19th WORLD CONFERENCE OF THE ASSOCIATED RESEARCH CENTRES FOR THE URBAN UNDERGROUND SPACE
Belgrade, Serbia, November 4-7, 2025.

ACUUS BELGRADE 2025

Paper No: 4.7.110
DOI: 10.46793/ACUUS2025.4.7.110

EVACUATION BEHAVIOR AND SAFETY EGRESS ANALYSIS IN TUNNEL FIRES: A VIRTUAL REALITY SIMULATION STUDY

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Abstract: The rapid development of underground transport tunnels is accompanied by the inevitable risk of road accidents, which can result in major fires. The required safety egress time (RSET) is a critical parameter in designing fire mitigation strategies for tunnels. In these environments, where visibility is severely reduced due to smoke, evacuation behavior—including pre-evacuation time, encompassing alarm response, reaction time, and vehicle abandonment—plays a significant role in overall safety. This study employed a virtual reality (VR) simulation in Unreal Engine of a full-scale road tunnel, paired with computational fluid dynamics (CFD) modeling, to examine occupant behavior during tunnel fires across different scenarios. These scenarios varied based on smoke presence, alarm activation speed, and proximity to the fire source. The key factors analyzed were: (a) evacuation decision-making, (b) pre-evacuation time, and (c) route-finding strategies. The results indicate that pre-evacuation time is influenced by the type of emergency warning signals, smoke spreading, alarms, and occupants' behavior. Most participants relied on exit signs to navigate their way out. However, smoke-filled routes often led some individuals to bypass nearby exits in favor of more distant ones, revealing important implications for tunnel design and safety planning.

Keywords: tunnel vehicle accident, virtual reality experiment, evacuation behavior, evacuation time

1. INTRODUCTION

The growth and dynamics of underground projects in recent years is driven by the general trend of sustainable development that determines the choices of the modern world at a strategic level. The rapid increase in population, combined with the lack of appropriate land-use planning, has often in the past led to a significant deterioration in the quality of life, particularly in urban areas, where the lack of space and environmental conditions for the development of vital activities has often been observed. The main concept in the design of an underground project is the safety of people during construction and operation. In case of emergency such as toxic release or fire, a core emergency response strategy for the safety of people is the structure evacuation.

Human behavior can highly influence the accident occurrence as well as the development of the event (e.g. fire) and the safe management of the incident. Depending on the situation, human behavior can be classified into several categories: routine behavior before an incident, including preventive measures; actions that may contribute to the occurrence of accidents or fires; responses to the presence of fire; behavior related to rescue and evacuation; and actions associated with firefighting (Thematic Network Fire in Tunnels, 2006). Several studies have been investigated the human behavior during emergency evacuation in road or rail tunnels either using computer software (Qin et al., 2020; Ronchi et al., 2012) or real scale experiments (Carlson et al., 2019; Fridolf et al., 2013; Storm & Celander, 2022). Similar studies have also been conducted to investigate evacuation procedures through real-scale fire drills in other underground facilities(Kallianiotis et al., 2022). It is widely acknowledged across the

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literature that one of the primary factors influencing human behavior and evacuation procedures during tunnel fire incidents is the reduction of visibility caused by smoke. Visibility refers to the distance at which an observer can discern an object against its background, while obscuration describes the reduction in light intensity as it passes through smoke. In fire safety analysis, calculated visibility is commonly used as a criterion for occupant tenability, whereas obscuration is primarily employed to visually represent smoke in simulations. The intensity of light passing a smoked environment is attenuated based on Beer–Lambert Law (1) in which I is the light intensity; K is the extinction coefficient; L is the distance that light travels in the smoked area; and I_0 is incident intensity. K is calculated from equation (2) in which K_m is the mass specific extinction coefficient and in FDS is equal to $8700m^2/Kg$ and ρ_s is the smoke density. Finally, the visibility S is calculated from equation (3) in which the constant C is depending on type of sign and for reflective one is between 2 to 4 and for illuminating is between 5 to 10 (Jin, 1997). The default value in FDS is 3 since the visibility refers to a reflective sign (McGrattan et al., 2023a, 2023b).

$$I = I_0 e^{-KL} \quad (1)$$
$$K = K_m \rho_s \quad (2)$$
$$S = \frac{C}{K} \quad (3)$$

A reduction in visibility does not directly impair occupants but significantly affects their movement speed (Fridolf et al., 2013; Jin, 1997), thereby increasing the time spent in hazardous environments with high concentrations of toxic gases (e.g., CO) and temperatures. The toxicity resulting from fire products is assessed based on the concentration of carbon monoxide (CO) and carbon dioxide (CO_2) generated during the combustion process, as well as the reduction of oxygen (O_2) levels, which may lead to hypoxic conditions (SFPE, 2016). The maximum value of the Fractional Effective Dose (FED_{tot}) is 1.0, indicating the threshold for incapacitation, and is calculated using Equation (4). The individual FED for carbon monoxide exposure (FED_{CO}) is determined according to Equation (5). The physiological effects of elevated CO concentrations on the human body are summarized in Table 1. According to SFPE (SFPE, 2016) and to NFPA (NFPA, 2014) the tenability limits of high temperature are presented in Table 2.

$$FED_{tot} = FED_{CO} \times V_{CO2} \times FED_{O2} \quad (4)$$
$$FED_{CO} = \sum_{t1}^{t2} \frac{[CO]}{35000} \times \Delta t \quad (5)$$

Table 1. *Consequences to human health after carbon monoxide exposure (Purser & McAllister, 2016)*

CO Concentration in ppm	Consequences
35	Headache and dizziness after constant exposure 6 to 8 hours.
100	Slight headache after 2 to 3 hours.
200	Slight headache after 2 to 3 hours. Loss of judgment
400	Frontal headache after 1 to 2 hours.
800	Dizziness, nausea, convulsions within 45 minutes. Unconsciousness within 2 hours.
1600	Headache, tachycardia, dizziness and nausea within 20 minutes. Death in less than 2 hours.
3200	Headache, dizziness and nausea within 5 to 10 minutes. Death within 30 minutes.
6400	Headache and dizziness in 1 to 2 minutes. Convulsions and respiratory arrest, death in less than 20 minutes.
12800	Unconsciousness after 2-3 inhalations. Death in less than 3 minutes.

Table 2. *Maximum exposure time per exposure temperature*

Expose Temperature (ºC)	Without Incapacitation (min)
80	3,8
75	4,7
70	6,0
65	7,7
60	10,1
55	13,6
50	18,8
45	26,9
40	40,2

Several studies have been conducted to investigate human behavior during tunnel evacuation procedures through the implementation of Virtual Reality (VR) applications (Moscoso et al., 2024; Ronchi et al., 2015; Skjermo et al., 2024). Nevertheless, the integration of Computational Fluid Dynamics (CFD) results into Virtual Environments has not yet been fully achieved with high precision; only a limited number of studies have attempted to address this gap (Cha et al., 2012; Zhang et al., 2023).

In the current study, the human behavior in a road tunnel accident, both in smoked and clear environment, is assesses. Fire Dynamic Simulator (FDS) a CFD software has been conducted to simulate fire and its products (smoke, toxic gases etc.) propagation inside a typical road tunnel section. The CFD results were converted into three-dimensional visual data and integrated into the virtual 3D environment. To record the human behavior a VR application has been designed and developed in Unreal Engine software to simulate emergency fire scenarios in road tunnel in order to record the user behavior and evacuation time.

In summary, an illustrative full-size road tunnel in virtual reality (VR) environment and CFD simulation were conducted to perform an experiment to study the occupant's behavior in a tunnel fire in 6 different scenarios (smoke presence/absence, alarm activation faster/slower, distance to fire source near/far). The main factors studied in this research are: (a) evacuation time (b) pre-evacuation time and (c) route-finding method.

