunnel exit and the stairwell exit. Their evacuation time and speed were monitored. The investigated speed might be considered as “unimpeded travel speed”, as the population density was much less than 0.54 persons/m. Therefore, the occupants moved at their own pace without considering any impeding [1].

During the second scenario, the participants were placed inside the office area and they evacuated through the tunnel exit. Non-irritant smoke was generated so the evacuation procedure was impeded by visibility conditions. Their walking speed along a specific distance was calculated.

After the tour of the site was completed, the first drill commenced. Participants were asked to disperse randomly in the underground rooms and were not allowed to access the office area. Figure 13 presents the age distribution of the participants in the underground area, at the beginning of evacuation in the first drill. Participants were asked to evacuate the site by selecting the nearest escape route from the two available (stairwell and tunnel). The speed on the staircase refers the travelling speed along the real travel path of the evacuation route, including both the stair length and the landing of each floor (Figure 14), as suggested in SFPE [1], unlike NFPA 130 where travel speed for stairs and escalators refers to the vertical distance [12].

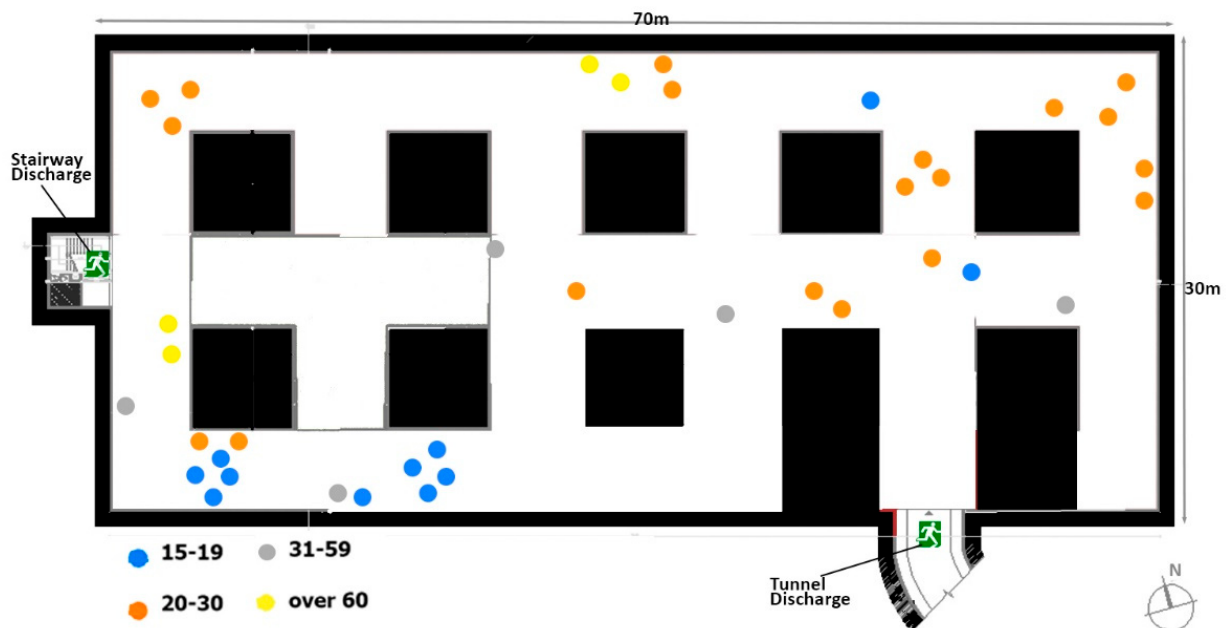


Figure 13. Participants distribution in the underground area during the first drill.

During the second evacuation drill, participants gathered in the office space and were invited to evacuate the area only from the tunnel exit in the presence of dense smoke that simulated fire conditions (Figure 15). The machine produced non-irritant smoke by combustion of mineral oil manufactured from crude petroleum oil (Figure 16). This kind of mineral oil is not classified as dangerous for supply or conveyance and has a low coefficient of friction presenting a slip hazard. Under normal conditions of use, inhalation of vapors is not feasible or likely to present an acute hazard and skin contact presents no acute health hazard except in the case of high-pressure injuries. The visibility conditions through the smoke are presented Figure 17.

