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Movement through fire smoke

Past research and current standards development

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ABSTRACT

People reduce their movement speed as fire smoke becomes denser and more irritant. This impact of smoke on movement is often not considered in performance-based fire safety design of everyday buildings, but for some types of built structures, such as tunnels, it can be considered in the design. Since the pioneering studies of the 1970s, much research has explored how people slow down in smoke-filled environments. However, there is no standardised way to represent the impact of fire smoke on movement speed in performance-based fire safety design, but an ISO Technical Specification (TS) is being developed. The objective of this TS is to provide guidance to designers on how to represent movement through fire smoke in performance-based fire safety design.

INTRODUCTION

In performance-based fire safety design, the visibility in fire smoke is often used as a tenability criterium. For example, New Zealand (MBIE, 2017) and Swedish (Boverket, 2013) building regulations state a tenability criterium of 10 meters of visibility for larger rooms (>100 m^2), and 5 meters of visibility for smaller rooms (≤100 m^2). In both regulations, it is stated that the visibility should be evaluated at a height of 2 meters. At this visibility, particularly at 10 meters of visibility at 2 meters, it is expected that people will not slow down because of fire as since they have enough time to adjust their movement, e.g., stop, if an obstacle suddenly becomes visible to them. This also means that designers rarely need to consider the impact of fire smoke on movement speed of occupants in fire safety design of everyday buildings.

There are, however, situations where the impact of fire smoke on the movement of occupants is considered in performance-based fire safety design. For example, rail and road tunnels are cases where movement through smoke can often be considered. As an example, the Swedish Transport Administration guidelines for road tunnels (Trafikverket, 2016) gives the designers some flexibility to choose tenability criteria, as long as the impacts of "*visibility, radiation, air temperature, toxic gases and the combination of temperature and toxic gases are considered*" (trans.). In practice, this means that performance-based fire safety design can include scenarios in which occupants move through fire smoke, but the impact of fire smoke on movement speed then needs to be considered. Due to lack of guidance, it is likely that a wide range of different correlations are applied.

Past research has clearly shown that fire smoke can severely impact both human behaviour and movement in case of fire. An early study showing the impact of fire smoke is the investigation of the MGM Grand fire in Las Vegas, USA (Bryan, 1977). The study revealed that people sometimes move into worsening smoke conditions and that most turn back before the visibility reaches 2 meters. Similarly, the Mont Blanc tunnel fire incident revealed how movement can be severely impacted by fire smoke in a single-bore road tunnel (Duffé and Marec, 1999), which suggests that care must be taken to accurately represent the impact of fire smoke in fire safety design.

Accurate representation of the impact of fire smoke on movement speed requires data, and much research has focused on quantifying the relationship between smoke density (expressed as extinction coefficient, C_s, which is inversely proportional to visibility) and movement speed. Jin (1978) performed one of the first studies on movement through fire smoke. Jin's participants moved down a smoke-filled corridor at different smoke densities. Two types of smoke were used, namely smoke from burning kerosene (non-irritant smoke) and smoke from burning wood (irritant smoke). Apart from generating the first known data set on movement through smoke, the study showed the impact of irritants. Jin (1978) suggests that people slow down as the smoke density increases, i.e., as visibility decreases, but also that people slow down quicker if the smoke contains irritants.

Since Jin's pioneering study, significant work has been done around the world to quantify the impact of smoke on movement speed. In an effort to compile available data, Fridolf et al. (2016) reviewed numerous past studies. Fridolf et al. also highlighted the lack of a standardised way to represent the impact of fire smoke on movement speed in performance-based fire safety design, which has likely led to ad-hoc approaches being applied in the past and resulting in inconsistent levels of safety.

In this paper, available data on movement through smoke is first presented, which is followed by a summary of the ongoing work in ISO TC92 SC4 Fire Safety Engineering to develop a Technical Specification entitled "*ISO/TS 21602 Fire safety engineering – Estimating the reduction in movement speed based on visibility and irritant species concentration*". ISO/TS 21602 contains correlations between movement speed and selected smoke characteristics, i.e., visibility and irritant species concentration, and provides recommendations on how to consider characteristics of occupants and features of the built environment. The objective of ISO/TS 21602 is to provide guidance to designers on how to represent movement through fire smoke in performance-based fire safety design.