2. METHODOLOGY

To develop a realistic virtual reality environment, all constituent components must be appropriately integrated. Initially, the 3D design of the tunnel structure, along with 3D models of vehicles, safety equipment, exit doors, and other relevant elements, was created to comply with national and international regulations (Greek Government Journal, 2007; NFPA, 2013; OMOE, 2002). Additionally, non-playable characters (NPCs) were incorporated into the Virtual Reality Environment (VRE) and programmed to behave as typical individuals would during an emergency evacuation—specifically, by attempting to locate the nearest exit without engaging in other activities (e.g., firefighting). A critical aspect in the event of a fire in a road tunnel is the significant reduction in visibility caused by smoke propagation within the enclosed space. To simulate this realistically, an initial fire and smoke propagation analysis was conducted using PyroSim software (Thunderhead Engineering, 2024b) which features a user-friendly interface and employs the Fire Dynamics Simulator (FDS) model developed by NIST (McGrattan et al., 2023a, 2023b, 2023c) . As there is currently no open-source plugin or application programming interface (API) available to directly integrate FDS results into Unreal Engine (UE), this study manually analyzed the time-dependent visibility data along the tunnel length and replicated the smoke effects in UE using the Niagara Effects system.

The completed virtual reality environment (VRE) is presented to users through the Meta Quest 2 VR headset, where head orientation is managed by the headset itself, and user movement is controlled via hand-held controllers. For each participant, reaction time, position, final exit choice and distance travelled are recorded and stored in a local database on the PC. As the smoke effect implemented in Unreal Engine (UE) includes only the visibility parameter, it does not incorporate data on toxic gas concentrations or smoke temperature, which are necessary for assessing the impact of smoke on tunnel users during evacuation. However, FDS results can be integrated into Pathfinder, an agent-based evacuation simulation software. Therefore, user trajectories obtained from the database are used to constrain virtual agents in Pathfinder to follow the same paths taken by real users, enabling an estimation of the smoke impact along those trajectories.

The aforementioned workflow methodology is presented in a Figure 1 and are analyzed in the following sections.

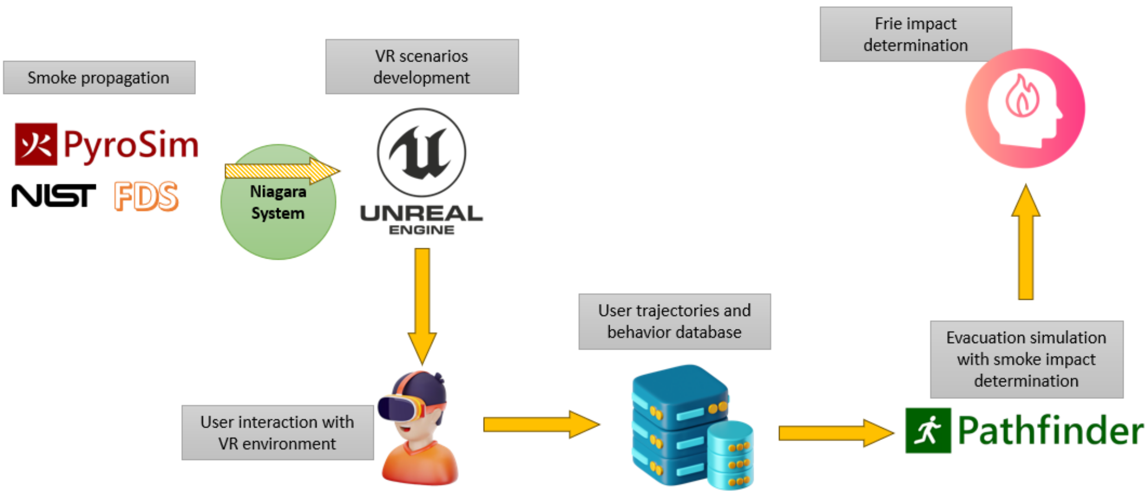


Figure 1. *Methodology graphical abstract*

2.1. Tunnel design

The tunnel model employed in this study is based on a typical single-bore road tunnel with a two-lane and circular cross-section (Figure 2-a,b), measuring 10m in width and 1,200 meters in length, with emergency exits positioned at intervals of 350m (Figure 2-c). The model also includes moving vehicles, human actors representing occupants of other vehicles, as well as dynamic elements such as fire and smoke.

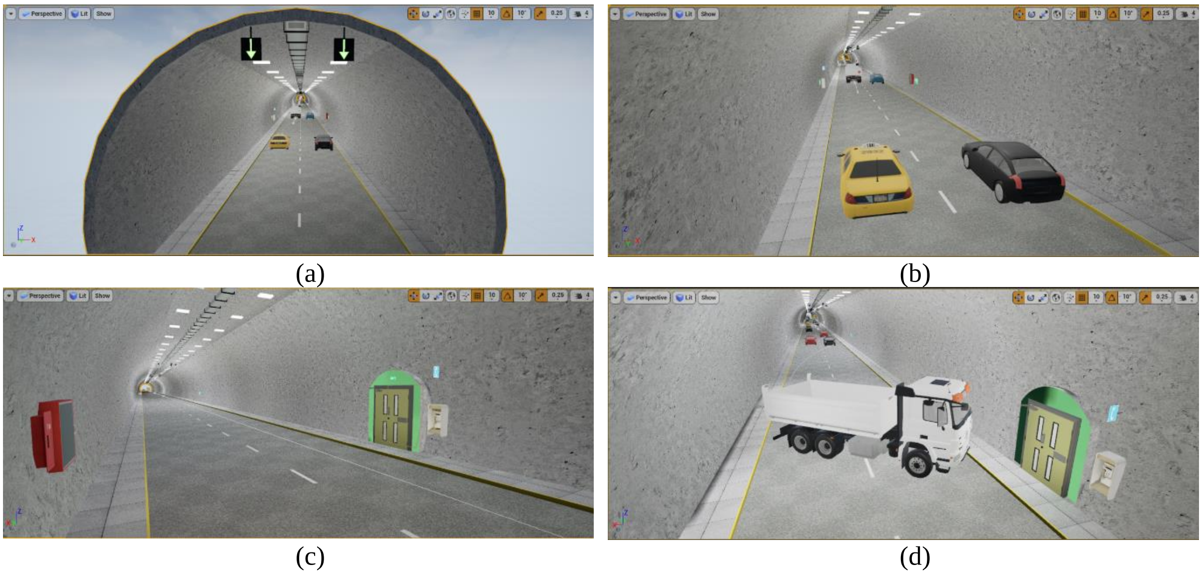


Figure 1. *3D visualization of tunnel model in UE: (a) tunnel model perspective: (b) tunnel indoor traffic; (c) exit door and emergency devices position; (d) truck fire event location.*

The background scenario of the simulated incident involves a truck driver losing control of the vehicle, resulting in a collision with the tunnel wall and the subsequent ignition of a fire in the truck's cargo. To represent a worst-case scenario, the crash is assumed to occur adjacent to an emergency exit—specifically, the second exit located 700 meters from the tunnel entrance—thereby rendering it inaccessible to users during the evacuation procedure (Figure 2-d).

2.2. Scenario design

The main scenario begins with the user positioned in the driver's seat of a car, simulating a typical tunnel transit. At a randomized point in time, the car comes to a stop due to a truck accident ahead. The stopping distance varies, placing the user either in close proximity to the accident—providing a clear line of sight—or farther away, where visibility of the incident is limited. The moment the truck collision occurs is defined as the "zero point", marking the start of the evacuation time. An emergency alarm is activated following the incident, and the overhead lane control signals change from green arrows to red "X" symbols (Figure1-a), instructing approaching drivers to stop their vehicles. The alarm activation time varies and is set to either 20 seconds or 60 seconds after the zero point, depending on the simulation scenario. Users must independently decide when to exit their vehicle and how to respond prior to initiating evacuation—this may include actions such as firefighting or investigating the cause of the accident. Ultimately, users must identify and select an available exit to evacuate the tunnel. Evacuation is considered complete once the user exits either through an emergency exit or returns to the tunnel entrance. Figure 2 illustrate the events timeline of the tunnel accident and evacuation.