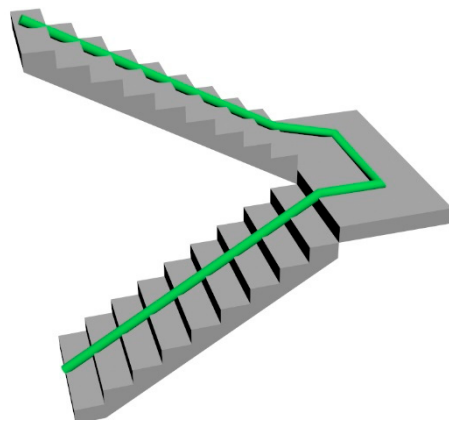


Figure 14. Travel path on stairs (green line).

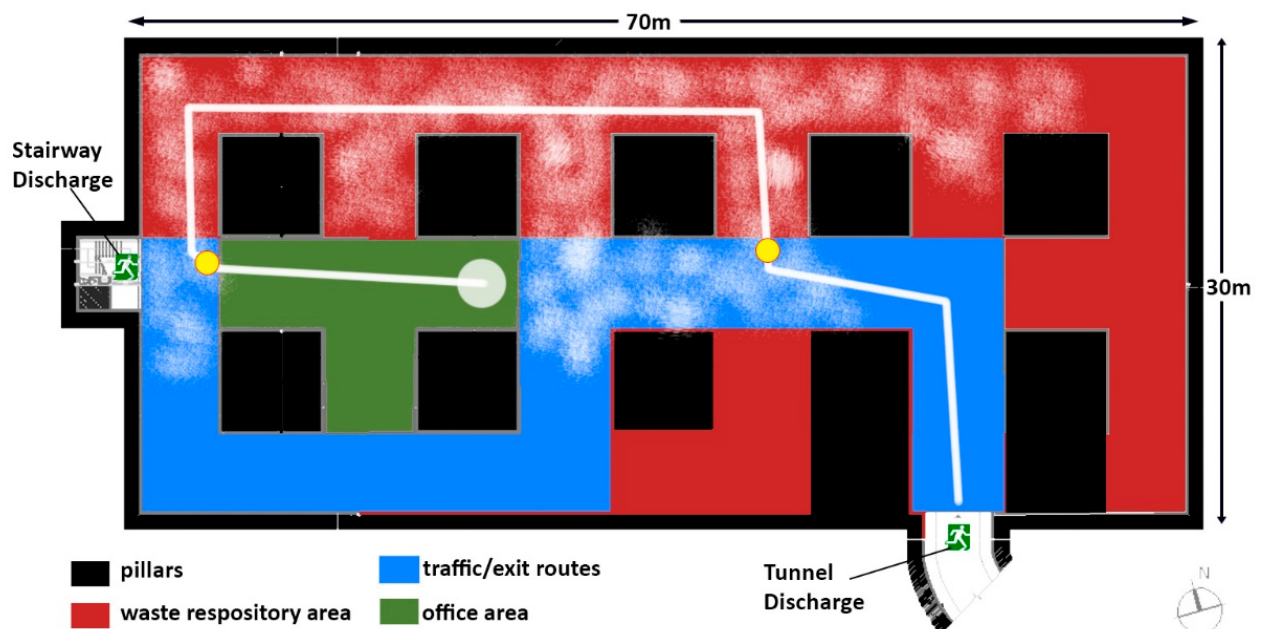


Figure 15. Exit route during second evacuation drill (smoke environment).



Figure 16. Smoke production machine.

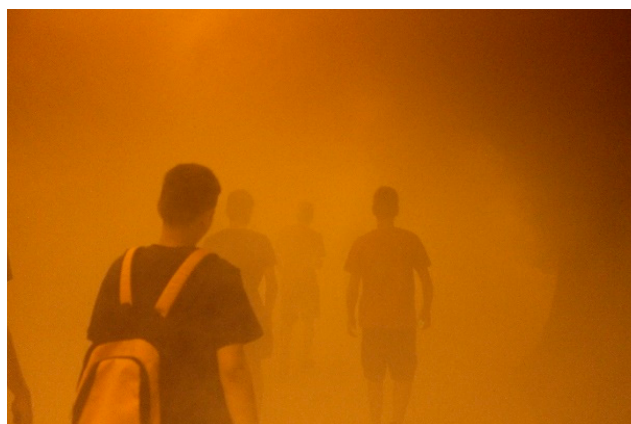


Figure 17. Visibility during evacuation in smoke environment.

