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Factors influencing the evacuation of people from underground spaces used for transport and operations during emergency events

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Abstract:

The evacuation of people from underground spaces used for transport and operational purposes is a complex process influenced by the characteristics of the space, the availability and passability of escape routes, technical equipment, environmental conditions, and human behaviour. The aim of this article is to identify and systematize the main factors affecting evacuation safety and to compare them with published experimental findings and the requirements of selected technical standards. The study was based on a structured narrative and comparative analysis of scientific literature focusing primarily on evacuation from tunnels and other underground spaces used for transport and operational purposes. After the predefined selection criteria had been applied, 38 scientific publications were included in the detailed content analysis, while the review of standards comprised eight technical and normative documents. Attention was paid to movement speed in smoke-filled environments, escape-route choice, wayfinding, and the effects of reduced visibility. To compare the significance of the individual factors, three model scenarios were developed: a fire accompanied by smoke, a hazardous gas release, and an explosion associated with the partial blockage of a circulation route. The result is a systematic framework comprising six groups of factors – spatial, technical, environmental, human, organizational, and emergency-response factors – supplemented by a temporal assessment of evacuation based on the relationship between Required Safe Egress Time (RSET) and Available Safe Egress Time (ASET). The results indicate that the significance of individual factors varies depending on the nature of the emergency and the current conditions along the escape routes.

Keywords:

Evacuation, underground spaces, emergency, escape routes, smoke, human factors, rescue services.

1. Introduction

Underground spaces are a distinctive environment in which emergencies can significantly affect occupant safety and the ability to reach a safe area in time. Compared with conventional above-ground structures, they are more dependent on technical systems, artificial



lighting, emergency signage, and controlled ventilation, while smoke, hazardous-substance releases, or damage to circulation routes can rapidly change evacuation conditions (Ingason et al., 2015). The underground spaces considered in this study include road and railway tunnels, underground transport stations and facilities, underground garages, technical and storage areas, civil protection shelters, and other facilities located entirely or partially below ground level. Despite their different functions, they share several evacuation-related characteristics, including a limited number of connections to safe areas, longer evacuation distances, elevation differences, and more demanding wayfinding (Yamamoto et al., 2018).

Experimental studies conducted in tunnels show that evacuation performance cannot be assessed solely on the basis of facility geometry. Smoke development, visibility, fire location, ventilation conditions, and the configuration of evacuation routes can significantly affect evacuation safety and escape-route selection (Wang et al., 2023; Chen et al., 2024). Familiarity with the environment, individual motivation, group behaviour, and the design and marking of emergency exits are also relevant, indicating that technical assessment should be combined with an assessment of human behaviour. Previous research has largely examined these aspects separately, particularly movement in smoke-filled environments, route selection, wayfinding, human behaviour, and technical systems associated with specific underground facilities (Zhang and Huang, 2022; Papakonstantinou and Benardos, 2025). Less attention has been paid to their integrated assessment and to how their relative importance changes according to the type of emergency.

The aim of this article is therefore to identify and systematize the main factors affecting the safety of occupant evacuation from underground spaces used for transport and operational purposes, compare them with published experimental data, assess their significance in three model scenarios, and relate them to selected technical and normative documents. The original contribution of the study is a systematic framework linking the nature of the emergency, the condition of escape routes, occupant response, and the operational conditions faced by rescue services.

2. Material and methods

2.1 Search strategy and source selection

The literature search was conducted on 1 September 2026 in Scopus and the Web of Science Core Collection and covered English-language scientific articles published between 2013 and 2026 on evacuation from underground spaces used for transport and operational purposes, particularly road and railway tunnels, metro facilities, and other underground environments.

The search combined the terms ‘*underground evacuation*’, ‘*tunnel evacuation*’, ‘*emergency egress*’, ‘*smoke*’, ‘*visibility*’, ‘*exit choice*’, ‘*human behavior*’, and ‘*wayfinding*’. Additional terms related to the model scenarios included ‘*underground space*’, ‘*gas release*’, ‘*toxic gas*’, ‘*explosion*’, and ‘*blocked escape route*’. The Boolean operators AND and OR were used; searches were performed in the Topic field in Web of Science and in titles, abstracts, and keywords in Scopus.

