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The representation of evacuation movement in smoke-filled underground transportation systems

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Limited guidance is available to engineers on how people’s walking speed in smoke can and should be represented in the fire safety design process of underground transportation systems, such as road and rail tunnels. To address this issue, the behaviour and movement of people in case of evacuation due to a fire in underground transportation systems has been investigated. In this paper, the relationship between walking speed and visibility conditions has been analysed by performing a systematic review of current experimental research conducted in the field. This includes data-sets collected in Sweden, Japan, UK, Norway, Finland, Canada, and The Netherlands. A design recommendation on how to represent walking speed in both smoke-free and smoke-filled environments is presented. Uncertainty in data is thoroughly discussed and addressed in the recommendation. Three different methods to represent walking speed during the design of an underground transportation system are suggested. The selection of the method depends on the required treatment of uncertainty in the design. The developed representation substantially differs from existing methods used in fire engineering design to represent walking speed in smoke since it describes walking speed as a function of visibility, rather than the extinction coefficient. This permits comparison of data-sets collected in relationship to the presence of reflecting or emitting lights. Finally, suggestions on future research to be conducted in order to reduce the current uncertainties are provided.

Keywords: evacuation, smoke, human behaviour, walking speed, underground transportation, tunnels
1. Introduction

The gradual transition from prescriptive to performance-based regulations has led to a worldwide development of methods and techniques for designing and verifying the fire and life safety performance of transportation infrastructure. During, for example, the design of complex underground transportation systems, such as road and rail tunnels, risk assessment methods are often adopted within which a number of fire and evacuation scenarios are identified, analysed and assessed using advanced calculations. Typically, these include an analysis of people’s ability to safely evacuate the infrastructure without being exposed to untenable conditions according to the so-called egress time-line model [1]. In practical terms, this means that the required safe escape time (RSET) is compared to the available safe escape time (ASET), which typically is defined by a number of tenability conditions, for each scenario in more or less independent fire and evacuation calculations or simulations. However, more advanced techniques also exist, with which is possible to consider the impact of toxic gases on humans. The toxic dose that is absorbed by inhalation can, for example, be calculated by considering the concentration of the gases and the exposure time. This dose can be used to estimate the probability of death using so called probit models [2]–[6]. As these models often consider the impact of toxicants on people at an aggregate level, a more commonly used technique in fire safety engineering applications is to assess the accumulated dose of irritating and/or toxic gases and compare them to the doses resulting in incapacitation or death according to the so-called fractional effective dose (FED) concept [7].

Regardless of technique adopted to quantitatively assess people ability to evacuate safely, information about the movement of people in general, and in smoke in particular, is a pre-requisite. This is for instance particularly important to calculate the time spent by people in a tunnel in case of a fire scenario, which is often considered as a design criteria in legislation frameworks [8]. One particularly important variable is information about walking speed. Walking speeds of people can be categorized in two categories: 1) movement speed, defined as the speed which is calculated excluding the stops made by people during their movement, and 2) modelling speed, defined as the speed calculated considering the movement between two points in the environment, including the duration of the stops made during the journey. Research on walking speed in different settings has been performed for a long time; see for example the summaries by Proulx and Fahy [9], Gwynne and Boyce [10] and Bosina and Weidmann [11]. However, the majority of these empirical studies has been carried out during “normal” conditions, i.e., in every-day situations, and almost exclusively in smoke-free environments. This is despite the fact that other related research within the field of human behaviour in fire quite early on demonstrated that people tend to evacuate through smoke [12], [13], and that the behaviour of people in smoke-filled environments tend to differ from those with no smoke.

Another problematic aspect is that few studies present quantitative correlations between walking speed and visibility. At the same time, fire protection engineers involved in, for example, the fire safety design of underground transportation systems, such as road and rail tunnels, are expected to perform life safety assessments that include scenarios in which people are exposed to smoke.

The experimental studies with human participants performed by Jin et al. during the 1970s in Japan are one of the few exceptions of research in this area [4], [5], [6]. According to Jin et al., there is a correlation between people walking speed and the visibility in smoke, which essentially means that the walking speed is reduced when the visibility level is reduced (this reduced speed can be defined as an obstructed walking speed, in contrast to an unobstructed
Different techniques. Therefore initiated will have a consequence on the final outcome, but due to the fact that only a few quantitative emphasizes that to help designers in their representation of application presents the work conducted with results of this methodology, execution and documentation variables such as the walking speed and visibility levels may, in addition, have been measured and documented using different techniques. Thus, the limited amount of available data in combination with the difficulties to combine this data may lead to an unwanted propagation of uncertainties in life safety analyses including evacuation in smoke. This has also been acknowledged in the past, both by developers of evacuation simulation software and fire safety designers [31]. The consequence is that this uncertainty has been often treated with crude and conservative assumptions regarding people walking speed in smoke for different visibility levels [32]. Hence, in addition to the limited amount of available data on people walking speed in smoke, there is a lack of knowledge and experience on how to use, represent and describe this data in practical RSET analyses.

The consequence of the above-mentioned issues is a lack of reliable and valid correlations for representing people walking speed in smoke, which may propagate through RSET analyses, and in the end affect the design and assessment of the fire and life safety performance of underground transportation systems, such as road and rail tunnels (as in these infrastructures evacuation in smoke can be expected to occur more often due to the lack of compartmentation). A research project was therefore initiated in 2015 and funded by the Swedish Transport Administration, responsible for the design, construction and maintenance of most Swedish road and rail tunnels. The purpose was to make an inventory of, investigate and describe the current knowledge about the movement of people during fire evacuation in smoke-filled underground transportation systems. Furthermore, the goal was to summarize the current understanding, and to describe and recommend how it can be used during practical engineering applications. The results of this project have been presented in a technical report in Swedish [27]. This paper presents the work conducted with an emphasis on a recommendation for practical engineering applications in underground transportation systems. The results presented are indeed deemed to help designers in their representation of walking speed in smoke. It must, however, be emphasized that the uncertainty related to many of the variables determining the walking speed will have a consequence on the final outcome, but due to the fact that only a few quantitative
experiments are available, this uncertainty has been treated at an aggregated level. For a full description of the technical details on which these conclusions rest, the reader is referred to the full report [27].