Due to visibility limitations in camera videos, there was an uncertainty regarding the investigation and the monitoring of individual travel speed of each occupant. Instead, as all occupants commenced the evacuation from the same area and used the same exit route, the walking speed was calculated by taking into account the first and the last occupant who exited the office safely. As presented in Figure 15, the smoke did not cover the whole area but was essentially limited to the red area (waste repository). Therefore, the investigated speed concerns the travelling between the yellow dots in which the distance was estimated to be about 43 m. In the smoke-filled area, the visibility was assessed by careful observation of the evacuation video and through photographs. From this data, it emerged that at the breathing zone, the visibility ranges from 5 m to 7 m along the escape route, while at the ceiling of the underground and at height greater than 4 m, the visibility is almost zero.

4. Results—Discussion

4.1. First Evacuation Drill—Clear Environment

This drill involved 40 participants, of which 19 evacuated through tunnel exit and 21 through the stairwell exit, and their detailed evacuation times and speeds are shown in Table A1 in Appendix A. Each participant was assigned a unique ID number. The results are presented from the first occupant who completed the evacuation to the last one out, for the two egress routes of the underground space.

In Table 3 the statistics of the experiment are presented. Regarding horizontal travelling (corridor) the mean speed was 1.14 m/s with minimum value of 0.63 m/s, maximum value of 1.7 m/s and standard deviation of 0.20 m/s (analytical results are presented in Table A1 in Appendix A). These values are similar to those in previous research, as presented in Table 1. In a 6% inclination ascending ramp (tunnel), the minimum and maximum observed speed was 0.95 m/s and 1.37 m/s respectively, with an average of 1.15 m/s and standard deviation of 0.10 m/s, that also meet the values recommended by previous research (Table 1). There are no significant differences between the mean travel speed values of the corridor and the ascending ramp. The mean value of stairwell travel speed is 0.51 m/s, significantly lower than the horizontal travel speed. This value is higher than the value proposed by the NFPA. It is probable that this is due to the different examined staircase grade. The standard deviation is 0.03 which reveals a small variation of stairwell speed in the experiment.

Table 3. Occupants' speed (m/s) distribution in drill no.1 (clear environment).

	Max	Min	Mean	Std Dev
Corridor Speed	1.70	0.63	1.14	0.20
Tunnel Speed	1.37	0.95	1.15	0.10
Stairwell Speed	0.59	0.44	0.51	0.03

Table 4 presents evacuation time during the first evacuation drill, through the tunnel exit and the staircase exit, and reveals that using the stairwell as evacuation route requires higher evacuation time.

Table 4. Occupants' evacuation time (sec) distribution in drill no.1 (clear environment).

	Max	Min	Mean
Tunnel Exit	205	141	174
Stairwell Exit	220	170	200

Regarding the participants' ages, there are significant differences in corridor travel speed, slight differences in tunnel speed and almost none in upward stair travelling (Figure 18). More specifically, the corridor travel speed varies from 1.41 m/s for the age group 15–19 years old to 1.02 m/s for the group over 60, whereas the stairwell travel speed is nearly constant at 0.51 m/s for all group ages.

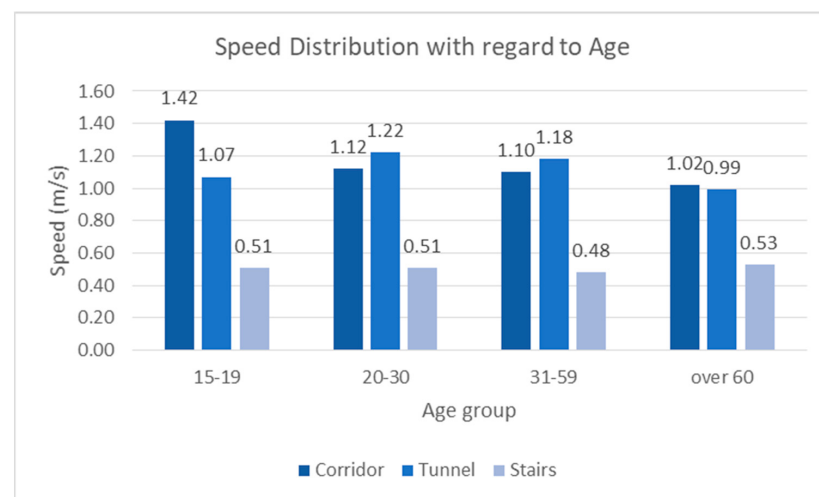


Figure 18. Speed distribution with regard to age group (clear environment).

