WALKING SPEED IN SMOKE: REPRESENTATION IN LIFE SAFETY VERIFICATIONS

Karl Fridolf, WSP Sverige AB

Daniel Nilsson, Håkan Frantzich, Enrico Ronchi and Silvia Arias, Lund University

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 buildings and infrastructure. During, for example, the design of complex underground structures, such as road and rail tunnels, a structured risk assessment method is often adopted within which a number of representative fire and evacuation scenarios are identified, analysed and assessed using advanced calculations. Typically, these include an analysis of peoples' 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) for each scenario in more or less independent fire and evacuation calculations or simulations. In addition, a more advanced technique may also be adopted, in which the accumulated dose of irritating and/or toxic gases are compared to the doses resulting in incapacitation or death according to the so-called fractional effective dose (FED) concept [2].

Regardless the technique adopted to quantitatively assess peoples' ability to evacuate safely, information about the movement of people in general and in smoke in particular, is a pre-requisite. One especially important variable is information about peoples' walking speed. Therefore, research about peoples' walking speed in different settings has been ongoing for a long time; see for example the summary by Gwynne and Boyce [3]. 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, and that the behaviour of people in smoke-filled environments tend to deviate from those with no smoke. Another problematic aspect is that of the few studies that have actually focused on peoples' behaviour and movement in smoke-filled environments, only a few have resulted in quantitative correlations between walking speed and visibility. An early exception is the studies performed by Jin et al. during the 1970s in Japan [4], [5], [6].

Despite the fact that the early studies by Jin et al. [4], [5], [6] were performed 25-40 years ago, and included fairly few participants, only a limited number of studies to verify the results have been performed thereafter. These include laboratory experiments in simple corridor settings, but also larger field experiments in buildings and road/rail tunnels. However, there is a large variation in results, and in addition, differences in experimental methodology, execution and documentation sometimes make the results difficult to directly combine in order to provide a more general description of peoples' movement during evacuation in smoke-filled environments. Thus, the little 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. The consequence is that the related uncertainty not seldom has been treated with crude and conservative assumptions regarding peoples' walking speed in smoke for different visibility levels. Hence, in addition to the little amount of available data on peoples' walking speed in smoke, there is a lack of knowledge and practice 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 predicting peoples' walking speed in smoke, which may propagate through RSET analyses, and in the end affect the design and verification of the fire and life safety performance of buildings in general, and underground infrastructure in particular (as it is in these infrastructures evacuation in smoke can be expected more often than in buildings). A research project on this topic was therefore initiated by the Swedish Transport Administration, responsible for the design, construction and maintenance of most Swedish road and rail tunnels, in 2015. The purpose was to make an inventory of, investigate and describe the current knowledge base about movement of people during fire evacuation in smoke-filled environments. Furthermore, the goal was to summarize the current knowledge base, and to describe and recommend how it can be used during practical application. The results of that project has been presented in a technical report in Swedish [7]. In this extended abstract, a summary of the report conclusions are presented with an emphasis on the recommendation for practical application. For a full account of the technical details on which these conclusions rest, the reader is referred to the full report.

METHOD

The first part of the project involved a thorough literature review of the identified empirical studies deemed relevant for the project (if a study was deemed relevant or not was based on a number of criterions defined early in the process). Each independent study was summarized with key information about the purpose and goal, test participants, test environment, procedure, analysis and results of that study. When possible, a quantitative summary of the test participants' walking speed as a function of the documented visibility conditions was also added.

In the second part of the project, the information and data retrieved in the first part was thoroughly analysed. Differences between the different empirical studies 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 peoples' walking speed in smoke. It was concluded that the recommendation on how to represent peoples' walking speed in smoke were 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 a more or less similar test environment.

In this part of the project, it was also decided to delimit the recommendation to the variable visibility. This was due to the limited amount of data. In other words, other parameters and variables, also likely to affect the walking speed of people during an evacuation, such as irritancy, walking posture, decision making, demographic differences, etc., were disregarded. Finally, an analysis were 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. Different methods to quantitatively represent walking speed in smoke were then assessed and selected.