The search identified 171 records in Scopus and 95 in Web of Science, giving 266 records in total. Duplicates were identified primarily by DOI and, where no DOI was available, by normalized publication titles. After 76 duplicates had been removed, 190 unique records remained. The procedure was intended to provide a defined body of literature for structured narrative and comparative analysis rather than to constitute a formal systematic review.

2.2 Inclusion and exclusion criteria for source selection

Studies were included if they directly addressed evacuation from underground spaces used for transport or operational purposes or provided relevant experimental or modelling data on occupant movement, evacuation speed, escape-route choice, wayfinding, reduced visibility, smoke or hazardous substances, technical support systems, or evacuation timing.

Studies dealing exclusively with mining operations, structural damage, mechanical effects of explosions, gas dispersion or detection without a direct relationship to evacuation, as well as non-English publications and unsuitable document types, were excluded. Of the 190 unique records, 19 were excluded because of language and 46 because of document type. The remaining 125 records underwent title and abstract screening, after which 87 were excluded for insufficient thematic relevance. A total of 38 scientific publications were therefore included in the detailed content analysis.

2.3 Data extraction and comparative analysis

The extracted data included the type of underground space, study or model characteristics, number of participants, visibility conditions, presence of smoke or other hazards, movement speed, pre-movement time, escape-route choice, wayfinding, effects of safety signage or voice messages, and the main limitations of the studies.

The findings were evaluated using structured narrative and comparative analysis. Because the studies differed substantially in spatial configuration, smoke conditions, experimental protocols, participant characteristics, and evaluation methods, numerical data were not pooled, and no meta-analysis was performed. The identified factors were classified into six groups – spatial, technical, environmental, human, organizational, and emergency-response factors – and assessed in relation to evacuation time, wayfinding, escape-route availability and passability, and rescue operations.

2.4 Development of model scenarios

Three model scenarios were developed to compare the significance of the identified factors: a smoke-producing fire, a hazardous gas release, and an explosion causing partial blockage of a circulation route. These scenarios represent an analytical synthesis of the reviewed literature and relevant safety principles rather than original physical experiments or numerical simulations.

For each scenario, the following aspects were considered: the dominant hazard, effects on visibility and escape-route passability, technical-system requirements, escape-route selection, and potential complications for rescue operations. In the fire scenario, evacuation timing was interpreted using the relationship between Required Safe Egress Time (RSET) and Available Safe Egress Time (ASET). RSET includes detection, warning, pre-movement, and movement time, whereas ASET represents the time available before conditions along an escape route become unsafe (Gwynne et al., 2026). The RSET–ASET relationship was used only as an interpretative framework.

2.5 Selection of standards and technical documents

Normative and technical documents were selected separately from the scientific literature according to their relevance to evacuation, safety way guidance, emergency lighting, human behaviour in fire, and design fire and behavioural scenarios. Their current designation was verified using the official ISO, NFPA, and Slovak standardization databases.

Eight documents were included: ISO/TR 16738:2009, ISO 16733-1:2024, ISO/TS 29761:2015, ISO 16069:2017, ISO 7010:2019, STN EN 1838:2025, STN EN 50172:2024, and NFPA 130:2023. Each was considered only within its intended scope and used for comparison with findings from the scientific literature (Fig. 1).