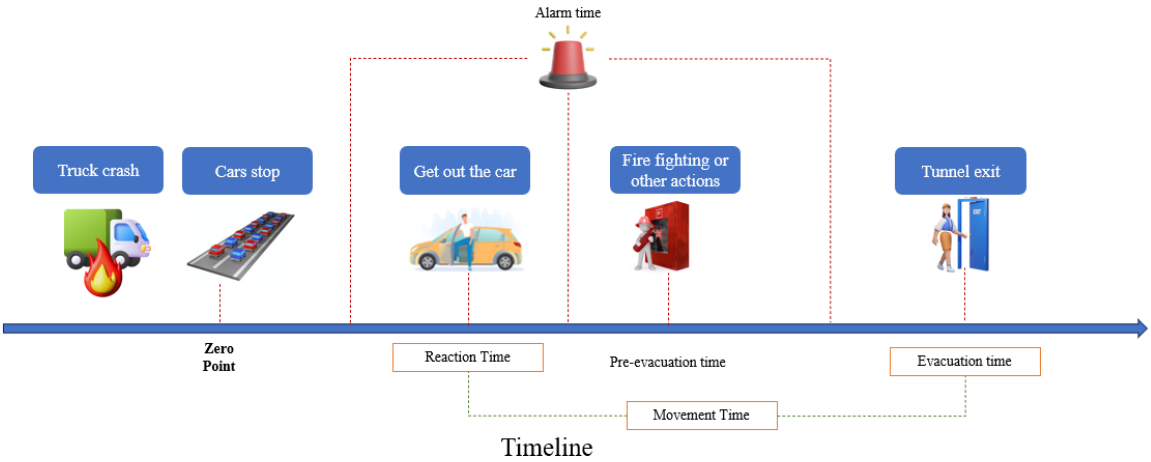


Figure 2. *Evacuation actions timeline*

In addition, several assumptions were made regarding other parameters:

- Car speed ranges from 50 to 80 km/h
- Air flow is opposite to cars direction, so as the smoke covers faster the area where the cars have been trapped inside the tunnel, with a velocity of 1m/s approximately
- Traffic load 20-30 trapped vehicles inside the tunnel
- Each vehicle transfers 1 or 2 passengers (driver or driver plus one)
- 10% of the NPCs will leave from the tunnel entrance and 90% will leave from the nearest exit (Kinateder et al., 2015)
- Unimpeded occupants' speed (both NPC and user) 1.2m/s (Nelson & Mowrer, 2002)
- NPCs are forced to get out of car and appear in the tunnel 30 sec after the zero point

In addition to the scenario design parameters, the presence of fire and smoke resulting from the accident is incorporated into the simulation to observe and record users' behavioral responses and the timing of their activation. Accordingly, six distinct scenarios were developed, varying the states of three key parameters, as summarized in Table 3.

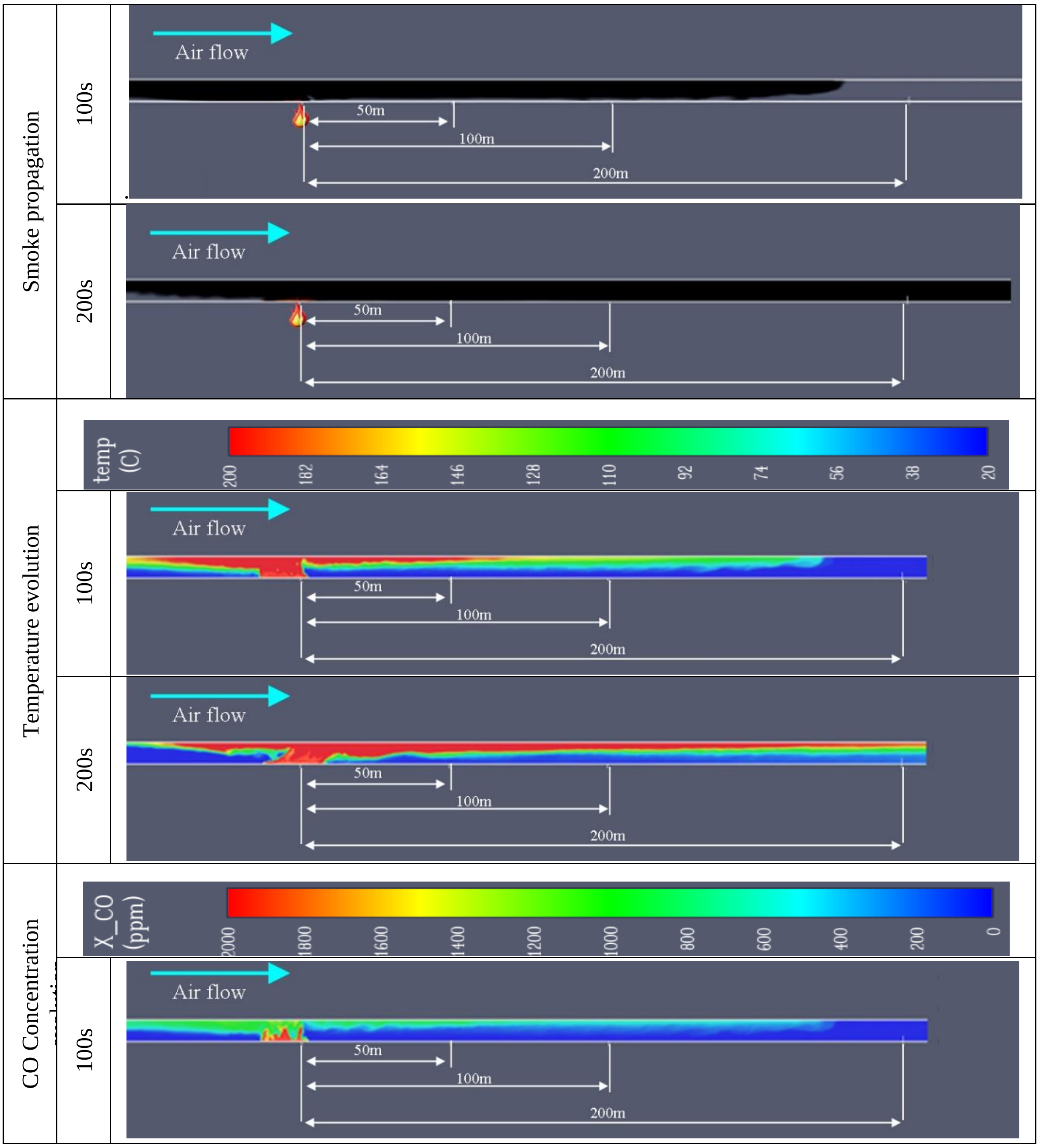
Table 3. *Simulated scenarios.*

Scenario ID	Fire and smoke	Visibility to fire incident	Alarm activation time (sec)
1	YES	Clear	60
2	NO	Clear	60
3	YES	Clear	20
4	YES	Limited	60
5	NO	Limited	60
6	YES	Limited	20

2.3. Fire simulation

The fire used in the analysis is caused by a heavy vehicle resulting a peak Heat Release Rate (HRR) up to 100MW (Greek Tunneling Society, 2011) and polyurethane (GM27) was chosen as the combustible material for simulation purposes, since it is a widely used material worldwide; it is highly flammable (McKenna & Hull, 2016; PIARC, 2004) and is included in a variety of other materials. The natural air flow of 1m/s inside the tunnel is achieved by the pressure differential between the tunnel portals which is 3 Pa.

The fire simulation results, along the tunnel length from the side view, are presented in Figure 3 and shows that the smoke covers the tunnel after 200s from fire ignition; the temperature reaches high values after 100s in the first 100m and more than 200m after 200s from fire ignition; CO concentration does not reach critical high values at the breathing zone; and the visibility drops dramatically even in breathing zone in short time.