2. Method
In this section, the method adopted to derive the recommendation on how to quantitatively represent people walking speed in smoke is presented. It can be broken down into three parts, namely: 1) literature review and analysis, 2) summary of information and development of a recommendation, and 3) documentation and quality control.

2.1. Literature review and analysis
The objective of this first part was to identify, review, analyse and present the available research on people walking speed in smoke. This information was then used to develop a recommendation as presented below. Initially, the general definition of walking speed in smoke was given, and the aspects affecting it identified. Thereafter, the search for available literature was initiated. The publications which were deemed to be of value for the formulation of the recommendation were selected for a detailed review, and summarized accordingly:

1. A short summary including key information about the purpose and goal, test participants, test environment, procedure, analysis and results of that study. All of these are available in the Swedish report [27].
2. A qualitative description of the experimental study, based on a pre-defined evaluation template. This description can be seen as a more technically detailed presentation than the short summary, and was done in order to ensure that the identified experimental studies were analysed consistently, and to facilitate a later comparison.
3. A quantitative summary (when this was possible) of the participants’ walking speed and the associated visibility conditions.

2.2. Summary of information and development of a recommendation
The objective of the second part was to clarify how the current data-sets and knowledge could be used in the fire safety design process. Differences between the empirical studies under review were investigated, and decisions were made about under what circumstances the information from one study could be combined with another in order to yield a more generalizable recommendation for representing people walking speed in smoke. It was concluded that the recommendation on how to represent people walking speed in smoke was to be based only on those empirical studies that had been reviewed and which:

1. shared a similar research method,
2. shared a similar data collection technique, and
3. had been performed in an (approximately) similar test environment.

It was also decided to delimit the recommendation to visibility. This was due to the limited amount of data concerning other variables. In other words, other factors likely to affect walking speed during an evacuation, such as irritancy, walking posture, decision making, demographic differences, etc., were disregarded or considered implicitly. Finally, an analysis was made in order to define the visibility level at which people in general can be assumed to start to reduce their walking speed in smoke, and also a lower threshold value of their walking speed, i.e., the assumed lowest walking speed to be used in the recommendation. This was based on the speed observed in the experiments that were more challenging for evacuees from evacuation
perspective, i.e., almost complete darkness. Different methods to quantitatively represent walking speed in smoke were then assessed and selected. A governing factor in this selection was that the method should be fairly easy to be applied in practice during the fire safety design of underground transportation systems, independent of whether or not the quantitative life safety assessment are done deterministically or probabilistically.

The objective of the third part of the project was to give suggestions on future research activities and give a recommendation on how to represent people walking speed in smoke, along with explaining the logic used to derive the recommendation.

3. People movement in smoke
In this section, the results of the initial literature review is presented. This is presented in the same format as it is presented in the original publications, i.e., it has not been manipulated or interpreted. The presentation is divided into a qualitative and a quantitative part. In the qualitative part, aspects that have been found to affect movement related factors in the reviewed studies are briefly presented. In the quantitative part, the available data are illustrated in diagrams.

3.1. Qualitative results
The qualitative results derived from the reviewed publications are summarized in Table 1. It is emphasized that this information stem from publications related to evacuation in dark and/or smoke-filled environments. It should be recognized that there are additional as well as more detailed information about other movement-related factors available in other publications [17], [20], [33]–[35]. In addition, the below information and conclusions should be considered valid only for evacuation in an environment that is dark and/or smoke-filled, i.e. they are not necessarily relevant for other scenarios, such as evacuation in smoke-free environments. It is, for example, likely that a handrail has a greater effect on people movement in smoke-filled environments than in smoke-free settings. It should also be noted that no information has been found in the literature on two of the factors which have been identified (i.e. pauses and behaviour towards other people in Table 1), thus they have not been considered in Table 1.
Table 1. Summary of qualitative results concerning the data-sets reviewed on people movement in smoke.