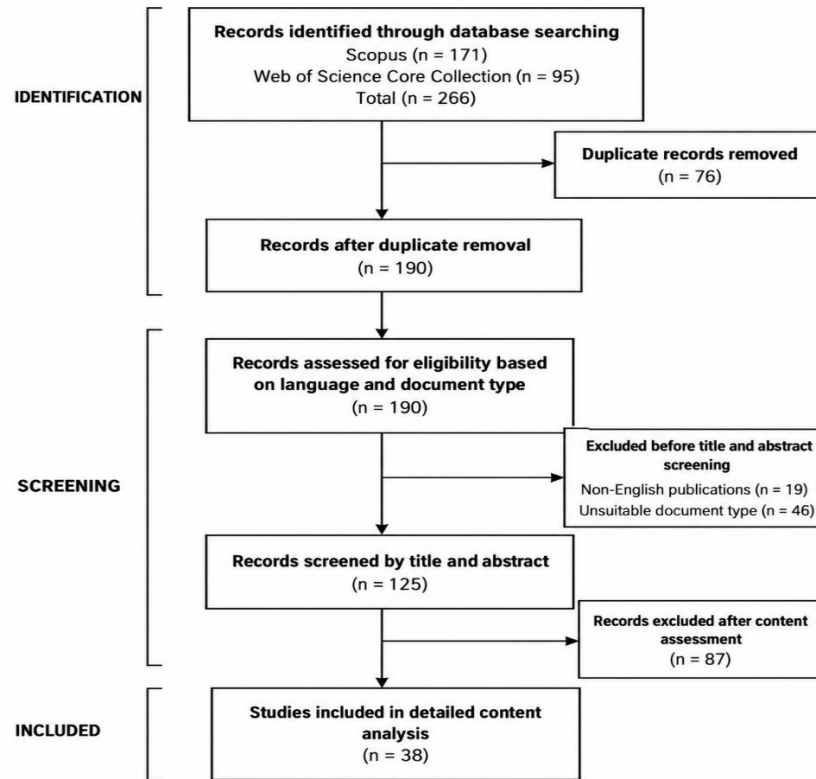


Fig. 1 Identification and selection of literature sources included in the analysis

3. Results and discussion

3.1 Characteristics of underground spaces from an evacuation perspective

Underground spaces differ in their purpose, spatial configuration, depth, and user characteristics, but evacuation is generally constrained to designated circulation routes such as corridors, ramps, stairways, passages, and emergency exits. Their availability, capacity, and appropriate signposting are therefore important for safe wayfinding, particularly when one of the routes becomes unavailable during an emergency (Hiroi and Aoyama, 2016). Evacuation distance and elevation differences can further affect movement, especially in deep stations and extensive underground facilities, where long-distance stair evacuation may significantly influence movement speed (You et al., 2025).

The enclosed nature of underground environments also increases the importance of ventilation and smoke control. Conditions along escape routes may change considerably during a fire, making their availability and passability time-dependent rather than static (Zhao et al., 2025). User characteristics are equally relevant: trained personnel or regular users may be familiar with the spatial layout, whereas occupants of publicly accessible facilities may have no previous knowledge of the environment. Such differences in familiarity can affect pre-movement behaviour, escape-route choice, and the ability to respond to changes in evacuation guidance.

3.2 Emergencies affecting evacuation

Evacuation conditions in underground spaces depend on both the characteristics of the facility and the type and development of the emergency. Primary hazards may rapidly be accompanied by secondary effects such as loss of lighting or ventilation, blocked circulation routes, or disruption of technical systems. Tunnel fires can result in casualties, damage to infrastructure and equipment, and substantial operational disruption (Bai et al., 2020).

Hazardous gas releases present a different challenge because the affected area may not be visually apparent and gas dispersion depends strongly on airflow and surrounding conditions (Zhang et al., 2022). Explosions may rapidly alter the physical condition of underground structures and routes through structural damage and spalling (Li et al., 2025). Consequently, evacuation planning should account for changing route availability, alternative escape paths, and the need to update evacuation instructions as conditions develop.