Figure 19 presents the evacuation rate of participants during the first drill. Although the fact that the first occupants to evacuate used the tunnel exit, the occupants' flow rate is higher in the staircase exit with 0.42 persons/s, compared to the tunnel exit with a flow rate of 0.30 persons/s.

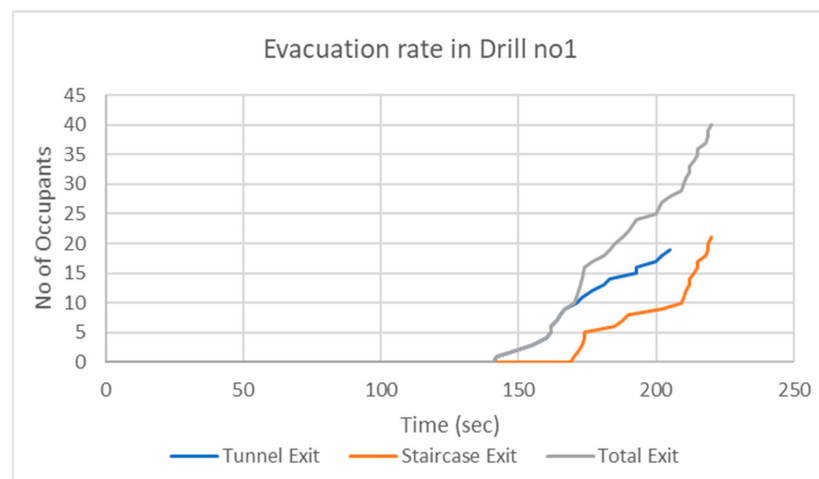


Figure 19. Evacuation rate during the first drill.

Figures 20 and 21 depict the variation of travel speed according to existing regulations and previous studies along a horizontal surface and upward staircase, respectively, with the results of the present study for a clear environment. It is observed that there is a good agreement between the previous studies and the current experiment for both cases.

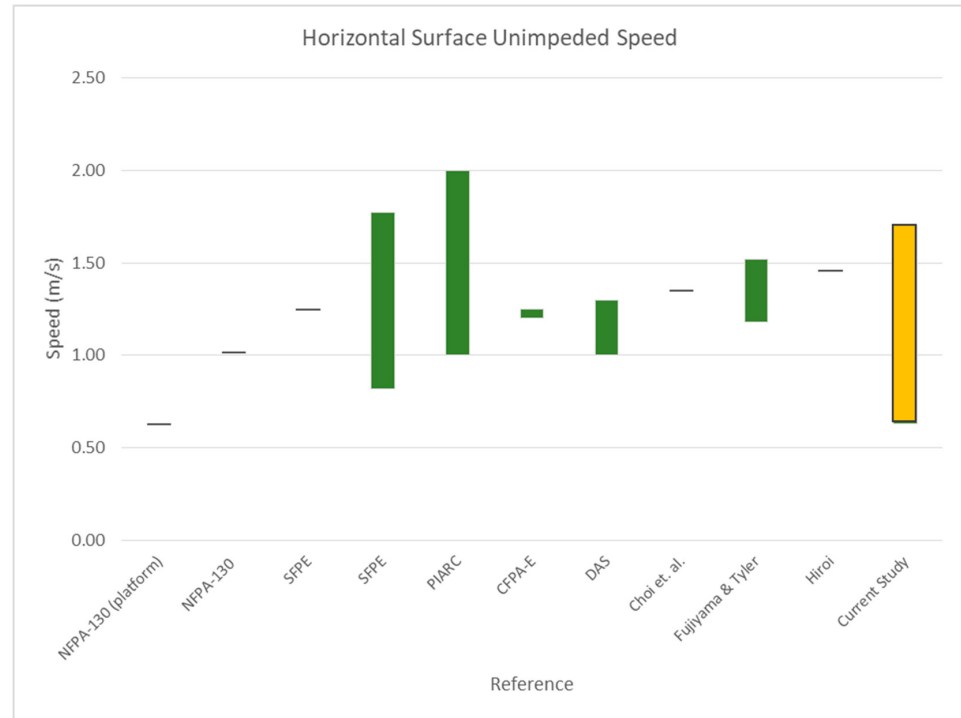


Figure 20. Walking speed (m/s) during unimpeded travelling in horizontal surface synopsis, database from previous studies and current experiment.