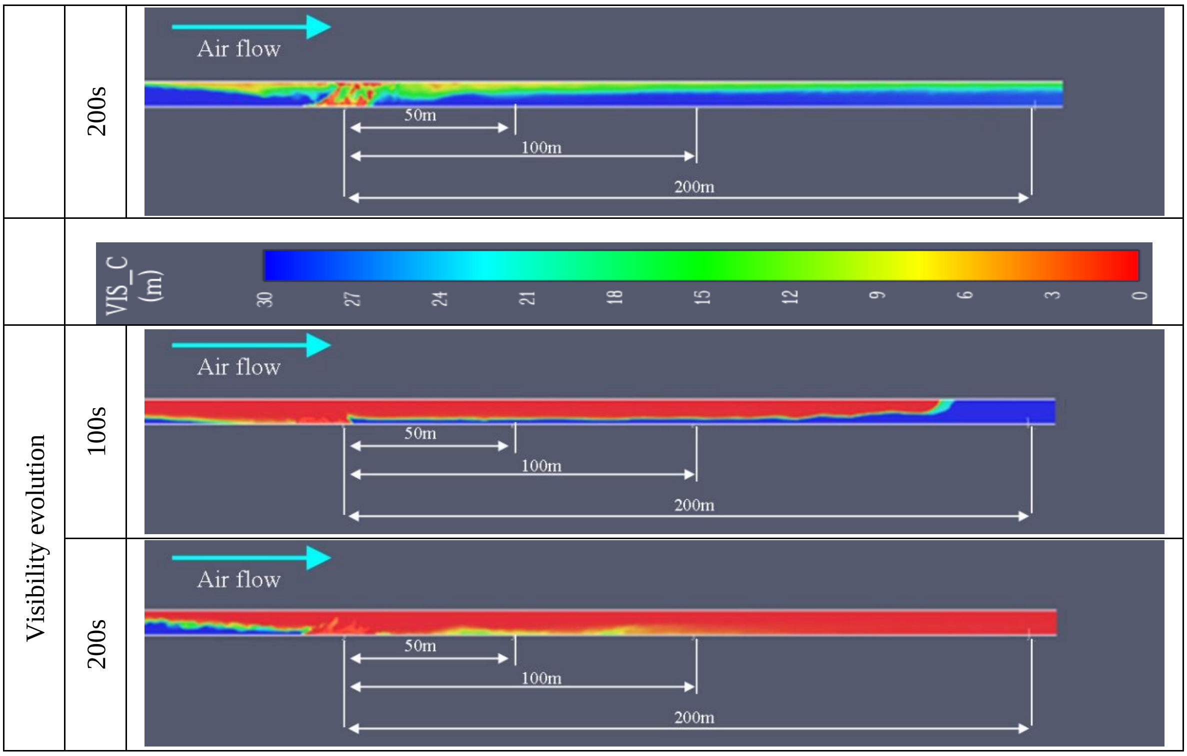
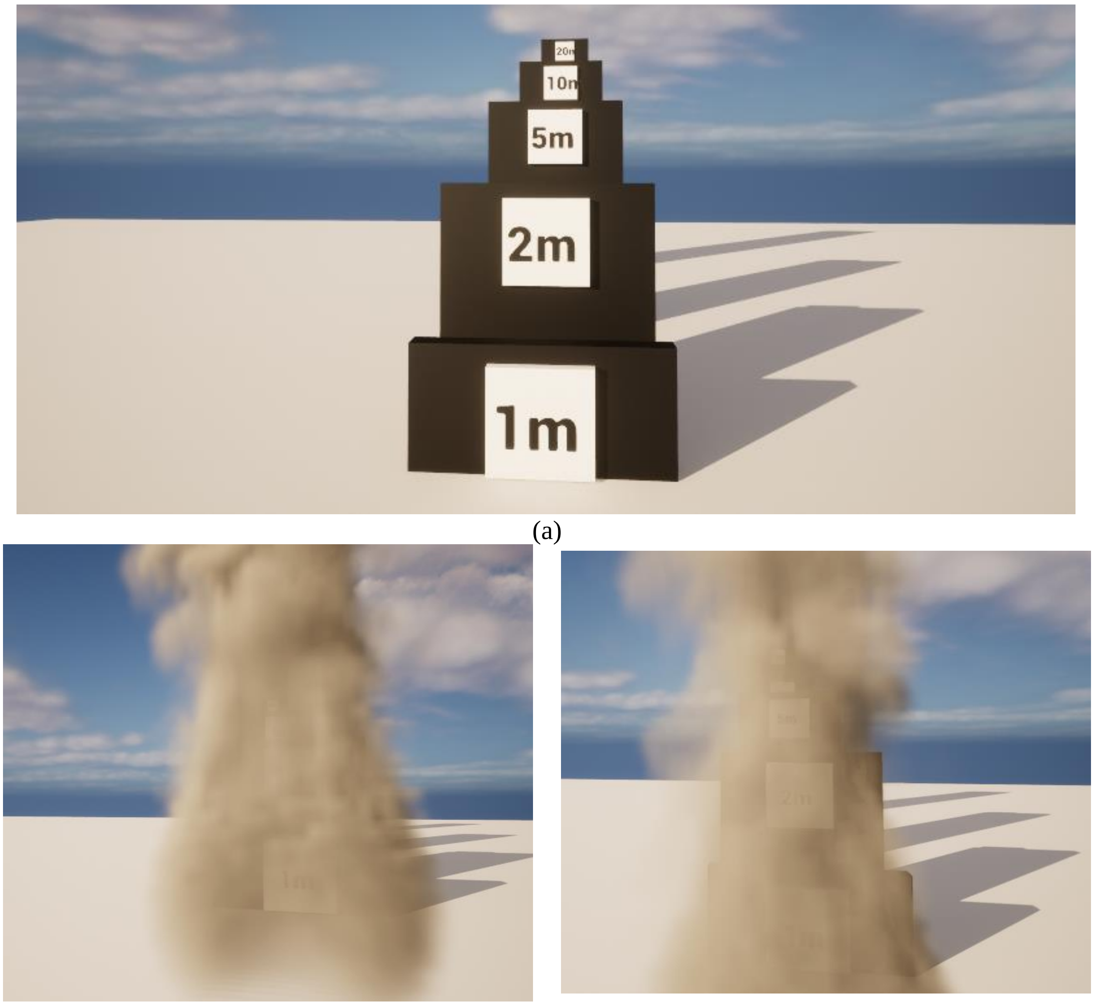


Figure 3. *Fire simulation results*

The results will be used in two ways:

1. The evolution of visibility along the tunnel, specifically within the breathing zone, will be used to define visibility limits in the virtual reality environment through the implementation of the Niagara effect in Unreal Engine (UE).
2. The evolution of carbon monoxide (CO) concentration and temperature will be integrated into the Pathfinder software to assess the impact of smoke and fire on occupants. This is achieved by constraining the movement of computer agents to match the user trajectories recorded during the VR experiment.

The Niagara Fluids effect is a plugin in UE that enables the creation and real-time simulation of dynamic particle effects. In this application, it is used to visually represent smoke generated from the truck fire scenario. To replicate the smoke propagation, the Niagara effect was instantiated multiple times along the tunnel length and activated at specific time intervals to align with the smoke evolution data obtained from the FDS (Figure 3). The properties of each instance were configured using time-based curves to match the visibility levels at corresponding locations, as calculated by FDS. To determine the visibility limitations produced by the Niagara effect settings, simple visibility markers—white squares placed on black backdrops—were positioned at varying distances from a Niagara instance within the UE environment (Figure 4-a). The properties of Niagara instance adjusted accordingly to achieve the desired visibility limit (Figure 4-b,c). A comparison between the FDS-derived visibility and the corresponding UE implementation is presented in Figure 5.