RESULTS

The results of the literature review and subsequent analysis described in the previous section can be divided into two parts: a qualitative and a quantitative. The qualitative part includes information about movement related aspects, such as walking speed, movement pattern, pauses, behaviour towards others and behaviours affecting individual decisions, and which parameters and/or variables that have been found to affect one or more of these aspects. For more information on this, the reader is referred to the technical report. This extended abstract is delimited to the quantitative part, as the results presented therein laid the foundation to the recommendation on how to represent peoples' walking speed in smoke.

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. These are summarized in Figure 1, which illustrates the individual walking speed of a test participant as a function of the extinction coefficient that test participant were exposed to. It must be recognized that there are great differences between some of the studies from which this data has been retrieved. It should also be noted that visibility is expressed in terms of an extinction coefficient in Figure 1, which is a term that is typically used to measure and calculate visibility in metres in smoke; for more information, see the SFPE handbook [8].

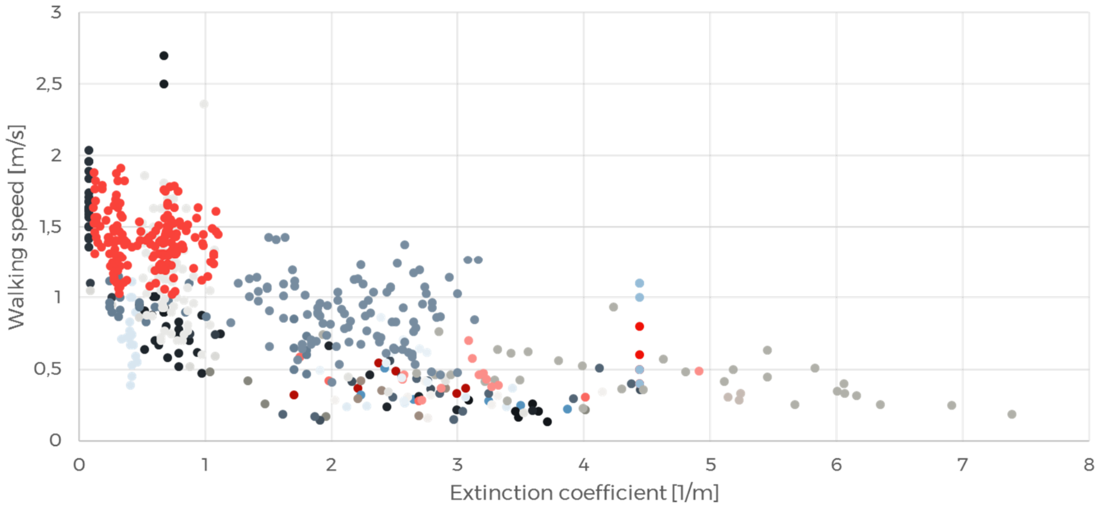

Figure 1. A summary of the data on walking speed in smoke, based on ten different empirical studies.

ANALYSIS

As mentioned above, differences between some of the empirical studies from which the data in Figure 1 was retrieved were large. Only the studies fulfilling the three requirements in the numbered list in the method section were, therefore, selected as a basis for the recommendation on how to represent peoples' walking speed in smoke. More specifically, these were (also summarized in Figure 2):

- Jin [4]: Only the data collected in an environment with non-irritant smoke
- Frantzich and Nilsson [9]: All presented data
- Akizuki et al. [10]: All presented data
- Fridolf et al. [11]: All presented data
- Fridolf et al. [12]: All presented data
- Seike et al. [13]: All presented data

Consequently, the selection of the data on which the below recommendations are based on, thus, stem from studies performed in environments with non-irritant smoke. The consequences of this, and the uncertainties that it introduces, is discussed further in the technical report mentioned earlier. Another important aspect to note is that the walking speed in Figure 2 is expressed as an individual, average walking speed, including pauses. Thus, the possible pauses that the test participants in each of the studies may have taken during their evacuations are implicitly included in the reported walking speed. For representation purposes during practical application, this is favourable, as today's evacuation simulation models seldom include modelling of such behavioural aspects.