<table>
<thead>
<tr>
<th>Affecting factor</th>
<th>Smoke properties</th>
<th>Familiarity</th>
<th>Physical obstacles</th>
<th>Lighting</th>
<th>Information (visible, audible, tactile, etc.)</th>
<th>Presence of other people</th>
<th>Individual characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>Familiarity with a layout has a very small effect on peoples’ walking speed in dark and smoke-free environments [40]. The walking speed does, however, seem to increase the longer a person is exposed to the environment, for example during longer evacuations in tunnels [41].</td>
<td>Lighting variations do not affect peoples’ walking speed in smoke filled environments [14], [39], at least not above 3 lux; between 0.3-3 lux a weak but positive relationship has been demonstrated [17]. The presence of lighting is more important than the lighting level [18], [19], [41]. Peoples’ walking speed is reduced when the lighting is reduced [41]. The walking speed starts to be affected at lighting levels below 1 lux in smoke free environments [40].</td>
<td>Peoples’ walking speed in smoke filled environments has a limited effect on peoples’ walking speed in dark and smoke free environments [40]. During an evacuation including many people in a tunnel environment, slow walking people are likely to affect other people’s walking speed [41].</td>
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<tr>
<td>Movement</td>
<td>An uneven surface or a surface with an inclination of 10 % does not affect peoples’ walking speed in smoke filled environments [23], [37].</td>
<td>Peoples’ walking speed in smoke filled environments are probably to a great extent affected by the shaping of the walls; differences in shaping possibly have a greater impact on walking speed than differences in visibility levels when visibility generally is reduced [14], [39].</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pattern</td>
<td>Local knowledge has limited importance on movement pattern in the dark (smoke-</td>
<td>Peoples’ movement patterns start to become negatively affected when lighting is below 1 lux in smoke filled environments [26]. Normal lighting may be an obstacle during evacuation in smoke filled environments as it risk reducing</td>
<td>People tend to follow a wall during evacuation in smoke filled environments [14], [23], [36], [37], [39]. Fluorescent markings in the ground, lighting, handrails and acoustic</td>
<td></td>
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<td></td>
<td>In smoke, people move slow and carefully, and not seldom with arms and hands in</td>
<td></td>
<td></td>
<td></td>
<td>The presence of other people (up to four people) has a very limited effect on peoples’ movement pattern in dark and smoke free environments [40]. Age has a limited effect on peoples’ movement pattern in dark and smoke free environments [40].</td>
<td></td>
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<tr>
<td>Behaviour affecting individual decision making</td>
<td>People’s cognitive ability is reduced by smoke in general, and heat radiation in particular [15], [16].</td>
<td>People with good knowledge about fire/evacuation as well as men react physiologically to smoke better than uninformed and women, who instead show a greater psychological reaction [15], [16].</td>
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<tr>
<td>front of themselves for protection, to identify obstacles in front of them and/or to use the wall for way guidance [23], [34], [37]</td>
<td>free) environments [40].</td>
<td>visibility in smoke and the visibility of technical installations [43]</td>
<td></td>
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</tr>
<tr>
<td>The presence of lighting is more important than the lighting level [24].</td>
<td>Lighting has, to some extent, an effect on peoples’ movement pattern in smoke filled environments. The level of lighting is, however, of secondary importance. Most importantly is that lighting is available (such as marker lights) for aiding navigation [19], [41], [43].</td>
<td>information are all examples of particularly good aids during evacuation in smoke filled environments [18], [19], [43], [44].</td>
<td></td>
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<tr>
<td>A wall is typically used during evacuation in smoke in order to facilitate movement [14], [23], [25], [37], [39]. Handrails are effective in that aspect, as they offer something to follow in a smoke filled environment [43]. Acoustic and tactile information is a good alternative to visual information during evacuation in smoke [18], [19], [23], [37], [43].</td>
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</table>
3.2. Quantitative results

In total, ten of the reviewed empirical studies were identified to contain quantitative data on walking speed in smoke, in which the walking speed can be explicitly presented as a function of the visibility conditions. Table 2 presents a summary of the main conditions in which these experiments were conducted prior discussing the quantitative results of the review. This summary includes information on the type of experiment, sample size, age of participants, type of smoke and type of participation for each data-set under consideration.

Table 2. Summary of the main conditions in which the experiments under review were conducted.

<table>
<thead>
<tr>
<th>Ref. [-]</th>
<th>ToE [-]</th>
<th>SS (M/W) [no.]</th>
<th>Age (min/mean/max) or (mean/std. dev.) [yrs]</th>
<th>ToS [-]</th>
<th>ToP [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tanaka [46]</td>
<td>20 m corridor, no obstacles, -.</td>
<td>8 or 9/0</td>
<td>28/-/-2</td>
<td>Artificial, both, bright, cold, non-toxic.</td>
<td>Individual, C, yes.</td>
</tr>
<tr>
<td>Akizuki e. al. [17]</td>
<td>30 m corridor, no obstacles, yes (1 lux for included scenario).</td>
<td>60 (-/-)</td>
<td>Young group: 25/5 Old group: 70/3</td>
<td>Artificial, non-irritant, bright, cold, non-toxic.</td>
<td>Individual, C, yes.</td>
</tr>
<tr>
<td>Fridolf et al. [23], [37]</td>
<td>200 m tunnel, no obstacles, yes (1 lux).</td>
<td>56/44</td>
<td>18/29/66</td>
<td>Artificial, semi-irritant, bright, cold, non-toxic.</td>
<td>Individual, C, no.</td>
</tr>
<tr>
<td>Fridolf et al. [25], [38]</td>
<td>120 m tunnel, obstacles, yes (75-120 lux).</td>
<td>46/20</td>
<td>18/36/71</td>
<td>Artificial, non-irritant, bright, cold, non-toxic.</td>
<td>Individual, C, no.</td>
</tr>
<tr>
<td>Seike et al. [26]</td>
<td>700 m tunnel, obstacles, yes (40-100 lux).</td>
<td>76/1 (from the included scenario)</td>
<td>-</td>
<td>Artificial, non-irritant, bright, cold, non-toxic.</td>
<td>Individual, C, yes.</td>
</tr>
</tbody>
</table>

Legend: Ref. [-]: Gives reference with year of publication. ToE [-]: Abbreviation for type of experiment, including information on setup – presence of obstacles – lighting (with lux levels for smoke free conditions). SS (M/W) [no.]: Abbreviation for sample size, including information on number of men/women taking part in the study. Age (min/mid/max) [yrs]: Age expressed in min/mid/max. ToS [-]: Abbreviation for type of smoke, including information on if smoke was real or artificial – irritancy – colour – heat – toxicity. ToP [-]: Abbreviation for type of participation, including information on if participation was done individually or in group - type of movement (A = detailed with pauses; B = detailed without pauses; C = shortest way with pauses; D = shortest way without pauses) – if the participants repeated the experiment. If no information is available, “-” is used for the specific parameter/variable.
**This experiment has a “semi-irritant smoke” as it was conducted with artificial cold smoke (non-irritant) but acetic acid was added to produce a mild irritancy level.**

The experiments are also briefly described below (for more information, the reader is referred to the full technical report [27] or the original reference of each data-set), and aggregated quantitative data are presented in Figure 1 which illustrates the individual walking speed of a participant as a function of the extinction coefficient that that participant was exposed to. Individual plots of experimental data can be found in the full report associated with this work [27]. It must be recognized that there are differences between some of the studies from which this data has been retrieved. These differences relate to the adopted scientific method, data collection technique, the experimental environment, if evacuations were done together with other people or individually, and the assumption adopted to calculate speed, etc. This variation in experimental conditions will, however, increase the total uncertainty in walking speed. Still, the overall trend is similar, i.e., the walking speed decreases with poorer visibility. The reason for combining all experiments, recognising the fact that conditions are different, is to have a full range of visibility conditions for the reported walking speeds. The selected experiments are still reasonably similar in terms of room configuration (ToE) and smoke conditions (ToS). Most experiments are also performed with a mixed population which is expected to be a fair representation of the general occupancy for a road or rail tunnel.