(a)

(b) (c)

Figure 4. *Niagara system smokeimpkementation and visibility measurment; (a) reflective sign positioning; (b) low visibility 1-2 m; (c) higher visibility 10 m*

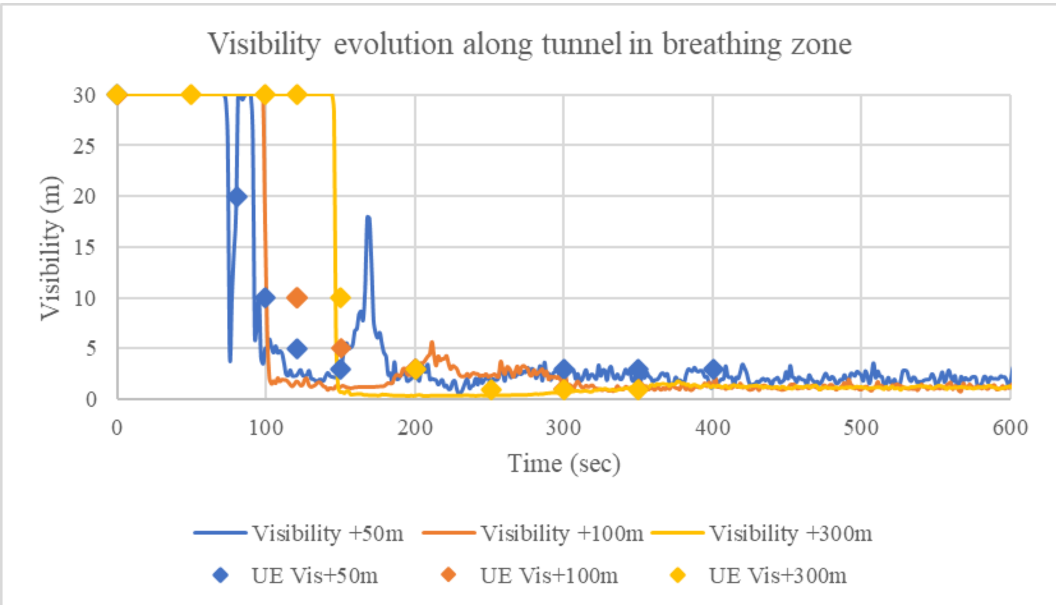


Figure 5. *Visibility evolution in FDS and in UE*

3. VR EXPERIMENT IMPLEMENTATION AND RESULTS

The VR experimental protocol consisted of four parts: i) information and guidelines concerning the VR headset and controllers operation to avoid self-injury and hardware damage, ii) familiarization with VR application, by offering 2-3 minutes moving freely in a demo level, iii) running the experiment in random level according to scenario ID (Table 1), iv) answering a questionnaire for demographics records and VR application based questions.

Participants (N=112) were recruited on a voluntary basis from the university community. The sample is relatively gender balanced (F(male)=51.8%) but very young (ages between 18-54 but only a few above 40) due to increased student participation. The experiment was conducted in the Laboratory of Mining Engineering and Environmental Mining at the National Technical University of Athens (NTUA), within an enclosed room. Participant movement within the virtual environment was controlled using a hand-held joystick. However, walking speed could not be adjusted and therefore remained fixed (1.2 m/s) across all participants and visibility conditions, which constitutes a limitation of the study. As the study took place during the COVID-19 pandemic, all official health and safety protocols were strictly followed (Figure 6).

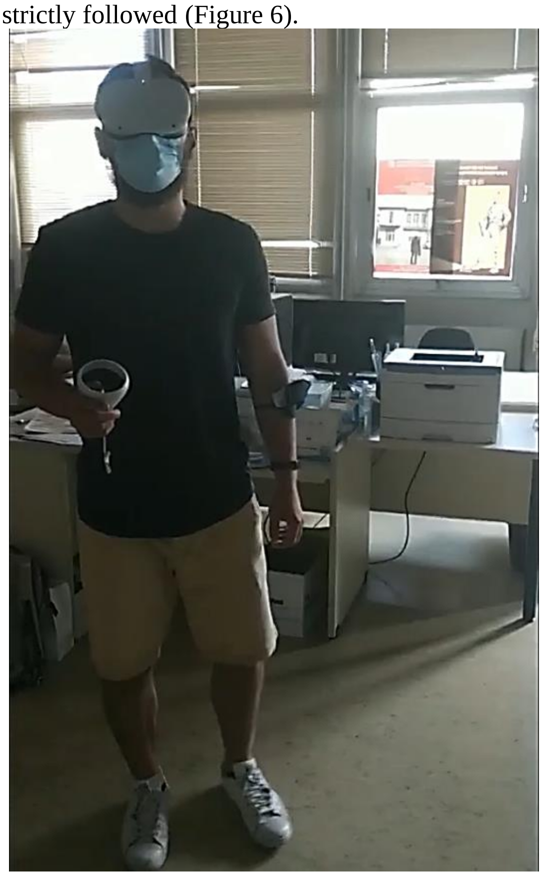


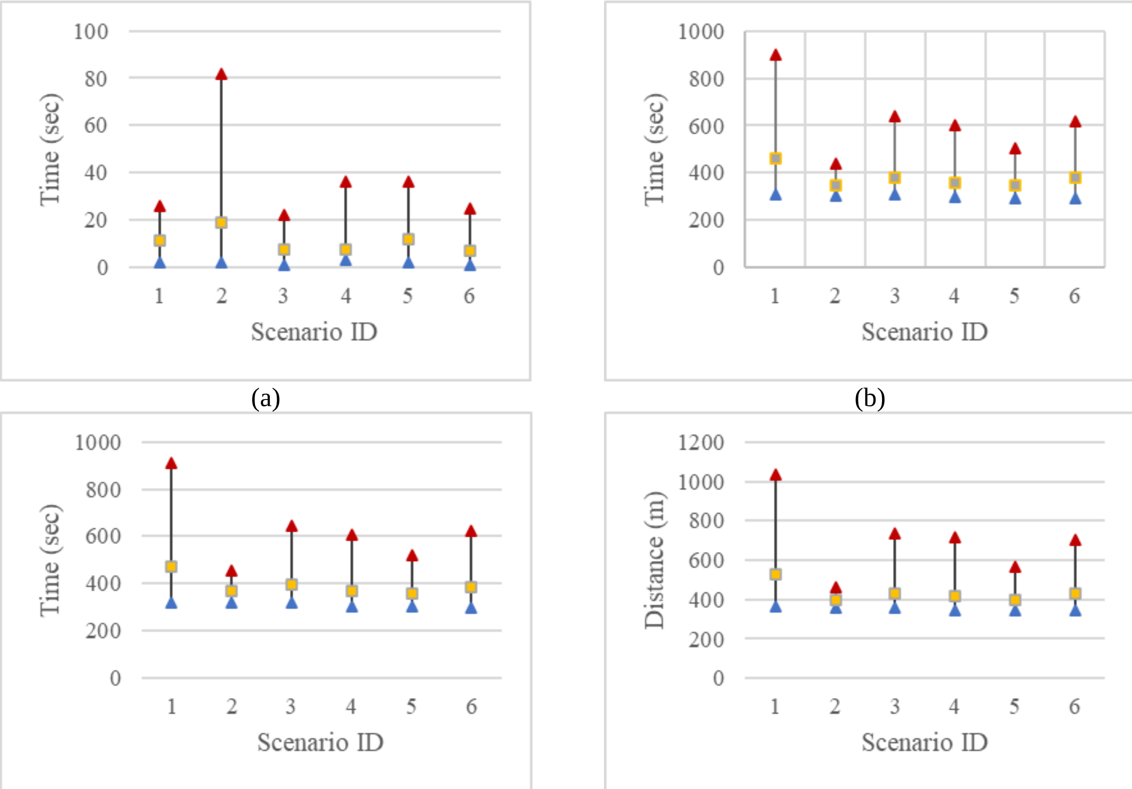
Figure 6. *VR experiment implementation*

The results related to reaction time indicate that the absence of visible smoke and fire (Scenarios 2 & 5) leads to an increase in reaction time (Figure 7-a) —that is, a delay in the decision to exit the vehicle—since users do not have a clear visual indication of forthcoming danger. Similarly, in the Scenarios 2 & 5 the movement time, the evacuation time and the travelled distance is smaller due to clear visibility (Figure 7-b,c,d).

In addition, Figure 8 indicates that in lack visibility conditions, users did not use emergency exit (56% of them confused and got lost and 44% used the tunnel entrance by their own initiative) or even failed to find a way out of the tunnel, in contrast to scenarios without smoke in which all users exited via the nearest exit (emergency exit). As illustrated in Figure 9, 59% of users across all scenarios relied on exit signage to navigate their way out, while 20% followed other occupants (NPCs), with this behavior being more prevalent in scenarios with a clear environment. The remaining 20% of users either exited through a familiar route (typically the tunnel entrance) or found their way out by chance (random choice). Moreover, the VR experiment revealed that 23% of participants (approximately one in four) moved toward the fire incident, driven by curiosity about the event.

Moreover, Figure 10 presents the reaction times of all participants across all scenarios, using a color-coded representation, in relation to other potential influencing events such as the appearance of NPCs (non-playable characters) within the visible field of the tunnel and the activation of the emergency alarm (in Scenarios 3 and 6 the alarm activated earlier; at 20th second). The results indicate that the majority of participants initiated evacuation independently and were not influenced by these external events. However, a small subset of participants appeared to be influenced by the visual presence of NPCs, as they became visible in the tunnel environment while participants remained in their vehicles.