Transformation from extinction coefficient to visibility

During evacuation in smoke, it's believed that people adjust their speeds based on what they can see in the smoke-filled environment, independent of if what they see is light emitting or light reflecting. 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 below recommendation is based on visibility, rather than extinction coefficient. A transformation of the data was, thus, necessary, and the result is presented in Figure 3.

Threshold values

In the recommendation below, two threshold values hold a central function. Firstly, the visibility level at which people in general can be expected to start reducing their walking speed must be defined. Based on the review of the literature, a thorough analysis and assessment of the data presented in Figure 3 and simple movement experiments conducted at Lund University, a visibility level corresponding to 3 meters was selected to represent this threshold value. Secondly, the visibility level at which people in general can be assumed to be walking with their slowest speed, as well as that particular speed, must be defined. Based on findings during the review of the literature, people in general walk with their slowest speed in smoke when the situation is similar to movement in complete darkness. In such a situation, people in general can be expected to walk at about 0,2 m/s. Thus, in the recommendation presented below, an peoples' walking speed is never represented by a value lower than 0,2 m/s.

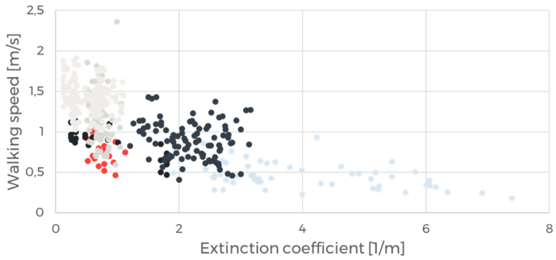

Figure 2. Data from the selected studies on which the recommendation in this extended abstract is based on.

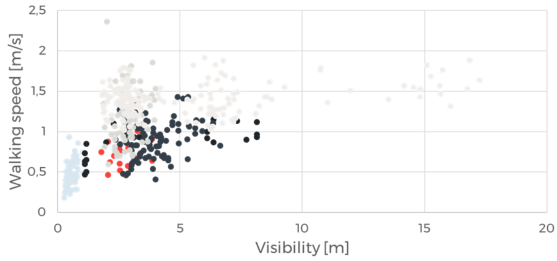

Figure 3. The data in Figure 3 instead presented as a function of visibility.

RECOMMENDATION ON HOW TO REPRESENT WALKING SPEED IN SMOKE

The recommendation on how to represent peoples' walking speed in smoke presented here is dependent on the treatment of uncertainties in the analysis. Three different methods are suggested, which all describe how peoples' walking speed can be represented in life safety verifications, both in smoke-free and smoke-filled environments. The differences between the methods is linked to the quality of the verification. 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 effort and longer assessment times.

Independent of method, 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, also is 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, independent of study, only have evacuated for one visibility level/smoke exposure. Based on the results presented by Fridolf et al. [14] it is, however, possible to see a tendency in that peoples' walking speed reduction in smoke is independent of their walking speed in smoke-free conditions. Principally, the walking speed reduction in smoke (for all methods) can be interpreted as a merge 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.

Method 1: The representation is identical for all individuals
All individuals in the life safety verification are assumed to be walking with the same speed. Practically, this is treated in the following way:

- Visibility levels > 3 meter: 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 [15] data).
- Visibility levels ≤ 3 meter: Peoples' walking speed is represented by a relative reduction of 0,34 m/s per meter visibility down to the minimum speed of 0,2 m/s. The relative reduction is based on a linear regression analysis of the data in Figure 3.

The correlation can then be described by the following equation (where w is the walking speed [m/s] and v the visibility [m]), and by Figure 4:

$$w = \min(1; \max(0{,}2; 1 - 0{,}34 * (3 - v)))$$

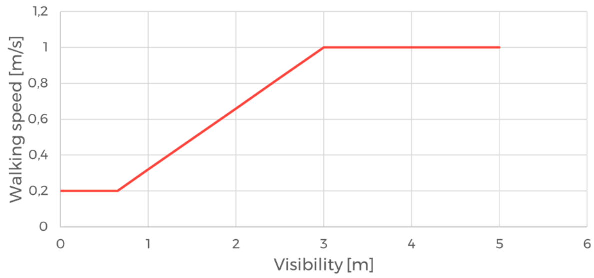

Figure 4. Representation according to method 1.