Visibility is expressed in Figure 1 in terms of extinction coefficient. Visibility can be presented in terms of visibility distance, i.e. the maximum distance at which it is possible to see an item. The correlation between visibility distance and extinction coefficient (defined as in [47]) makes use of a visibility factor which changes in relation to light-reflecting or light-emitting items and it is presented in Equation 1 [47].

\[ x = \frac{A}{K_s} \]  

[Equation 1]

where:
- \( x \) = visibility distance (m)
- \( A = 2 \) for light-reflecting items and \( 8 \) for light-emitting items
- \( K_s \) = extinction coefficient (m\(^{-1}\))
Figure 1. A summary of the data on walking speed in smoke (considering the extinction coefficient as reference variable), based on ten different empirical studies. The values presented in the figure represent the average of the speed and extinction coefficient for each participant. ToS in the legend refers to type of smoke in Jin’s experiments. Please refer to the online version of the article for the colours in the legend.

Jin [14], [39]

In the experiment performed by Jin [14], [39], ten participants (all male), evacuated a 20 m straight corridor, which was either filled with irritant (smoke from burnt wood cribs) or non-irritant (smoke from burnt kerosene) smoke. Results are presented as individual walking speed values for each smoke type. The walking speed is presented as the average speed including possible pauses made by the participants (i.e. modelling speed).

Jin and Yamada [16], [45]

In the experiment performed by Jin and Yamada [16], [45], 31 participants (17 female) evacuated a 11 m straight corridor, which was 1.2 m wide. The participants did the test individually, and prior to each evacuation the corridor was filled with white smoke generated from smouldering woodchips. Results are presented as grouped averaged values for male and females for varying extinction coefficients. The walking speed is presented as the average speed including possible pauses extinction coefficients made by the participants (i.e. modelling speed).

Jensen [43]

In the experiment performed by Jensen [43], 84 participants took part one at the time in one of 13 scenarios. Each scenario included some type of evacuation aid, such as a lighting installation or a tactile installation. The experiment was conducted in a specific experimental environment in three storeys, similar to the inside of a passenger ship or a hotel. Thus, the participants evacuated also in stairs. In the experiment, both irritant and non-irritant smoke was used (no information is given on how it was generated). In the scenarios in which irritant smoke was used, the participants wore protective masks. Results are presented both as grouped averaged...
values for each scenario and as individual values. In either case, the walking speed is presented as the average speed including possible pauses made by the participants (i.e. modelling speed).

**Tanaka** [46]
In the experiment performed by Tanaka [46], eight or nine participants (the documentation is not clear on this point) evacuated a 20 m corridor. The participants were divided into two groups, one of which consisted of four people who evacuated the corridor twice: one time with non-irritant smoke and one time with no smoke. The other group included five people who evacuated the corridor three times: one time with no smoke, one time with non-irritant smoke and one time with irritant smoke. Results are presented as individual values. The walking speed is presented as the average speed including possible pauses made by the participants (i.e. modelling speed).

**Janse et al.** [42]
In the experiment performed by Janse et al. [42], 20 participants (9 male, 11 female) evacuated a 10 m corridor in three different scenarios. In scenario 1, smoke generated by smouldering wood was used; in scenario 2, smoke generated by burning cotton was used, and; in scenario 3, smoke generated by burning polyurethane was used. Results are presented as each participants’ averaged walking speed value based on the three evacuations. The walking speed is presented as the average speed including possible pauses made by the participants (i.e. modelling speed).

**Frantzich and Nilsson** [36]
In the experiment performed by Frantzich and Nilsson [36], 46 participants evacuated an environment similar to a road tunnel, which was approximately 40 m long. The tunnel was filled with artificial smoke, into which gaseous acetic acid was added to create an irritating environment. In total, two scenarios were studied: with or without lighting. Results are presented as individual walking speed values. The walking speed is presented as the average speed including possible pauses made by the participants (i.e. modelling speed).

**Akizuki et al.** [17]
In the experiment performed by Akizuki et al. [17], 60 participants evacuated a 30 m straight corridor filled with smoke. Each participant conducted the experiment several times in scenarios with varying lighting and smoke density conditions. Only results for the scenario with smoke and 1 lux lighting were used within the project. The walking speed is presented as the average speed including possible pauses made by the participants (i.e. modelling speed).

**Fridolf et al.** [23], [37]
In the experiment performed by Fridolf et al. [23], [37], 100 participants (56 male, 44 female) evacuated an approximately 200 m long underground tunnel similar to a rail tunnel environment. During the experiment, the tunnel was filled with artificial smoke, into which gaseous acetic acid was added to create an irritating environment. Results are presented as individual walking speed values. The walking speed is presented as the average speed including possible pauses made by the participants (i.e. modelling speed).

**Fridolf et al.** [25], [38]
In the experiment performed by Fridolf et al. [25], [38], 66 participants evacuated an approximately 120 m long road tunnel. During the experiment, the tunnel was filled with artificial smoke. Results are presented as individual walking speed values. The walking speed
is presented as the average speed including possible pauses made by the participants (i.e. modelling speed).