Additionally, both reaction time and total evacuation time were recorded and analyzed based on participants' prior training in fire safety. Only 25% of the participants had received even minimal fire event training. As shown in Figure 11, the group without fire training exhibited slightly longer reaction and evacuation times; however, the increase was relatively small.



(a) (b) (c) (d)

Figure 7. *VR experiment results for each scenario: (a) Raction time; (b) Movement time; (c) Evacuation time; (d) Travelled distance*

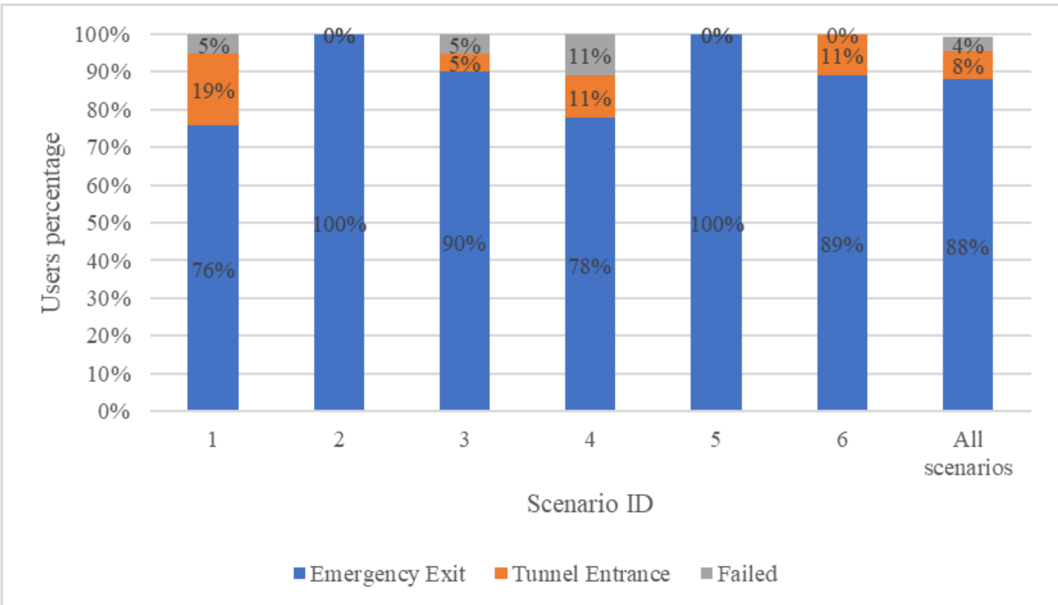


Figure 8. *Users exit preference results*

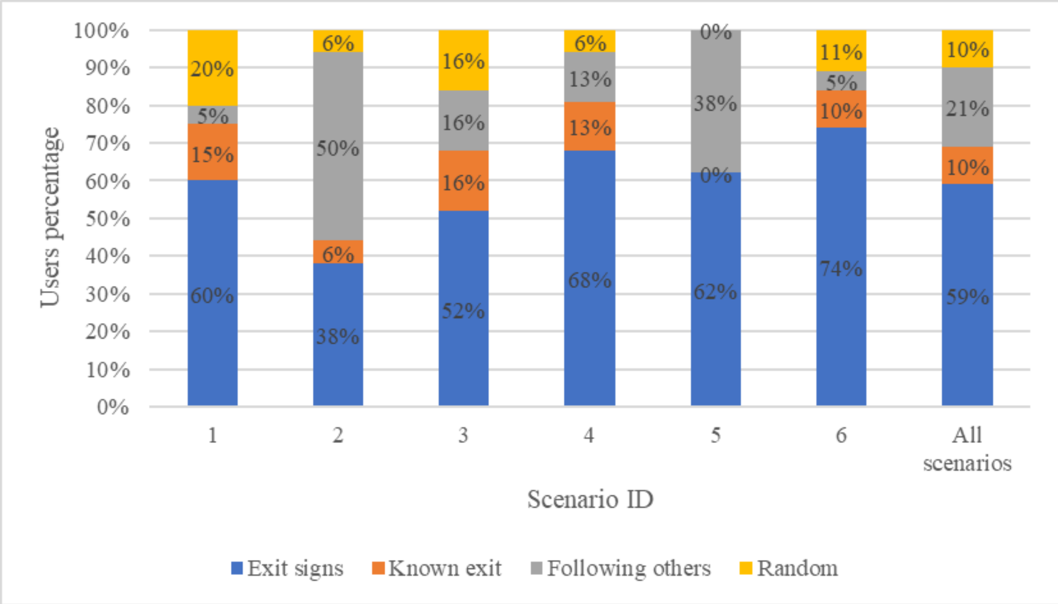


Figure 9. *How the users choose their exit*

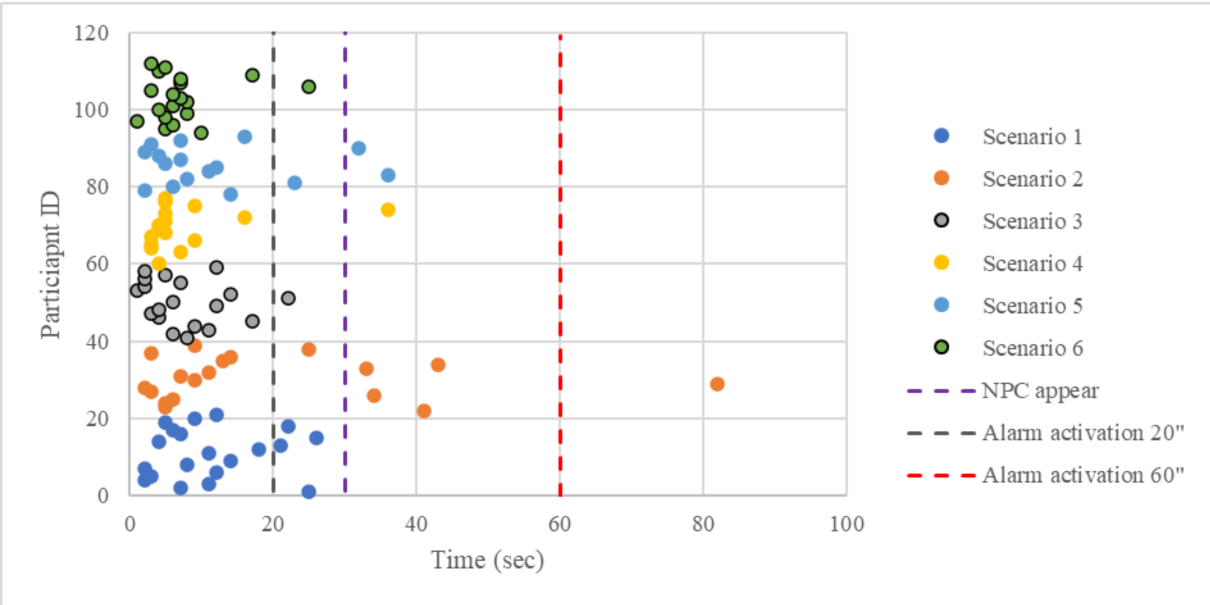


Figure 10. *Users reaction time in contrast to alrm activation and NPC reaction*

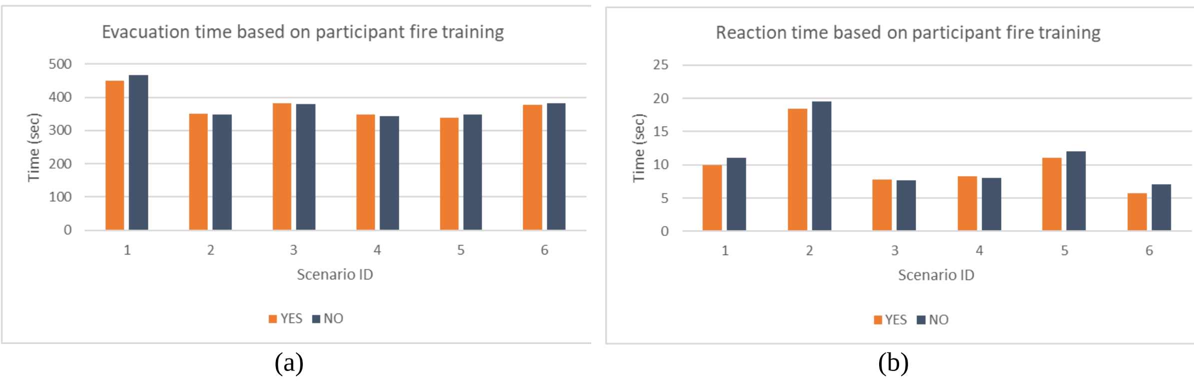


Figure 11. *Participants results based on fire training; (a) evacuation time); (b) reaction time*