PAST RESEARCH ON MOVEMENT THROUGH SMOKE

Empirical research on movement through smoke has resulted in knowledge and information, which essentially can be split into two categories: qualitative and quantitative data. Qualitative data relates to information about movement related aspects, e.g., movement patterns, 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. Quantitative data relates to information by which individual movement speeds can be explicitly presented as a function of the visibility conditions. In the following sections, some of the most important findings of past experimental research studies are summarized. For a full account of the technical details, the reader is referred to earlier publications by the authors, particularly the inventory, investigation and description of the (at the time) current knowledge base about movement of people during fire evacuation in smoke-filled environments, which was presented by Fridolf et al. (2016).

Qualitative data

An early, and fairly straightforward conclusion, which has later been confirmed in numerous studies, is that peoples' movement speed is lower in smoke filled environments compared to smoke free, independent of whether or not the smoke is irritant or non-irritant (Jin, 1978; Boyce, 1985; Jin, 1997; Akizuki et al., 2007; Fridolf et al., 2013; Fridolf et al., 2015; Ronchi et al., 2017). Furthermore, research has shown that the movement speed in very smoke obscured environments is comparable to the movement speed in complete darkness (Jin, 1978; Frantzich, 2000), i.e., without smoke. Not only do people seem to walk slow in smoke, but also more carefully, and often with arms and hands in front for protection and to identify obstacles and/or use the wall for way-guidance (Jin, 1997; Frantzich and Nilsson, 2003; Fridolf et al., 2013). Thus, people typically tend to follow a wall during evacuation in smoke filled environments (Jin, 1978; Frantzich and Nilsson, 2003), and the movement speed can be expected to be affected by the shape of the walls. Consequently, handrails are believed to be effective to facilitate movement, as they offer something to follow in smoke-filled environments (Frantzich and Nilsson, 2003). In addition, acoustic and tactile information is a good alternative to visual information to aid evacuation in smoke (Heskestad and Pedersen, 1998; Heskestad, 1999).

Familiarity with a layout has not been shown to affect peoples' movement speed in dark and smoke-free environments much, but rather the opposite (Janse et al., 1998). The movement speed does, however, seem to increase the longer a person is exposed to the environment, for example during longer evacuations in tunnels (Frantzich, 2000). Regarding lighting, variations in illuminance does not seem to affect peoples' movement speed in smoke filled environments (Jin, 1978), at least not above 3 lux However, at between 0.3-3 lux a weak but positive relationship has been demonstrated (Akizuki et al., 2007). Instead, the actual presence of lighting seems to be more important than the lighting level (Jensen, 1993; Heskestad and Pedersen, 1998; Heskestad, 1999).

Table 1. Summary of empirical studies generating quantitative data on movement through smoke.

Ref. [-]	**ToE [-]**	**SS (M/W) [no.]**	**Age (min/mean/max) or (mean/std. dev.) [yrs]**	**ToS [-]**	**ToP [-]**
Jin (1978; 1997)	20 m corridor, no obstacles, -.	10/0	23/29/37	Real, irritant, -, cold, toxic.	Individual, C, yes.
Jin & Yamada (1989; 1990)	11 m corridor, no obstacles, yes (30-100 lux).	14/17	20/-/51	Real, irritant, bright, cold, toxic.	Individual, C, yes.
Jensen (1993)	Three storey ship-alike environment, -, varying (scenario-dependent).	84 (-/-)	16/26/62	Both, both, -, -, -.	Individual, C, no.
Tanaka et al. (1996)	20 m corridor, no obstacles, -.	8 or 9/0	28/-/42	Artifical, both, bright, cold, non-toxic.	Individual, C, yes.
Janse et al. (1998)	10 m corridor, no obstacles, yes (180 lux).	9/11	25/46/72	Real, irritant, -, -, toxic.	Individual, C, yes.
Frantzich & Nilsson (2003)	40 m long tunnel, obstacles, varying (scenario-dependent; complete darkness to 2-21 lux with light).	30/16	18/22/29	Artificial, semi-irritant*, bright, cold, non-toxic.	Individual, C, yes (some).
Akizuki et al. (2007)	30 m corridor, no obstacles, yes (1 lux for included scenario).	60 (-/-)	Young group: 25/5 Old group: 70/3	Artificial, non-irritant, bright, cold, non-toxic.	Individual, C, yes.
Fridolf et al. (2013; 2014)	200 m tunnel, no obstacles, yes (1 lux).	56/44	18/29/66	Artificial, semi-irritant, bright, cold, non-toxic.	Individual, C, no.
Fridolf et al. (2015), Ronchi et al. (2017)	120 m tunnel, obstacles, yes (75-120 lux).	46/20	18/36/71	Artificial, non-irritant, bright, cold, non-toxic.	Individual, C, no.
Seike et al. (2016)	700 m tunnel, obstacles, yes (40-100 lux).	76/1 (from the included scenario)	-	Artificial, non-irritant, bright, cold, non-toxic.	Individual, C, yes.