Seike et al. [26]
In the experiment performed by Seike et al. [26], 164 participants evacuated an approximately 700 m long tunnel. The tunnel was filled with artificial smoke during the experiment, and the participants’ walking speed was measured in different parts of the tunnel. In total, the experiment comprised 3 different scenarios with varying smoke density. Results are presented as individual walking speed values. The walking speed is presented as the average speed including possible pauses made by the participants (i.e. modelling speed).

3.3. Analysis
Before a recommendation on how to represent people walking speed in smoke could be formulated, a thorough analysis of the available data was necessary. The first question that was addressed was if, and to what extent, it is possible to combine data stemming from different sources. This was deemed possible only for those empirical studies that had been reviewed and which:

1. shared a similar research method,
2. shared a similar data collection technique, and
3. had been performed in a comparable test environment.

Only the studies fulfilling the three requirements were, therefore, selected as a basis for the recommendation on how to represent people walking speed in smoke. Given the fact that the number of experimental data-sets is limited, it was deemed important to scrutinise and eventually analyse as many as possible of the data-sets currently available (including experiments that were conducted in corridors rather than only in tunnel environments). More specifically, these were:

- Jin [14], [39]: Only the data collected in an environment with non-irritant smoke
- Frantzich and Nilsson [36]: All presented data
- Akizuki et al. [17]: All presented data
- Fridolf et al. [23], [37]: All presented data
- Fridolf et al. [25], [38]: All presented data
- Seike et al. [26]: All presented data from selected scenario (i.e., the scenario which had the most similar experimental procedure to the other experiments used in this paper)

Consequently, the selection of the data on which the recommendation is based on stem from studies performed in environments with non-irritant smoke. The consequences of this, and the uncertainties that it introduces, are discussed further below. The walking speed in Figure 1 is expressed as an individual, average walking speed, including pauses (i.e. a modelling speed). Thus, the possible pauses that the test participants in each of the studies may have taken during their evacuations are included in the reported walking speed. For representation purposes during practical application, this is favourable, as today’s evacuation simulation models rarely include modelling of such behavioural aspects.
3.3.1. Transformation from extinction coefficient to visibility

The available quantitative data on people walking speed in smoke has generally been presented in the literature as a function of the extinction coefficient. This is a variable developed and typically used to measure and evaluate smoke density, for example, during fire testing of products. However, it is deemed unlikely that people in an evacuation situation adjusts their speed based on this rather theoretical coefficient, which is fairly difficult to understand and interpret. In contrast, it is more likely people adjust their walking speed based on what they can see in the smoke-filled environment, independent of if what they see is light emitting or light reflecting objects. The latter is, however, of importance to the perceived visibility in smoke. As an example, a light emitting lamp can be seen from a greater distance in smoke compared to a reflecting emergency evacuation sign. For that reason, the recommendation presented in this paper is based on visibility, rather than extinction coefficient.

Another important aspect is that current evacuation models [48] do not allow for the explicit implementation of visibility factors and ambient lighting conditions when representing evacuation conditions. This undermines the usability of a relationship based on extinction coefficient; i.e., evacuation models cannot predict the actual visibility based on extinction coefficient and the presence of illuminated objects and associated visibility factors. In other words, factors which allow to calculate visibility in smoke is based on the object being observed, either light-emitting or light reflecting, see [49]. Along with the current lack of implementation of illuminated objects in evacuation models, the main reason to use visibility rather than extinction coefficient is that experiments have been conducted in different lighting conditions (e.g., with or without illumination, different types of illumination, illuminated way-finding signs, etc.). This information is lost when considering correlations based on extinction coefficients (and the representation of visibility conditions based on fire modelling predictions is not trivial, see [49], [50]), while the use of visibility vs. walking speeds allows to normalize the data-sets in accordance to the actual visibility conditions of the experiments.

For the above reasons, a transformation of the selected data was, thus, necessary, and the result is presented in Figure 2. The transformation was based on the analysis of the experimental conditions in which each data-set was collected (i.e. presence or not of light-emitting objects). This is used to derive the visibility factor [51], a parameter that is used to obtain visibility conditions starting from extinction coefficient values and that depends on the type of objects being observed. Different visibility factors have therefore been chosen (based on the recommended values from [47]) for the transformation of each data-set in relation to the experimental conditions under consideration. It should be noted that attempts to provide non-linear model fits to the data-points were giving relatively low goodness of fit. For this reason, Figure 2 does not present non-linear models fitting the data.
3.3.2. Threshold values for visibility and speed

The development of a recommendation on the representation of people walking speed in smoke relies on two threshold values which hold a central function. The visibility level at which people in general can be expected to start reducing their walking speed had to be identified. Based on the review of the literature, a thorough analysis and assessment of the data presented in Figure 2 and simple movement experiments conducted at Lund University, a visibility level corresponding to 3 meters was selected to represent this threshold value. This value is deemed to represent a sufficient level of conservativism when used in practical application. Practically, the threshold value means that a person’s walking speed is assumed not to reduce in smoke-filled environments, if the visibility level is more than 3 meters. In other words, the individual walking speed can be expressed as an unobstructed speed (i.e. smoke does not affect movement) above 3 m of visibility. This can, though, also be seen for cases with lower visibility, i.e. even from 2 m visibility, but the threshold distance is still chosen to be 3 m to reflect some degree of conservativism. As can be seen in Figure 3, the variation around the average walking speed in the order of 3 m of visibility is approximately the same as in the regions with greater visibility.

The visibility level at which people in general can be assumed to be walking with their slowest speed, as well as that particular speed, had to be defined as well. Based on the literature review, people seem to walk with their slowest speed in smoke when the situation is similar to movement in complete darkness. In such a situation, people can be expected to walk at about 0.2 m/s [52]. Thus, in the recommendation presented below, people walking speed is never represented by a value lower than 0.2 m/s.