Method 2: The representation is almost identical for all individuals
The individuals are divided into three categories based on their walking speed in smoke-free conditions: average, slow, and very slow. Individuals in one group are assumed to be walking with the same speed.

For this method, the designer has to decide on the proportions of average, slow and very slow walkers in their verification. Practically, method 2 means that:

- Visibility levels > 3 meter
  - Category average: Peoples' walking speed is represented by 1,35 m/s (~50 % can be expected to move slower than this).
  - Category slow. Peoples' walking speed is represented by 1,10 m/s (~85 % can be expected to move slower than this).
  - Category very slow. Peoples' walking speed is represented by 0,85 m/s (~97,5 % can be expected to move slower than this).
- Visibility levels ≤ 3 meter: Peoples' walking speed is represented by a relative reduction of 0,34 m/s per meter visibility down to the minimum speed of 0,2 m/s.

The correlation can then be described by the following equation (where *w* is the walking speed [m/s] and *k* the visibility [m]), and by Figure 5:

- Category average: $w = \min(1{,}35; \max(0{,}2; 1{,}35 - 0{,}34 * (3 - v)))$
- Category slow: $w = \min(1{,}1; \max(0{,}2; 1{,}1 - 0{,}34 * (3 - v)))$
- Category super slow: $w = \min(0{,}85; \max(0{,}2; 0{,}85 - 0{,}34 * (3 - v)))$

Method 3: The representation is done individually
Each individual's walking speed in smoke-free conditions is randomised, and is then assumed to reduce linearly as for method 1 and 2 in smoke. Practically, method 3 means that:

- Visibility levels > 3 meter: Peoples' 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 [15]) with minimum and maximum thresholds of 0,85 and 1,85 m/s.
- Visibility levels ≤ 3 meter: Peoples' walking speed is represented by a relative reduction of 0,34 m/s per meter visibility down to the minimum speed of 0,2 m/s.

The correlation can then be described by the following equation (where w is the walking speed [m/s], $w_{smoke\text{-}free}$ is the walking speed [m/s] in smoke-free conditions and *v* the visibility [m]), and by Figure 6:

$$w = \min(w_{smoke-free}; \max\left(0{,}2; w_{smoke-free} - 0{,}34 * (3 - v)\right))$$

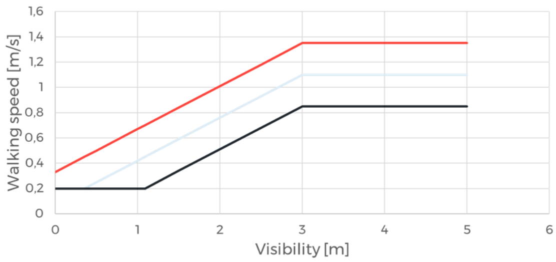

Figure 5. Representation according to method 2.

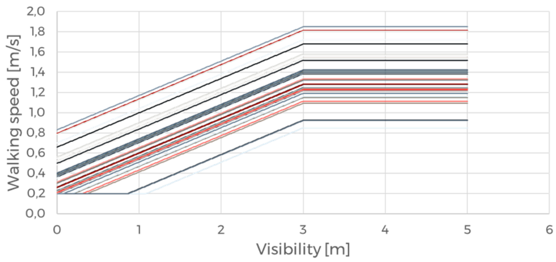

Figure 6. Representation according to method 2.

CONCLUDING REMARKS

In this extended abstract, a recommendation on how to represent peoples' walking speed in smoke has been presented. It is based on the currently available literature and data on human behaviour and movement in smoke filled environments, and builds on the information, data and conclusions that has been presented in a range of studies. The reader must be aware of the fact that representing walking speed in smoke is a complex task related with many uncertainties, and the recommendation suggested in this extended abstract does not take all aspects of movement related parameters and variables into account. In addition, the correlation is limited to the independent variable visibility and the dependent variable walking speed. It is likely that other independent variables will have an effect on the walking speed in smoke-free environments, in smoke-filled environments or in both. This has not been possible to cover in the proposed recommendation. Another important aspect to have in mind is that the recommendation is based on a selected number of empirical studies, all of which have been carried out in simple corridors or tunnels. In other words, these represent environments in which exit choice, etc., is very limited. To use the recommendation for representing peoples' walking speed in smoke in buildings where many exit choices are available is therefore not recommended. In these environments, the walking speed in smoke can be expected to be lower than what the recommendation suggests.