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.

Quantitative data

Overall, a rather limited number of empirical studies have produced results on individual movement in smoke, i.e., data that can be presented as a function of the visibility conditions.
Table 1 (reproduced from a paper by Fridolf et al., 2019) summarizes these studies, and the main conditions for which the data was collected.

Aggregated quantitative data related to the studies mentioned in
Table 1 are presented in **Error! Reference source not found.** (also reproduced from the paper by Fridolf et al., 2019). Each data point in this **Error! Reference source not found.** should be interpreted as a participant's movement speed given a particular extinction coefficient. The correlation between visibility distance and extinction coefficient makes use of a visibility factor, which changes depending on the object viewed, i.e., a light-reflecting versus a light-emitting object:

$$V = \frac{A}{C_s}$$

where V is the visibility distance [m], A is 2 for light-reflecting items and 8 for light-emitting items, and C_s is the extinction coefficient [m^{-1}].

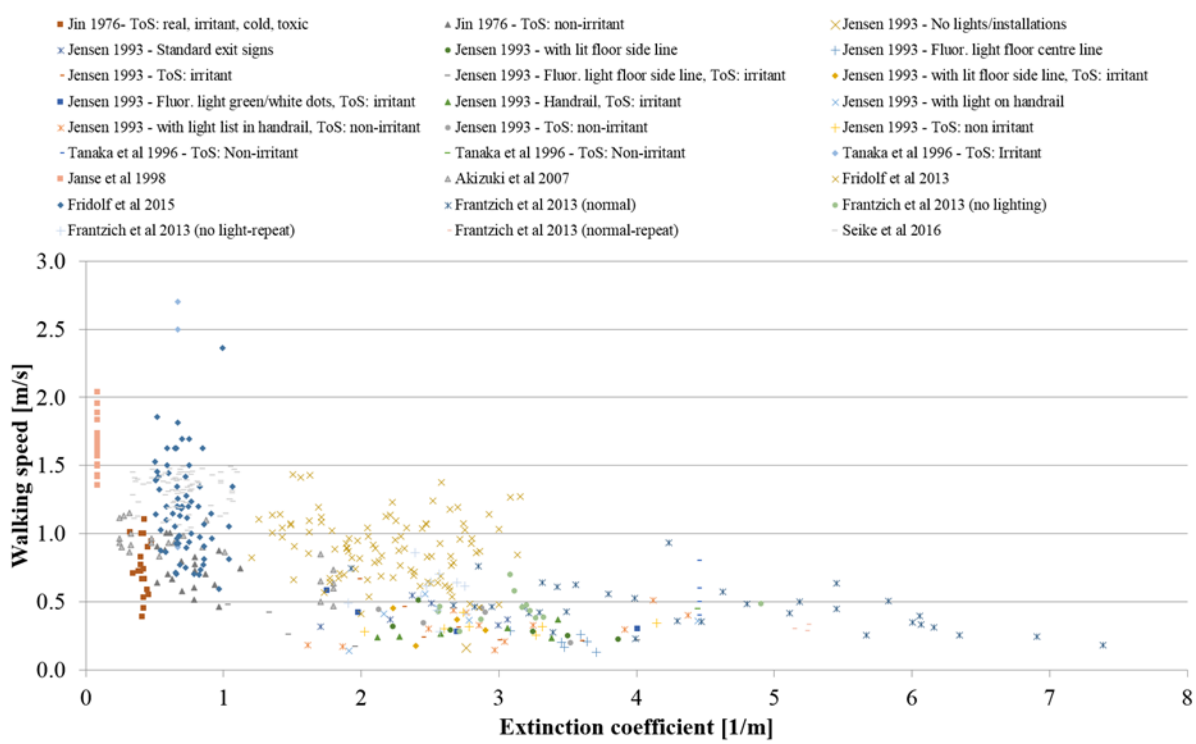

Figure 1. A summary of the data on movement speed in smoke (considering the extinction coefficient as reference variable), collected in the studies mentioned in
Table 1. The values represent the average of the speed and extinction coefficient for each participant. ToS in the legend refers to type of smoke (Fridolf et al., 2019).