4. COMPUTER EVACUATION SIMULATION RESULTS

This chapter presents the results of the scenarios executed in the Pathfinder simulation software. During the analysis, several key variables were selected for observation:

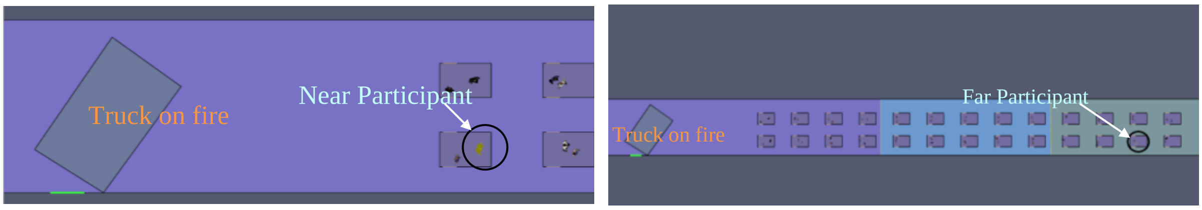
- Temperature
- Carbon monoxide exposure
- Fractional Effective Dose (FED)

The FED is a metric used to assess the cumulative exposure of occupants to atmospheric pollutants. Gases such as carbon monoxide and carbon dioxide can accumulate as an occupant moves through a burning structure. Pathfinder utilizes data derived from the FDS, including gas concentrations, visibility, and temperature, to calculate these variables and evaluate the impact of fire and smoke on evacuees (Thunderhead Engineering, 2024a).

In the pathfinder software 1 scenario was designed so as to cover the different participants behavior concerning four parameters:

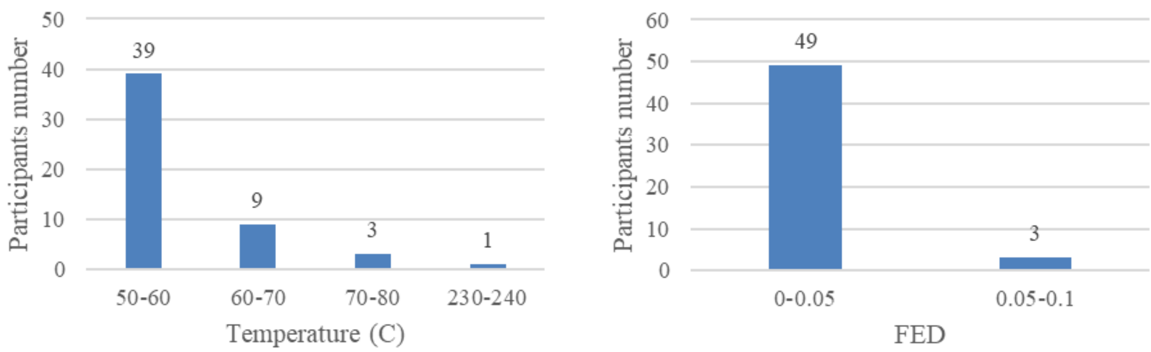
- Distance from fire (Figure 12)
- Reaction time
- Move toward to fire incident
- Exit choice

Figures 13-a and 13-b present the maximum exposure temperature and the maximum FED value at the end of the evacuation for all participants, respectively. Only those participants who moved toward the fire incident prior to initiating evacuation exceeded the established tenability limits, as defined in Table 1 & 2. Figure 14 illustrates the temperature exposure of one such participant in relation to their distance from the fire. The data show a rapid increase in temperature as the participant approaches the fire source, with temperatures returning to tenable levels only after moving away from the fire zone.



(a) (b)

Figure 12. *Pathfinder fire event desgin and (a) near to fire participant; (b) far from fire participant*



(a) (b)

Figure 13. *Evacuation simulation results: (a) maximum exposure temperature; (b) maximum FED value*

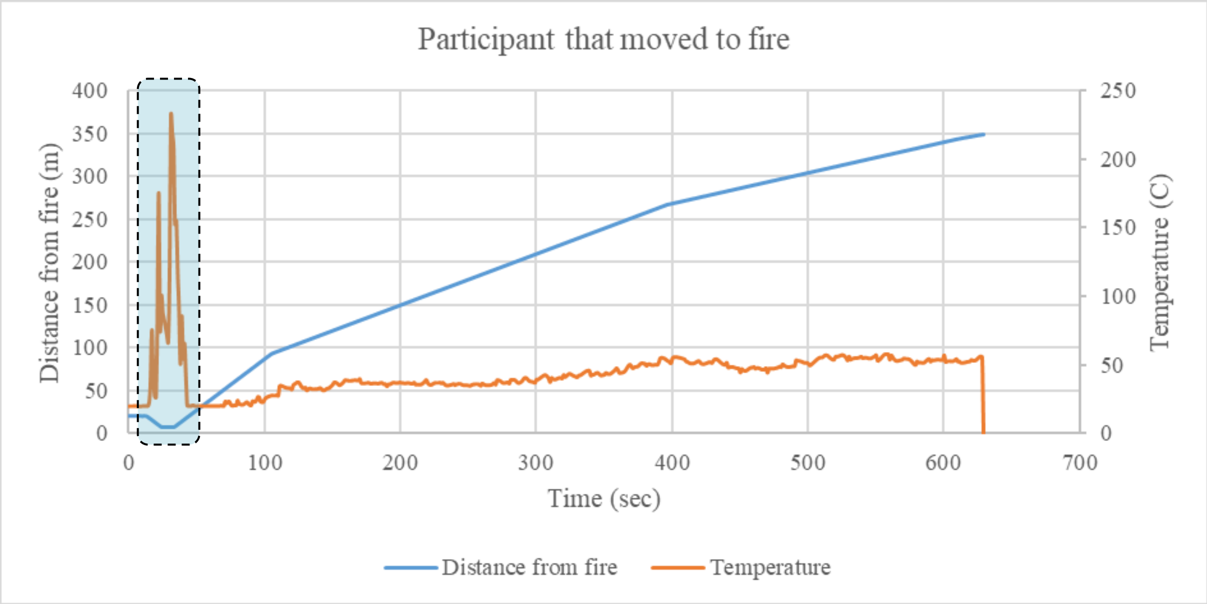


Figure 14. *Behaviour and temperature exposure of the participant that moved toward to the fire*

5. DISCUSSION-CONCLUSION

A full-scale virtual reality (VR) model of a road tunnel, integrated with CFD-based fire and smoke simulation, was developed to investigate occupant behavior during tunnel fire incidents across six distinct scenarios. These scenarios varied in terms of smoke presence, alarm activation time (early or delayed), and proximity to the fire source (near or far). The primary behavioral factors analyzed in this study include; evacuation decision-making; pre-evacuation time; total evacuation time; and route-finding strategies.

As shown from the experiment results, the shortest travel distances were recorded in Scenarios 2 and 5, where no smoke was present. This is attributed to the unobstructed visibility in these cases. In contrast, in Scenario 1—where smoke is present and the user is positioned closer to the accident—the longer travel distances may be explained by users mistakenly moving toward the incident or becoming disoriented during the evacuation process. The initial movement decisions of the users were examined—specifically, whether they moved toward the accident or not and found that approximately one in four participants initially moved toward the accident. Regarding the exit selection and the decision-making process behind exit choice, in one hand 88% of users evacuated through an emergency exit, 8% exited via the tunnel entrance, and 4% failed to evacuate and on the other hand 59% of participants actively searched for signage to guide their exit, 22% followed other individuals (NPCs), 12% exited from the point of entry, and 7% found their way out by chance. Among the occupants who chose to exit through the tunnel entrance, 56% did so intentionally, while 44% selected this route due to confusion or failure to locate the emergency exit. No significant differences were observed in response times or total evacuation times between participants with prior fire safety training and those without and in the scenarios where no smoke was present, visual and auditory cues did not serve as primary triggers for vehicle abandonment.