3.3 Empirical findings

Experimental studies demonstrate that evacuation speed in underground spaces cannot be treated as a constant value independent of environmental and behavioural conditions. In a smoke-filled railway tunnel, Fridolf et al. (2013) observed 100 participants at a mean extinction coefficient of 2.2 m^{-1} and reported an average movement speed of approximately 0.9 m.s^{-1} , while also demonstrating the importance of emergency-exit design and voice guidance. In full-scale tunnel experiments, Seike et al. (2016) found that increasing the extinction coefficient from 0.30 to 0.75 m^{-1} reduced the maximum evacuation speed from 3.55 to 2.53 m.s^{-1} . Ronchi et al. (2018), studying 66 participants at a visibility of approximately 2–4 m, further confirmed the importance of wayfinding and emergency-exit choice under smoke conditions.

More recent full-scale experiments also indicate that movement speed is influenced not only by smoke density but also by familiarity, motivation, and learning effects; under the most severe smoke conditions, the mean movement speed in the main tunnel was reduced to 31.46% of the corresponding unobstructed speed (Schmidt-Polończyk, 2024). Social behaviour is another relevant factor: experiments under zero visibility showed that social groups may achieve higher evacuation efficiency than isolated individuals under the tested conditions, although this effect depends on the specific experimental setting (Zeng et al., 2024). Overall, the findings summarized in Tab. 1 confirm that no single universal movement speed adequately represents evacuation behaviour in underground spaces.

Tab. 1 Selected empirical data on the conditions and progress of evacuation from underground spaces

Source	Environment / sample	Conditions	Selected result	Relevance to the study
Fridolf et al. (2013)	railway tunnel, 100 participants	smoke, extinction coefficient 2.2 m ⁻¹	mean movement speed approximately 0.9 m.s ⁻¹	effect of smoke, wayfinding, and emergency-exit design
Seike et al. (2016)	road tunnel, full-scale experiment	extinction coefficient 0.30–0.75 m ⁻¹	maximum speed decreased from 3.55 to 2.53 m.s ⁻¹	effect of reduced visibility on movement speed
Ronchi et al. (2018)	road tunnel, 66 participants	visibility approximately 2–4 m	movement speed and emergency-exit choice assessed	importance of visual and voice guidance
Schmidt-Polończyk (2024)	road tunnel, group experiments	various smoke conditions	mean speeds of 1.056–1.321 m.s ⁻¹ in the main tunnel	effects of smoke, familiarity, and motivation
Zeng et al. (2024)	tunnel, individuals and social groups	various smoke conditions	social groups were more efficient under the tested conditions	importance of social relationships and group behaviour

3.4 Evacuation modelling and time-based assessment

Evacuation modelling may employ macroscopic or microscopic approaches, including social-force, cellular-automata, and agent-based models. Their results depend strongly on the selected input parameters, particularly movement speed, response to reduced visibility, and escape-route choice. Differences in datasets and in the representation of the relationship between visibility and movement speed may therefore lead to different simulation outcomes.

For time-based evacuation assessment, RSET and ASET are commonly used. RSET comprises detection, warning, pre-movement, and movement time and can be expressed as (Gwynne et al., 2026):

$$RSET = t_{det} + t_{alarm} + t_{pre} + t_{move} \quad (1)$$

where:

t_{det} – detection time,

t_{alarm} – warning time,

t_{pre} – pre-movement time,

t_{move} – time required for occupants to reach a safe area.

ASET represents the time from the onset of the emergency until conditions along an escape route become unsafe because of factors such as reduced visibility, elevated temperature, toxic substances, or loss of route passability. The basic safety condition is:

$$ASET > RSET \quad (2)$$

A sufficient margin between ASET and RSET is therefore required for safe evacuation. In this study, the RSET–ASET relationship is used as an interpretative framework rather than as the result of original numerical modelling.

3.5 Model scenarios

The model scenarios were developed as an analytical tool to compare how the significance of individual evacuation factors changes according to the type of emergency. They do not represent original physical experiments or numerical simulations, but a qualitative synthesis of findings derived from the analysed literature and selected safety principles applicable to underground spaces. The assessment focused on the dominant hazard, effects on visibility and escape-route passability, route selection, technical-system requirements, and potential complications for rescue operations.