Finally, it must be emphasized that the recommendation is based on data stemming from empirical studies in which non-irritant smoke has been used. Can it, for example, be expected that people move even slower than what the recommendation yields for the different visibility levels? As, given one exception, no studies have been documented using irritant smoke it is difficult to evaluate the consequence on the walking speed given this effect. However, a comparison can instead be made with conclusions drawn in accident reports from, for example, tunnel fires in order to give the recommendation some credibility. As an example, people evacuating in the Gudvanga tunnel in Norway in 2013 has been reported to have done so for visibility levels of 0-2 meters, at the same time moving with an average speed of 1,4 metres [16]. This indicates that: 1) people possibly walk faster in smoke at low visibility levels than what has previously been assumed in a typical life safety verification, and 2) that the recommendation proposed in this extended abstract may very well be applicable, also for a scenario with real fire smoke.

REFERENCES

1. G. Proulx, "Evacuation Time," in The SFPE Handbook of Fire Protection Engineering, Quincy, National Fire Protection Association, 2008.
2. D. Purser and J. McAllister, "Assessment of Hazards to Occupants from Smoke, Toxic Gases and Heat," in The SFPE Handbook of Fire Protection Engineering, Springer, 2016.
3. S. Gwynne and K. Boyce, "Engineering Data," in The SFPE Handbook of Fire Protection Engineering, Springer, 2016.
4. T. Jin, "Visibility through Fire Smoke," Journal of Fire & Flammability, vol. 9, no. 2, pp. 135-155, 1978.
5. T. Jin, "Studies of Emotional Instability in Smoke from Fires," Journal of Fire & Flammability., vol. 12, pp. 130-142, 1981.
6. T. Jin and T. Yamada, "Experimental Study of Human Behavior in Smoke Filled Corridors," Fire Safety Science, vol. 2, pp. 511-519, 1989.
7. K. Fridolf, D. Nilsson, H. Frantzich, E. Ronchi and S. Arias, "Människors gånghastighet i rök: Förslag till representation vid brandteknisk projektering," SP Sveriges Tekniska Forskningsinstitut, Borås, 2016.
8. T. Jin, "Visibility and Human Behavior in Fire Smoke," in The SFPE Handbook of Fire Protection Engineering, Quincy, National Fire Protection Association, 2008.
9. H. Frantzich and D. Nilsson, Utrymning genom tät rök: beteende och förflyttning, Lund: Lunds universitet, 2003.
10. Y. Akizuki, K. Yamao och T. Tanaka, "Experimental Study On Walking Speed In Escape Route Considering Luminous Condition, Smoke Density And Evacuee's Visual Acuity," i The 7th Asia-Oceania Symposium on Fire Science and Technology, 2007, 2007.
11. K. Fridolf, E. Ronchi, D. Nilsson and H. Frantzich, "Movement speed and exit choice in smoke-filled rail tunnels," Fire Safety Journal, vol. 59, pp. 8-21, 2013.
12. K. Fridolf och H. Frantzich, "Test av vägledande system i en tunnel," Lunds universitet, Lund, 2015.
13. M. Seike, N. Kawabata och M. Hasegawa, "Experiments of evacuation speed in smoke-filled tunnel," Tunnelling and Underground Space Technology, vol. 53, pp. 61-67, 2016.
14. K. Fridolf, H. Frantzich, E. Ronchi and D. Nilsson, "The relationship between obstructed and unobstructed walking speed: Results from an evacuation experiment in a smoke filled tunnel," in The 6th International Symposium on Human Behavior in Fire, Cambridge, 2015.
15. J. Fruin, Pedestrian planning and design, New York: Metropolitan association of urban designers and environmental planners, 1971.
16. AIBN, Report on Fire in a Heavy Goods Vehicle in the Gudvanga Tunnel on the E16 Road in Aurland on 5 August 2013, Lilleström, 2015.