Evidently, there are differences between some of the studies from which the data in **Error! Reference source not found.** has been retrieved related to, for example, 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. It is imperative to consider these differences before presenting a standardised way to represent the impact of fire smoke on movement speed in performance-based fire safety design. Typically, combination of data to reach a more generalizable conclusion is only possible if the data has been collected in empirical studies that (1) share a similar research method, (2) share a similar data collection technique, and (3) have been performed in a comparable test environment. In addition, other aspects may need to be considered, which evidently will affect people's movement speed in smoke, such as irritancy.

CURRENT STANDARDS DEVELOPMENT

In order to address the need of a standardised way to represent the impact of fire smoke on movement speed in performance-based fire safety design, work on a Technical Specification (TS) was initiated in March 2016 in the ISO standardisation committee *TC92 SC4 Fire Safety Engineering*. The TS, which is tentatively called *ISO/TS 21602 Fire safety engineering – Estimating the reduction in movement speed based on visibility and irritant species concentration*, is currently at the stage of Working Draft (WD) in the ISO hierarchy.

The main aim of ISO/TS 21602 is to provide correlations for performance-based fire safety design that represent the reduction of movement speed of occupants walking in low visibility conditions, with and without irritants. The document takes account of the type of risk analysis approach used, and provides different correlations for deterministic versus probabilistic analyses.

The correlations presented in ISO/TS 21602 are based on past research on movement through smoke, and are inspired by the literature review of Fridolf et al. (2016). Recognizing the large scatter in available data, the document discusses how to consider variation in occupant characteristics, e.g., visual acuity and mobility, and varying features of the build environment, e.g., uneven surfaces, way-guidance systems, etc. However, no correlations are given for specific occupant characteristics or building features, but the designer is cautioned to carefully consider special circumstances.

In ISO/TS 21602, correlations are provided for both the impact of visibility as well as irritant species concentration on movement speed (see Figure 2). The designer should first specify the unimpeded movement speed for the considered population, i.e., the speed at which a person would walk without fire smoke, or (if applicable) use the unimpeded movement speed specified in the document. Furthermore, ISO/TS 21602 stipulates that a person will move at the unimpeded speed (1 in Figure 2) until the visibility forces the person to slow down (2 in Figure 2). The document provides different correlations between the movement speed and visibility depending on the risk analysis approach used in the performance-based fire safety design, e.g., a deterministic versus a probabilistic approach. According to ISO/TS 21602, the effect of irritant species shall be continuously considered, and the movement speed is assumed to instantly reduce to the lowest movement speed value once an irritancy threshold is reached (3 and 4 in Figure 2).

ISO/TS 21602 acknowledges that much of the available research on movement speed in smoke presents data as correlations between the movement speed and the extinction coefficient (C_s). As stated earlier, the correlation between C_s and the visibility depends on the type of light source being observed. ISO/TS 21602 therefore provides guidance and equations related to the conversion of C_s (from computer simulations or available research data) to visibility.

In ISO/TS 21602, it is stressed that the most relevant data shall always be used as a first choice, and that the correlations provided in the document shall be used only when applicable. As an example, the provided generic correlations shall not be used for very specific populations, like elderly, children or people with movement or visual impairments.

The sub-sections below explain, in more detail, the correlations between (A) movement speed and visibility and (B) movement speed and irritant species concentration, as specified in ISO/TS 21602.

It should be noted that the document is currently at the stage of WD, and that any values/figures provided below may therefore change during the standards development process.