Three scenarios were considered. **Scenario A** represents a fire with smoke development, in which visibility, ventilation, smoke propagation, pre-movement time, and the RSET–ASET relationship are of particular importance. **Scenario B** represents a hazardous gas release, where the main issues are detection, contaminant dispersion, ventilation, and the availability of uncontaminated escape routes. **Scenario C** represents an explosion causing partial blockage of a circulation route, with emphasis on structural damage, route passability, alternative escape options, and coordination between evacuees and rescue services. The main differences between the scenarios are summarized in Tab. 2.

Tab. 2 Comparison of model scenarios

Parameter	Fire	Hazardous gas release	Explosion
Dominant hazard	smoke, thermal exposure, toxic combustion products	toxicity, reduced oxygen concentration, possible flammability or explosiveness depending on substance properties	mechanical effects, structural damage, secondary fire
Visibility	often significantly reduced	may remain unchanged or vary depending on the substance and associated effects	may be reduced by dust, smoke, or lighting failure
Route selection	according to smoke conditions and passability	according to the extent of contamination, direction of dispersion, and ventilation	according to physical passability and availability of alternative routes
Technical priorities	fire detection, ventilation, smoke control, emergency guidance	substance detection, ventilation, warning, and updated information on the safe direction of escape	emergency lighting, communication, backup systems, and alternative routes
Emergency-response risk	counterflow of rescue personnel and evacuees, smoke exposure	entry into a contaminated zone, exposure to hazardous substances	unstable or blocked routes, secondary damage

3.6 Normative framework

The normative framework was not intended to establish universal design criteria for all types of underground facilities, as the selected standards differ in scope and application. ISO/TR 16738:2009 addresses human behaviour and movement in fire, ISO 16733-1:2024 the selection of design fire scenarios, and ISO/TS 29761:2015 the selection of behavioural scenarios. ISO 16069:2017 and ISO 7010:2019 provide requirements for safety way guidance systems and safety signs used during emergency evacuation.

Emergency lighting is addressed by STN EN 1838:2025 and STN EN 50172:2024, including requirements for escape-route illumination, installation, verification, operation, and

maintenance. NFPA 130:2023 provides specialized requirements for fixed guideway transit and passenger rail systems, including stations, routes, emergency ventilation, and emergency procedures. In this study, each document was considered only within its specific scope and used as a reference framework for comparison with the findings from the scientific literature.

3.7 Factors affecting evacuation performance and safety

On the basis of the synthesis of the analysed literature, the factors affecting evacuation were classified into six groups: spatial, technical, environmental, human, organizational, and emergency-response factors. The categories were derived inductively from recurring findings rather than adopted from a single existing classification and are intended to reflect how the factors interact during evacuation. Spatial factors include escape-route length and width, exit availability, elevation differences, bottlenecks, and alternative routes, all of which may influence movement capacity and evacuation time (You et al., 2025). Technical factors include detection, emergency lighting, safety signage, voice warning, ventilation, smoke control, and backup power; the design and marking of emergency exits can directly affect their recognition and use (Hiroi and Aoyama, 2016; Ronchi et al., 2018).

Environmental factors include visibility, smoke, heat, toxic substances, dust, water, and physical obstacles, which may progressively reduce escape-route usability. Experimental studies confirm that movement speed under smoke conditions varies considerably with visibility and other situational factors and should not be represented by a single universal value (Fridolf et al., 2013; Schmidt-Polończyk, 2024). Human factors include pre-movement behaviour, familiarity with the environment, risk perception, stress, physical capability, and social interaction, while group behaviour may also influence evacuation performance under limited visibility (Zeng et al., 2024). Organizational and emergency-response factors include alarm procedures, the clarity of instructions, trained personnel, route management, rescue-team access, communication, casualty transport, and potential conflicts between evacuation and rescue movement. Together, these groups provide the basis for the systematization presented later in the study.