Regarding the assessment of participants' exposure to fire and smoke, only those who approached the fire zone exceeded the established temperature tenability limits. All other occupants were able to reach an exit while maintaining a safe margin within acceptable tenability thresholds. These findings highlight the importance of evacuating in the direction away from the fire, as temperatures near the fire source increase rapidly due to both hot smoke gases and radiant heat from the flames.

The results of this study provide valuable insights into human behavior during tunnel fire evacuations under varying conditions of visibility, alarm timing, and proximity to the hazard. These findings can support the scientific community in refining evacuation models, improving safety protocols, and enhancing the design of tunnel emergency systems. Future studies could build upon this work by incorporating physiological monitoring of participants, expanding scenario diversity, improving VR interactivity and immersivity or validating results with real-world drills and observational data.

6. ACKNOWLEDGMENTS

The authors would like to all staff members and student of Mining Engineering and Environmental Mining laboratory for supporting the experimental procedure. In addition, they would like to extend a special note of appreciation to Thunderhead Engineering group, for providing educational license to use and work on Pathfinder and Pyrosim platform as well as for the excellent and direct cooperation of its members.

7. BIBLIOGRAPHY

[1] Carlson, E.-S., Kumm, M., Zakirov, A., & Dederichs, A. (2019). Evacuation tests with elevated platforms in railway tunnels. *Fire Safety Journal*, *108*, 102840. https://doi.org/10.1016/j.firesaf.2019.102840

[2] Cha, M., Han, S., Lee, J., & Choi, B. (2012). A virtual reality based fire training simulator integrated with fire dynamics data. *Fire Safety Journal*, *50*, 12–24. https://doi.org/10.1016/j.firesaf.2012.01.004

[3] Fridolf, K., Ronchi, E., Nilsson, D., & Frantzich, H. (2013). Movement speed and exit choice in smoke-filled rail tunnels. *Fire Safety Journal*, *59*, 8–21. https://doi.org/10.1016/j.firesaf.2013.03.007

[4] Greek Government Journal. (2007). *Greek Government Journal 230/2007*. *1*.

[5] Greek Tunneling Society. (2011). *Guidelines of risk analysis without the involvement of vehicles transporting dangerous goods through road tunnels falling within the scope of Decree 230/07 (Scenario Approach)*. GTS.

[6] Jin, T. (1997). Studies On Human Behavior And Tenability In Fire Smoke. *Fire Safety Science*, *5*, 3–21. https://doi.org/10.3801/IAFSS.FSS.5-3

[7] Kallianiotis, A., Papakonstantinou, D., Giouzelis, N., & Kaliampakos, D. (2022). Evacuation in an Underground Space: A Real-Time Investigation of Occupants' Travel Speed in Clear and Smoked Environments. *Infrastructures*, *7*(4), 57. https://doi.org/10.3390/infrastructures7040057

[8] Kinateder, M., Gromer, D., Gast, P., Buld, S., Müller, M., Jost, M., Nehfischer, M., Mühlberger, A., & Pauli, P. (2015). The effect of dangerous goods transporters on hazard perception and evacuation behavior – A virtual reality experiment on tunnel emergencies. *Fire Safety Journal*, *78*, 24–30. https://doi.org/10.1016/j.firesaf.2015.07.002

[9] McGrattan, K., McDermott, R., Hostikka, S., Floyd, J., & Vanella, M. (2023a). *Fire Dynamics Simulator (6th Edition) Technical Reference Guide, Volume 2: Verification*. U.S. Department of commerce National Institute of Standards and Technology.

[10] McGrattan, K., McDermott, R., Hostikka, S., Floyd, J., & Vanella, M. (2023b). *Fire Dynamics Simulator (6th Edition) Technical Reference Guide, Volume 3: Validation*. U.S. Department of commerce National Institute of Standards and Technology.

[11] McGrattan, K., McDermott, R., Hostikka, S., Floyd, J., & Vanella, M. (2023c). *Fire Dynamics Simulator User's Guide*. U.S. Department of commerce National Institute of Standards and Technology.

[12] McKenna, S. T., & Hull, T. R. (2016). The fire toxicity of polyurethane foams. *Fire Science Reviews*, *5*(1), 3. https://doi.org/10.1186/s40038-016-0012-3

[13] Moscoso, C., Skjermo, J., Karlsson, H., Arnesen, P., Södersten, C.-J., Hoem, Å. S., & Jenssen, G. D. (2024). Analysis of spatial and design factors for users' acceptance of rescue rooms in road tunnels: An exploratory study using Virtual Reality. *Fire Safety Journal*, *150*, 104272. https://doi.org/10.1016/j.firesaf.2024.104272

[14] Nelson, H. E. "Bud," & Mowrer, F. W. (2002). Emergency Movement. In *SFPE Handbook of Fire Protection Engineering 3rd edition* (pp. 367–380). NFPA.

[15] NFPA. (2013). *NFPA 502: Standard for road tunnels, bridges, and other limited access highways* (2014 edition). NFPA.

[16] NFPA. (2014). *NFPA 130, Standard for Fixed Guideway Transit and Passenger Rail Systems*. NFPA.

[17] OMOE. (2002). *OMOE Road Project Design Guidelines*. OMOE.

[18] PIARC. (2004). *Fire and Smoke Control in Road Tunnels*.

[19] Purser, D. A., & McAllister, J. L. (2016). Assessment of Hazards to Occupants from Smoke, Toxic Gases, and Heat—Chapter 63. In *SFPE Handbook of Fire Protection Engineering* (pp. 2308–2428). Springer.

[20] Qin, J., Liu, C., & Huang, Q. (2020). Simulation on fire emergency evacuation in special subway station based on Pathfinder. *Case Studies in Thermal Engineering*, *21*, 100677. https://doi.org/10.1016/j.csite.2020.100677

[21] Ronchi, E., Colonna, P., Capote, J., Alvear, D., Berloco, N., & Cuesta, A. (2012). The evaluation of different evacuation models for assessing road tunnel safety analysis. *Tunnelling and Underground Space Technology*, *30*, 74–84. https://doi.org/10.1016/j.tust.2012.02.008

[22] Ronchi, E., Kinateder, M., Müller, M., Jost, M., Nehfischer, M., Pauli, P., & Mühlberger, A. (2015). Evacuation travel paths in virtual reality experiments for tunnel safety analysis. *Fire Safety Journal*, *71*, 257–267. https://doi.org/10.1016/j.firesaf.2014.11.005

[23] SFPE. (2016). *SFPE Handbook of Fire Protection Engineering, 5th Edition*. Springer.

[24] Skjermo, J., Moscoso, C., Nilsson, D., Frantzich, H., Hoem, Å. S., Arnesen, P., & Jenssen, G. D. (2024). Analysis of visual and acoustic measures for self-evacuations in road tunnels using virtual reality. *Fire Safety Journal*, *148*, 104224. https://doi.org/10.1016/j.firesaf.2024.104224

[25] Storm, A., & Celander, E.-S. (2022). Field evacuation experiment in a long inclined tunnel. *Fire Safety Journal*, *132*, 103640. https://doi.org/10.1016/j.firesaf.2022.103640

[26] Thematic Network Fire in Tunnels. (2006). *Fire in Tunnels* [General Report].

[27] Thunderhead Engineering. (2024a). *Pathfinder Verification and Validation*.
[28] Thunderhead Engineering. (2024b). *PyroSim User Manual*.
[29] Zhang, X., Chen, L., Jiang, J., Ji, Y., Han, S., Zhu, T., Xu, W., & Tang, F. (2023). Risk analysis of people evacuation and its path optimization during tunnel fires using virtual reality experiments. *Tunnelling and Underground Space Technology*, *137*, 105133. https://doi.org/10.1016/j.tust.2023.105133