3.3.3. Additional treatment of the data

Based on the above assumption that the individual walking speed is not affected by smoke at visibility levels above 3 m, the recommendation on walking speed in smoke is based only on the data available within 0-3 m of visibility. This data is presented in Figure 3, along with a linear regression line. The dotted line around this linear regression line represents the confidence bounds (confidence level 95%).
Assuming that the data in Figure 3 is valid to represent the walking speed of people in smoke, the regression line can be stated to represent an average value of walking speed at different visibility levels in the range between 0 and 3 m. It should be noted that this is not necessarily the same as a single individual’s walking speed $w$ at the same visibility level $x$. The linear relationship can be expressed by Equation 2.

$$w = 0.34 \cdot x + 0.31$$

[Equation 2]

The $R^2$-value for this relationship is 0.54. Two points are particularly interesting in Figure 3. The first is the lowest average walking speed, which theoretically can be calculated by assuming a visibility equal to 0 m, corresponding to 0.31 m/s. Thus, the relationship implicitly assumes that the lowest walking speed, on average, is 0.31 m/s. This seems reasonably in line with the assumed minimum speed. The second point of interest is at visibility = 3 m, at which the relationship yields an average walking speed of 1.33 m/s. This is very close to people unobstructed walking speed in smoke-free conditions according to Fruin [53]. Referring back to the above assumption, the selected threshold value of 3 m visibility does seem appropriate.

The regression analysis performed on the data do not fulfil the formal criteria for the ordinary least squares method as the variability for the individual data points along the trend line is not constant. However, as a first approximation of the relationship between walking speed and visibility, the regression results are deemed to be sufficiently accurate, especially considering the magnitude of the uncertainty and the number of individual data points. A more accurate prediction would not yield a significantly different trend line and for simplicity the chosen method is presented. The key aspect is also not to imply that the relationship presented is well established or well understood by presenting a mathematically more correct regression equation. This may come as a result when better data are presented and the fundamental relations describing the walking speed in poor visibility is available.
3.4. A recommendation on the representation of walking speed in smoke

The uncertainty that is associated with walking speed, both in smoke-free environments and in smoke-filled environments must be taken into consideration during the selection of input data for a specific design situation. In principle, this can be addressed in several ways: 1) adopting a qualitative analysis in which the areas of increased risk are identified (i.e. the fact that smoke can affect walking speed), 2) selecting a deterministic conservative value (i.e. worst credible case of one individual walking speed) or 3) a quantitative risk analysis (i.e. a probabilistic distribution of a group of walking speed). Whatever choice is made, the result is usually deterministic, even if the input of the calculation is probabilistically defined.

The final recommendation on how to represent people walking speed in smoke is dependent on the treatment of uncertainties during the analysis and the previously mentioned strategies adopted for the calculation. Three different quantitative methods are suggested, which all describe how people walking speed can be represented in life safety assessments, both in smoke-free and smoke-filled environments. The differences between the methods is linked to the quality of the assessment. Applying method 1 is simpler than method 3, but is likely to lead to a more conservative result in the form of a longer RSET. Method 3, however, is likely to lead to shorter RSETs and a more detailed representation of the evacuation phase, but do on the other hand require more user effort and longer assessment times.

Regardless of the method employed, an underlying assumption is that each individual reduces his/her speed in smoke based on his/her speed in smoke-free conditions. Implicitly, this means that an individual who is walking faster than another in smoke-free conditions, is also assumed to do so in smoke, which is supported by data [32]. Based on the review of the literature and analysis of the data, there is no strong support for this assumption as the test participants, independent of the study under consideration, have evacuated only for one visibility level/smoke exposure. Based on the results presented by Fridolf et al. [25], [38] it is, however, possible to see a tendency in that people walking speed reduction in smoke is independent of their walking speed in smoke-free conditions. The walking speed reduction in smoke has, therefore, been interpreted as a combination of an absolute and fractional reduction. It is absolute in the sense that it is the same for all individuals, and it is fractional in the sense that the walking speed for a specific visibility level is dependent on (a fraction of) the individual’s walking speed in smoke-free conditions. As an example (applying Equation 2), assuming person A having an unimpeded walking speed of 1.2 m/s in smoke-free conditions and person B having an unimpeded walking speed of 1 m/s in smoke-free conditions. At a visibility corresponding to 2 m, person A and person B would both reduce their unobstructed speed of the same quantity (i.e. 0.34 per 1 m of visibility reduction). The resulting speed corresponds to 72% of the walking speed in clear conditions for person A (0.86 m/s) and 66% of the walking speed in clear conditions for person B (0.66 m/s).

The three recommended methods for the representation of walking speed in smoke are presented below.

3.4.1. Method 1: The representation is identical for all individuals

In method 1, the representation of people walking speed is the same for all individuals during a life safety assessment. This means that inherent uncertainties are treated implicitly by the selection of conservative values (i.e., this is a worst credible case). The representation is, as for all three methods, based on the regression line presented in Equation 2. In other words, the
reduction of peoples’ walking speed when visibility is below 3 m is represented as a linearly decreasing value with a slope that is parallel to the regression line. Practically, this means that peoples’ walking speed in smoke is represented in the following way:

- Visibility levels > 3 m: Peoples’ walking speed is represented by 1 m/s, a level at which only ~10 % can be expected to walk slower (based on Fruin’s [53] data).
- Visibility levels ≤ 3 m: Peoples’ walking speed is represented by a relative reduction of 0.34 m/s per metre of visibility down to the minimum speed of 0.2 m/s. The relative reduction is based on a linear regression analysis of the data as presented in Figure 4.