3.8 Critical phases of evacuation and rescue operations

The evacuation process comprises detection, warning, pre-movement, escape-route selection, movement, and reaching a safe area, all of which contribute to the overall RSET, while deteriorating environmental conditions may progressively reduce ASET (Gwynne et al., 2026). The pre-movement phase is particularly important because occupants may delay evacuation while seeking additional information or assessing the credibility of a warning. The psychological state of evacuees can also influence evacuation speed and overall evacuation efficiency in railway tunnels (Qi et al., 2020). Clear and actionable information is therefore essential, especially when route conditions change during an emergency. Experimental studies also confirm that exit identification, voice guidance, and familiarity with the environment influence route selection and evacuation behaviour (Hiroi and Aoyama, 2016; Ronchi et al., 2018).

Rescue operations may overlap with ongoing evacuations, particularly in narrow underground routes, creating potential conflicts between outgoing evacuees and incoming rescue personnel. Smoke, complex layouts, lighting failure, and hazardous-substance releases can further complicate responder orientation, communication, and access. Long evacuation distances, stairways, and elevation differences may also increase the time and effort required to transport injured people; this should be taken into account in emergency planning.

3.9 Systematization of factors affecting evacuation safety

The resulting systematization links each factor group with its potential immediate effect, consequence for the evacuation process, and corresponding mitigation measure in Tab. 3. It is not intended as a universal scoring system but as a framework adaptable to the type of underground facility and the nature of the emergency.

Tab. 3 Systematization of factors affecting evacuation safety

Factor group	Example	Potential effect	Consequence	Possible measure
Spatial	long route, bottleneck, stairs	reduced movement speed	increased RSET	alternative routes, capacity assessment
Technical	lighting or ventilation failure	loss of orientation, deteriorating conditions	reduced route usability	backup systems, adaptive guidance
Environmental	smoke, gas, heat	deterioration of conditions for safe egress	reduced ASET	detection, ventilation, and isolation of the hazardous area
Human	hesitation, stress, unfamiliarity	prolonged pre-movement phase	increased RSET	clear voice and visual instructions
Organizational	unclear or delayed alarm	delayed response	uneven use of exits	emergency procedures, staff training
Emergency-response	counterflow	route obstruction	slower evacuation and rescue operations	separation of routes, controlled responder access

4. Conclusions

The studies analysed confirm that evacuation from underground spaces cannot be assessed solely on the basis of escape-route length or a single constant movement speed. Experimental results demonstrate considerable variability depending on smoke conditions, visibility, familiarity with the environment, experimental design, and occupant behaviour (Fridolf et al., 2013; Seike et al., 2016; Schmidt-Polończyk, 2024). Wayfinding, emergency-exit design, safety signage, and voice guidance also influence evacuation performance, while social behaviour may affect movement under severely reduced visibility (Ronchi et al., 2018; Zeng et al., 2024).

The comparison of the three model scenarios showed that the relative importance of evacuation factors changes according to the type of emergency. Fire scenarios are dominated by smoke development, visibility, and the RSET–ASET relationship; hazardous gas releases increase the importance of detection, contaminant dispersion, and uncontaminated escape routes; and explosions place particular emphasis on physical route passability and alternative evacuation options. The proposed framework therefore links spatial, technical, environmental, human, organizational, and emergency-response factors rather than considering them independently.

From a practical perspective, underground facilities require timely hazard detection, clear and actionable information, reliable emergency lighting and safety signage, effective ventilation, and alternative escape routes. Evacuation strategies should account for changing

conditions during an emergency rather than relying on a single fixed scenario. The relationship between RSET and ASET provides a useful basis for assessing whether sufficient time remains for occupants to reach safety.

The main limitation of the study is the heterogeneity of the analysed experimental studies in terms of facility type, smoke conditions, participant characteristics, and evaluation methods. The model scenarios therefore represent a qualitative synthesis and were not validated through original physical experiments or numerical simulations. Future research should test the proposed systematic framework in specific underground facilities and integrate evacuation modelling with smoke or hazardous-substance dispersion models to enable more precise quantification of RSET, ASET, and evacuation safety margins.

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