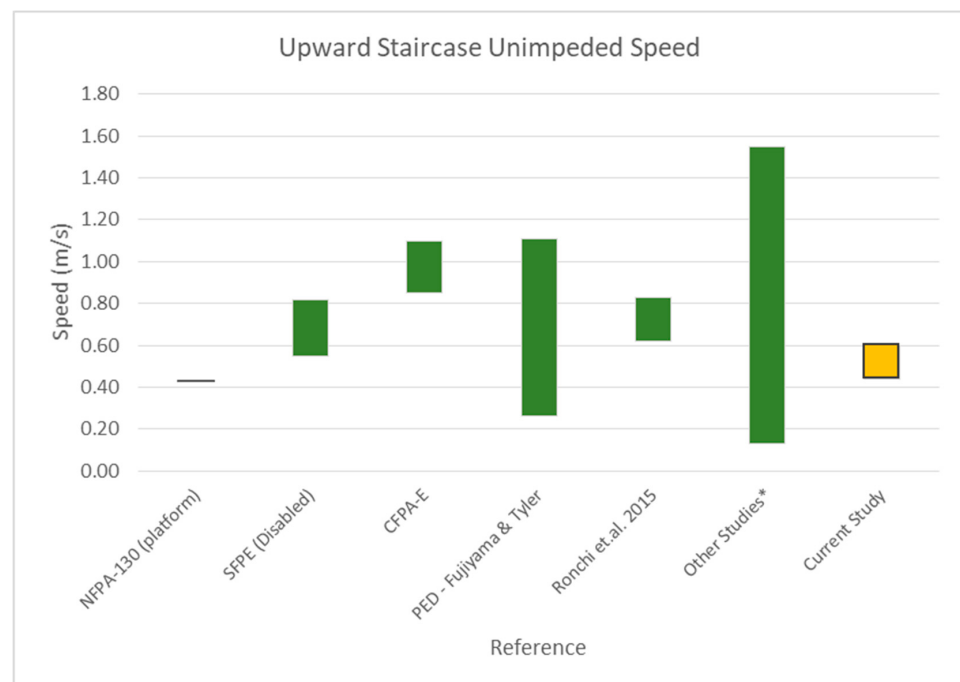


Figure 21. Walking speed (m/s) during unimpeded travelling in upward staircase synopsis, database from previous studies and current experiment.

4.2. Second Evacuation Drill—Smoke Environment

As mentioned above, a second evacuation drill took place, only this time the area was filled with non-irritant smoke. There were no devices to accurately measure the visibility conditions, but the visibility is estimated by the provided cameras. Therefore, the visibility is considered to be approximately between 6 m to 7 m (Figure 17). Due to the smoke propagation in the examined area, the travel distance in which each participant's speed was investigated is approximately 43 m (distance between yellow dots in Figure 15). The video records showed that the first occupant traveled the distance in 38" and the last in 42", so the speed is calculated as 1.08 m/s and 1.01 m/s respectively (Table 5). Compared to the first evacuation drill, one can observe that there is a decrease of the higher and the mean speed values while the lower value of speed does not have significant variation. There are two main reasons for this: (a) the low crowd density and the wide corridors of the exit route and (b) the fact that there were several guides (security managers) that constantly instructed the occupants on how to follow the exit route path. This speed value comes to agreement with the value proposed by Jin's experiment for non-irritant smoke and similar visibility conditions [8].

Table 5. Occupants' speed (m/s) in drill no.2 (smoke-filled environment).

Occupant ID	Time Travelling (sec)	Speed (m/s)
First	38	1.08
Last	42	1.01
Mean speed (m/s)	1.05	

Figure 22 depicts the variation of travel speed according to existing regulations and previous studies along a horizontal surface, with the results of the present study for smoke-filled environment. In this case there is also a good agreement between the previous studies and the current experiment, taking into account that the speed values depend strongly on the particular characteristics of each experiment and mainly on visibility conditions.