The correlation can then be described by the following Equation 3 (where w is the walking speed [m/s] and x the visibility [m]), and by Figure 4.

\[ w = \min\{1; \max\{0.2; 1 - 0.34 \times (3 - x)\}\} \quad \text{[Equation 3]} \]

![Figure 4. Recommended representation of people walking speed in smoke when the representation is assumed identical for all individuals.](image)

### 3.4.2. Method 2: The representation is almost identical for all individuals

An alternative to method 1 is to treat the inherent uncertainties to a greater extent, however, without representing each individual’s walking speed separately. This can be done by dividing walking speed in smoke into, for example, three categories: medium, slow and very slow walkers. The term medium is used here as the values for this are based on the sample average, including the variations due to, for example, gender, age, etc. The method is deemed at better representing reality, without yielding as conservative results as method 1.

For this method, the designer has to decide on the proportions of medium, slow and very slow walkers in their assessment. Apart from this difference, the methodology is identical to method 1. Practically, method 2 implies that people walking speed in smoke is represented in the following way:

- Visibility levels > 3 m
  - Category medium: People walking speed is represented by 1.35 m/s (~50 % can be expected to move slower than this speed).

- Category slow. People walking speed is represented by 1.10 m/s (~15 % can be expected to move slower than this speed).
- Category very slow. People walking speed is represented by 0.85 m/s (only ~2,5 % can be expected to move slower than this speed).
- Visibility levels ≤ 3 meter: People walking speed is represented by a relative reduction of 0.34 m/s per metre of visibility down to the minimum speed of 0.2 m/s.

The correlation can then be described by the following Equations 4-6 (where \( w \) is the walking speed [m/s] and \( x \) the visibility [m]), and by Figure 5.

- Category medium: \( w = \min(1,35; \max(0,2; 1,35 - 0,34 \times (3 - x))) \)  [Equation 4]
- Category slow: \( w = \min(1,1; \max(0,2; 1,1 - 0,34 \times (3 - x))) \)  [Equation 5]
- Category very slow: \( w = \min(0,85; \max(0,2; 0,85 - 0,34 \times (3 - x))) \)  [Equation 6]

![Figure 5. Recommended representation of people walking speed in smoke when the representation is assumed almost identical for all individuals. The solid line represents the category medium, the dotted line represents the category slow, and the dashed line represents the category very slow.](image)

3.4.3. Method 3: The representation is done individually

In method 1 and 2, the representation of people walking speed is based on either one or three essential regression lines, independent on how many people are assumed to be included in the life safety assessment. Thus, the representation is done in such a way that the uncertainty related to people walking speed is implicitly treated by rather conservative input choices. The uncertainty can, however, also be treated explicitly by taking into account the variation between slow and fast individuals in the calculation. This is done in method 3, which is deemed to best represent population movement characteristics. The basis for method 3 is that each individual’s unobstructed walking speed is randomized and then assumed to linearly decrease similar to method 1 and 2. Practically, method 3 means that people walking speed in smoke is represented in the following way:

- Visibility levels > 3 m: People walking speed is represented by a randomised value from a normal distribution with mean 1.35 m/s and standard deviation 0.25 m/s (based on Fruin [53]) with minimum and maximum thresholds of 0.85 and 1.85 m/s.
Visibility levels ≤ 3 m: People walking speed is represented by a relative reduction of 0.34 m/s per metre of visibility (which results in the slowest individuals going down to the minimum speed of 0.2 m/s).

The correlation can then be described by the following Equation 7 (where \( w \) is the walking speed \([\text{m/s}]\), \( w_{\text{smoke-free}} \) is the walking speed \([\text{m/s}]\) in smoke-free conditions and \( x \) the visibility \([\text{m}]\)), and by Figure 6. As can be seen in Figure 6, people walking speed in clear conditions is initially randomized to take into account the variation in population movement characteristics. This initial speed is then assumed to linearly decrease until a minimum speed is reached (0.2 m/s).

\[
w = \min\left( w_{\text{smoke-free}}; \max\left(0.2; w_{\text{smoke-free}} - 0.34 \times (3 - x)\right) \right)
\]  

[Equation 7]

![Figure 6. Recommended representation of people walking speed in smoke when the representation is done individually.](image)

### 4. Discussion and conclusions

This paper presents a comprehensive compilation of existing data-sets concerning people movement in smoke as well as a recommendation concerning their use in underground transportation systems applications. The issue is of particular interest during the design of underground transportation systems (e.g. the case of road/rail tunnels), that do not present compartmentations, and thus leading to a more frequent case of having people walking in smoke in case of fire evacuation scenarios [23].

It is important to note that the number of data-sets available for this analysis is rather limited and varied. A large proportion of the experimental studies that have been carried out with the purpose to study people movement and walking speed in smoke has been in fact executed in either fairly simple experimental setups, such as straight corridors, or in tunnels (or environments similar to a tunnel). This means that the information presented in this paper, and the final recommendation on how to represent people walking speed in smoke, mainly apply to the experimental conditions in which data were collected. In other words, the recommendation presented in this paper are mainly valid for evacuation in underground transportations systems, such as road and rail tunnels, with relatively simple geometrical layout (i.e. straight corridors). Application of the recommendation may, however, result in an overprediction of the uncertainty.
for a specific design scenario, but due to the fact that the number of high quality experiments is low, the alternative to have a more case specific and valid relation for walking speed vs. visibility currently does not exist.

The selection of the studies to be included in the recommendation has been made in accordance to a systematic and rigorous methodology. Criteria included the data collection method in use, the environment for the experiment and the quantity of data collected. In this context, it has been deemed important to consider only such studies that were in a way comparable and thus could possibly be combined and used for the recommendation. As an example, it was decided to include data collected in a corridor rather than only in tunnels. This is based on the scientific argument that when visibility is as low as 1-3 meters, a participant in an evacuation experiment (or an evacuee in a real fire in a previously unknown environment) will not be fully aware of his or her surroundings. Therefore, the walking speed is not dependent on the perceived length of the corridor/tunnel/distance to a safe location.