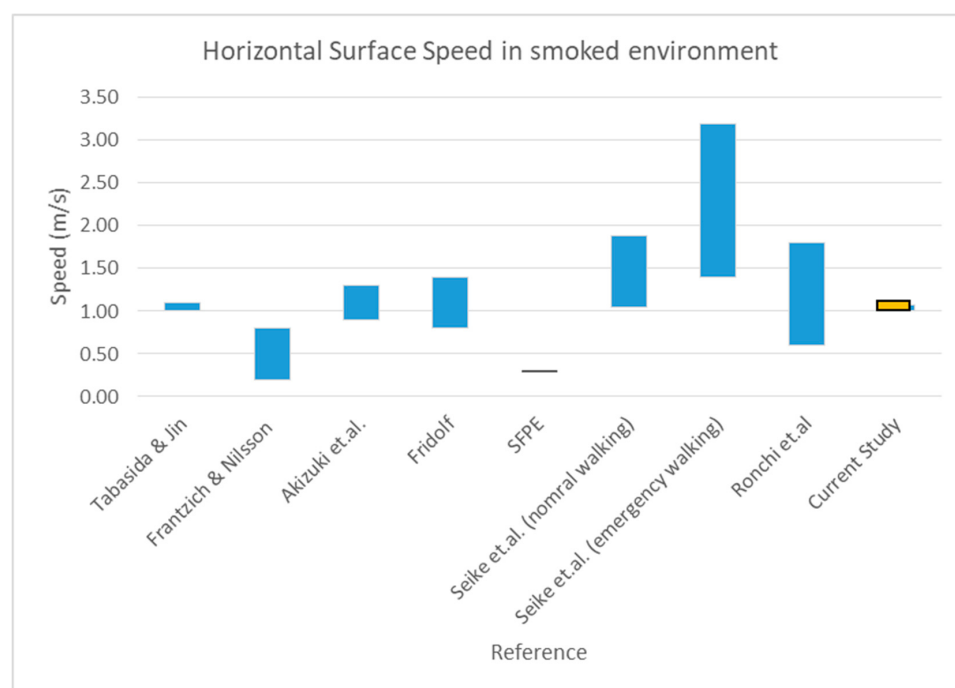


Figure 22. Walking speed (m/s) during evacuation in smoke-filled environments—previous and current experiment.

4.3. Participant Survey

At the end of the drills, the participants were asked to fill out a questionnaire (Appendix A). This was done to gain more information about their evacuation experience and to obtain information regarding the reliability of our participant “sample”. Their answers are presented in the following figures (Figures 23–27).

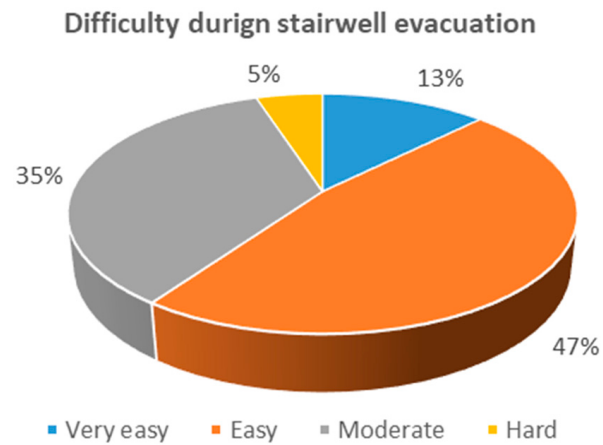


Figure 23. Difficulty during stairwell evacuation.

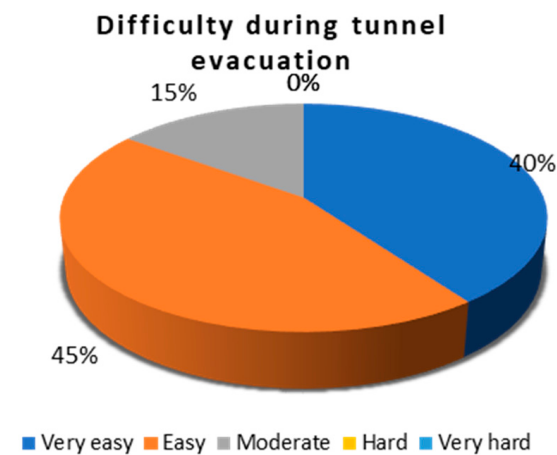


Figure 24. Difficulty during tunnel evacuation.

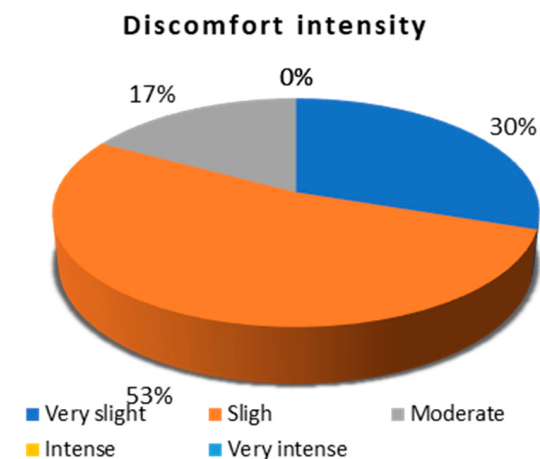


Figure 25. Discomfort intensity under smoke-filled environment.

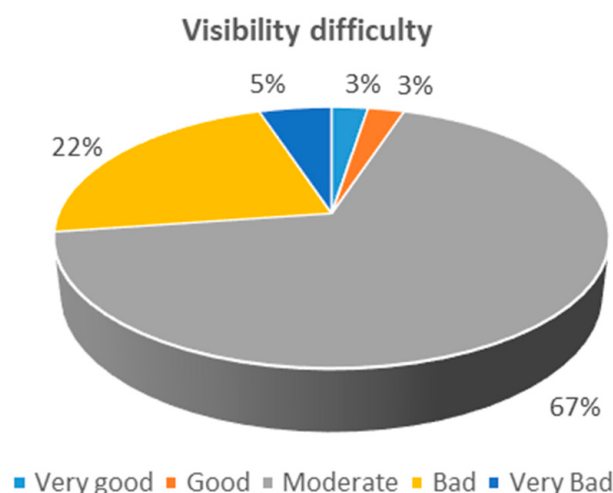


Figure 26. Visibility during evacuation under smoke-filled environment.

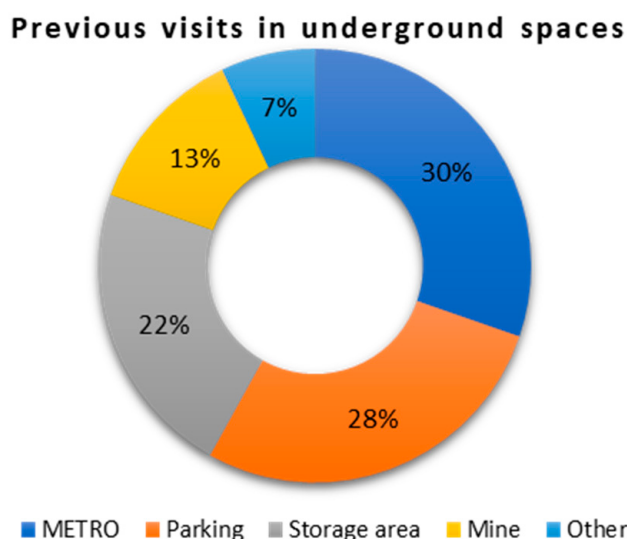


Figure 27. Previous visits in underground spaces.

All the occupants had previously visited an underground space, allowing them to be more-or-less aware of underground conditions. Regarding the evacuation procedure, 100% of the occupants mentioned that the travelling route through the tunnel was very easy to moderate and 50% of them mentioned that the escape route from the staircase was moderate to hard. Finally, regarding the conditions during evacuation in the smoke environment, most of the occupants declared a lack of visibility but they did not feel any high discomfort.

5. Conclusions

Significant conclusions arise from this study concerning the evacuation speed and the need for clear information and guidance during evacuation.

The maximum travelling speed on the horizontal surface reduced with the presence of smoke from 1.70 to 1.08 m/s, while the minimum speed increased from 0.63 to 1.01 m/s. This observation, along with the fact that in the smoke environment the maximum value of travel speed almost coincides with the minimum value, leads to the conclusion that in “difficult” environments, people tend to act more as groups and their behavior is somewhat homogenized.

The same conclusion derives from the evacuation through the staircase exit route, where one can observe a small variation of travel speed values, regardless of factors such

as occupants' age. From the experiment, one can see that there is a remarkable difference between travelling on horizontal corridor and the staircase, only concerning the maximum travelling speed value, while the mean speed value is practically identical. Travelling by the staircase requires attention and causes fatigue, which makes it a "difficult" environment for the users of the underground space and people are obliged to travel as a group.

Since the development of underground facilities is on the rise, the need for research on ascending evacuation, especially in deeper constructions, is urgent.

The avoidance of the further reduction of the minimum speed value during the smoke-induced experiment is due to the guidance provided to the evacuees during the procedure by the trained personnel. This reveals the importance of an effective guidance system in underground spaces, the existence of an adequate evacuation plan for emergency situations and the continuous training of the working personnel as well as for the users of underground spaces.

The effective and continuous guidance improves the occupant's psychology and minimizes stress which could lead to panic and unpredictable human behaviors that compromise their safety. This fact is also revealed from the answers that the participants gave to the questionnaire at the end of the experiment, where the majority claimed that they had no feelings of anxiety.