The validity of the data under consideration is also affected by the experimental conditions in which they have been collected (i.e. artificial white smoke is generally adopted in the experiments rather than smoke from a real fire). In fact, a common limitation with the research examined regarding people walking speed in smoke is that it has almost exclusively been executed in environments with artificial, often cold, smoke. Typically, this smoke consists of small water droplets that are evenly distributed in a volume of air, and can thus be said to look like fog. The colour of the smoke has often been white, and has not had any adverse or irritating effects on the participants. Sometimes, acetic acid has been introduced to create an irritating effect [23], [25], however, this can be assumed to have a much milder irritating effect than smoke from a real fire [14]. Consequently, the recommendation on how to represent people walking speed in smoke are based on experimental studies that have been executed in this type of environments, i.e. more conservative assumptions might be needed in relation to the irritancy level of the smoke. Very limited data available on irritant smoke are available (i.e. the experiments from Jin [14]) since this type of experiments is very difficult to collect given ethical restrictions. Jin’s experiments showed that the scatter and average walking speeds were similar for irritant and non-irritant smoke, but for irritant smoke, reduced walking speeds occurred at greater visibilities (around 5 m) than for non-irritant smoke (<3 m). For this reason, the recommendation of this paper should therefore be considered carefully when assuming a fire which presents a level of irritancy which is deemed to significantly affect people movement. This is directly linked with the type of smoke present in the environment, which in turns is linked to the fire under consideration [54].

Regardless of the method adopted, an underlying assumption is that each individual reduces his/her speed in smoke based on his/her speed in smoke-free conditions. Implicitly, this means that an individual who is walking faster than another in smoke-free conditions, is also assumed to do so in smoke. Based on the review of the literature and analysis of the data, there is no strong support for this assumption as the test participants, regardless of the study under consideration, have only evacuated for one visibility level/smoke exposure. Based on the results presented by Fridolf et al. [38] it is, however, possible to see a tendency in that walking speed reduction in smoke is not dependent on walking speed in smoke-free conditions. The walking speed reduction in smoke (for all methods) can be interpreted as a combination between an absolute and fractional reduction. It is absolute in the sense that it is the same for all individuals, and it is fractional in the sense that the walking speed for a specific visibility level is dependent on (a fraction of) the individual’s walking speed in smoke-free conditions. Future research
should systematically investigate how individual modify their walking speed in smoke at different visibility levels (including the case of a smoke-free environment). Possibly a wide range of individuals should be taken into consideration in future experimental studies (including people with different types of disabilities, since their behaviour may differ quite significantly from able-bodied individuals).

The path of travel adopted by people in smoke could also play a role in the observed walking speed. In fact, the recommended speed is assumed to include the time people spend on way-finding activities (i.e. people may have a trajectory which is not necessarily straight). This is deemed to be an assumption on the conservative side since walking speed is assumed to not be necessarily on the shortest path. Future studies should further investigate the process of way-finding in more complex geometrical layouts in smoke. It should be also noted that walking speed in smoke could also be affected by additional factors (i.e. factors other than visibility, such as group behaviours, the influence of way-finding installations, etc.) and future recommendations should consider the mutual relationship between the impact of visibility and these other factors.

A consequence of the recommendation provided in this paper relate to the assessment of the suitability of the existing correlations available in evacuation models for fire engineering design of underground transport systems. Evacuation models may indeed rely on a limited number of (different) data-sets and correlations that may not be always customizable [55]. This issue is exaggerated by the case of commercial evacuation simulation software in which the user might not even have transparent information on the correlation in use (i.e. models may be a “black box”) or default settings might be not clearly explained [56].

In order to further assess the applicability of the proposed recommendation, a comparison has been made against an actual fire that has occurred. Such example consists of the 2013 accident in the Gudvanga tunnel in Norway, in which a fire occurred in a truck, leading to extensive smoke spread as a consequence [57]. Testimonies from the rescue service claimed that the visibility was very low, with a visibility level for illuminated objects in some places between 0-2 meters. The accident investigation shows that walking speed were on average in the order of 5 km/h, i.e. 1.4 m/s. They reported, for example, about a family of two adults and a 10 year old child who managed to escape a distance corresponding to approximately 8 km in 90 minutes. Certainly, data from actual fires that occur are often associated with major uncertainties, especially when it comes to the timing of different events during the fire disaster. The relatively high walking speeds observed in the 2013 Gudvanga tunnel fire could be linked to the limited irritating effects of the fuel gases due to the large air volume over in which they were. For example, it is more likely that a fire in a smaller space, e.g., an apartment, generates eye, nose and throat irritation to a greater extent than in a tunnel because the fuel gases are spread over a very limited air volume.

The data-sets and correlations employed today during engineering applications in underground transportation system design and their interpretation present several inconsistencies. To address this issue, this paper aims at filling this gap by considering and scrutinizing the most used available data-sets and providing a recommendation for their use in relation to the type of representation under consideration (i.e. probabilistic vs. deterministic). The suggested recommendation differs in some important aspects from the interpretations that are commonly used today in fire safety engineering design of underground transportation systems. In fact, to the best of our knowledge, this work is the first one proposing the use of visibility rather than
extinction coefficient as a variable to relate to walking speed. This is based on the assumption that to increase understanding of how walking speed is affected by different smoke densities, it seems more appropriate to consider, analyse and discuss walking speed in relation to the actual visibility levels rather than extinction coefficients. This assumption is linked to the fact that people are more likely to adjust their speed in relation to what they actually can see in the smoke-filled environment.

The practical implications of the proposed recommendation are that the fire engineering designers of underground transportation systems will have the opportunity to choose the appropriate approach for managing the inherent uncertainty in relation to the type of scenario under consideration and the level of the analysis conducted. In other words, this means that more or less conservative assumptions could be performed in relation to the global fire safety design solutions adopted by the designer as well as the type of implementation of the smoke vs speed correlation (i.e. in hand calculations or computer simulations).

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