Regarding existing regulations and previous research, the unimpeded speed from the current experiment in wide corridor and ramp during evacuation in an underground space is within the proposed range, approximately 1–1.25 m/s. The same conclusion derives also for the stairway mean speed value, approximately 0.4–0.7 m/s. Therefore, the results of the experiment are generally in accordance with existing regulations. The speed value in a smoke-filled environment is, as mentioned above, strongly dependent on visibility conditions. The speed value derived from the experiment, 1.05 m/s, comes to an agreement with the value proposed by Jin's experiment for non-irritant smoke and visibility conditions (approximately 6 m to 7 m), as observed from the cameras [8].

As seen from the experiment, there is a significant difference in speed values among the distinctive exit paths of the underground space, tunnel ramp, horizontal surface and staircase. This difference directly affects the required egress time and the safety of the underground space. Therefore, occupants' speed is a crucial parameter which should be taken into account along with other technical and economic factors, in order to decide the selection of the egress routes type, during the design of an underground infrastructure.

The need for evacuation procedure improvement is a continuous project. This experiment shows that if the occupants' awareness through education and training is high, the evacuation can be completed on time and without any losses. Thus, the safety systems and guidance in workplaces constitute a major factor for the effectiveness of the evacuation procedure and should be taken into account when designing an underground space prior to construction.

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Appendix A

QUESTIONNAIRE

Please tick with an X the following information:

1. Gender: Male ☐ Female ☐
2. Age:
3. Have you ever been to an underground space? If so choose which of the following.
METRO ☐ Parking ☐ Storage area ☐ Mine ☐ Other ☐
4. Which exit did you use in the first evacuation drill;
Tunnel ☐ Stairwell ☐
5. Describe the degree of difficulty you encountered when leaving the tunnel (if you used this escape route at least once).
Very easy ☐ Easy ☐ Moderate ☐ Hard ☐ Very hard ☐
6. Describe the degree of difficulty you encountered when leaving the stairwell (if you used this escape route at least once).
Very easy ☐ Easy ☐ Moderate ☐ Hard ☐ Very hard ☐
7. Describe your visibility during the second evacuation drill.
Very bad ☐ Bad ☐ Moderate ☐ Good ☐ Very good ☐
8. Describe the discomfort you felt during the second evacuation drill due to the smoke.
Very slight ☐ Slight ☐ Moderate ☐ Intense ☐ Very intense ☐

Figure A1. Questionnaire that shared to volunteers.

Table A1. First drill results (clear environment).

ID	Age	Evacuation Time (min:sec)	Corridor Speed (m/s)	Tunnel Speed (m/s)	Staircase Speed (m/s)
ID1	32	2:22	1.42	1.30	
ID2	20	2:29	1.25	1.37	
ID3	30	2:35	1.00	1.22	
ID4	24	2:40	1.36	1.22	
ID5	21	2:42	0.63	1.22	
ID6	24	2:42	1.70	1.23	
ID7	35	2:44	1.10	1.14	
ID8	35	2:45	0.83	1.13	
ID9	22	2:47	1.25	1.22	
ID10	21	2:51	1.13	1.19	
ID11	24	2:53	1.00	1.17	
ID12	26	2:57	1.38	1.13	
ID13	47	3:01	1.25	1.13	
ID14	15	3:03	1.25	1.11	
ID15	15	3:13	1.25	1.05	
ID16	15	3:13	1.36	1.05	
ID17	68	3:20	1.07	1.02	
ID18	63	3:22	1.00	0.95	
ID19	66	3:25	1.00	1.01	
ID20	24	2:50	1.25		0.56
ID21	27	2:52	0.83		0.59
ID22	60	2:53	1.00		0.53
ID23	15	2:54	1.25		0.55
ID24	15	2:54	1.25		0.55
ID25	24	3:05	0.83		0.54
ID26	28	3:08	0.83		0.54
ID27	15	3:10	1.00		0.54
ID28	25	3:22	1.25		0.49
ID29	24	3:29	1.00		0.48
ID30	26	3:30	1.00		0.49
ID31	39	3:31	0.92		0.48
ID32	15	3:32	1.25		0.49
ID33	15	3:32	1.25		0.49
ID34	19	3:34	1.43		0.50
ID35	15	3:35	1.13		0.49
ID36	15	3:35	1.25		0.49
ID37	25	3:38	1.13		0.44
ID38	25	3:39	1.25		0.49
ID39	21	3:39	1.13		0.50
ID40	26	3:40	1.19		0.49

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