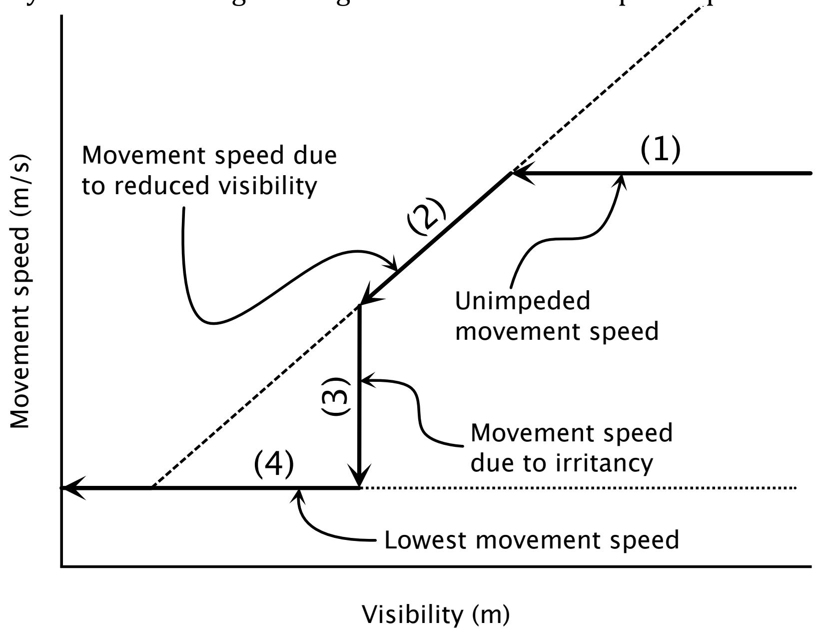

Figure 2: Schematic representation of movement speed correlations specified in ISO/TS 21602.

A. <u>Movement speed and visibility</u>

Three different methods for representing the reduction of movement speed as a function of visibility are currently incorporated in ISO/TS 21602, namely:

Method I – Single conservative estimate for deterministic analysis
Method II – Multiple conservative estimates for deterministic analysis
Method III – Representative estimate for probabilistic analysis

The intent is that Method I be used for simple calculations of movement through fire smoke when a deterministic analysis is employed, i.e., an analysis in which worst credible scenarios are used to evaluate the design. A design involving single occupants evacuating through fire smoke, e.g., a sparsely populated single-bore road tunnel evacuation, is an example of a suitable application case. The correlation between movement speed and visibility according to Method I (see Figure 3) is a conservative estimate based on available data.

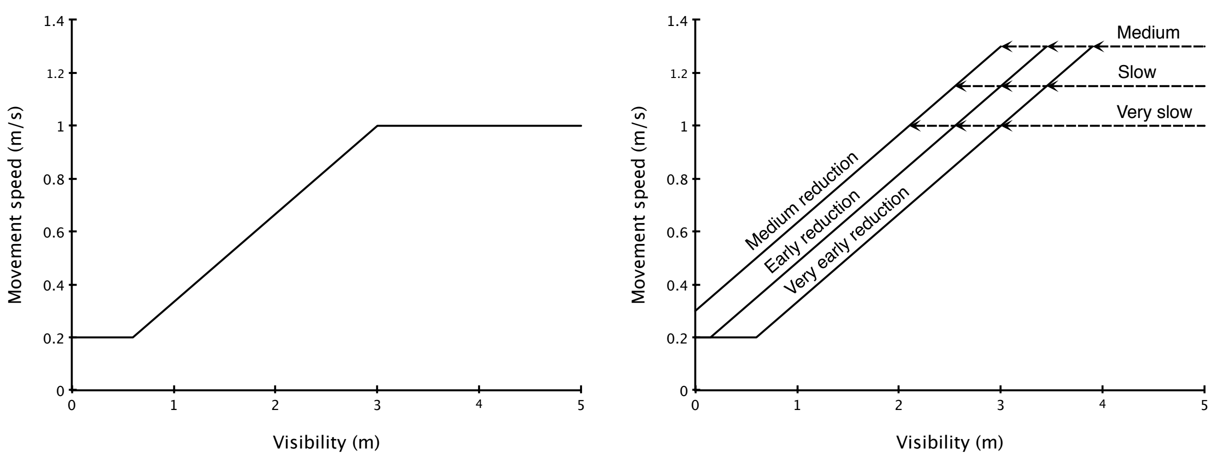

Figure 3: The correlations between movement speed and visibility for Method I (left) and Method II (right) in ISO/TS 21602 (at the WD stage of the standards development process).

Method II is intended to be used for more complex calculations of movement through fire smoke when a deterministic analysis is employed. A design involving multiple occupants evacuating through fire smoke, e.g., a more densely populated single-bore road tunnel evacuation, is an example of a suitable application case. According to Method II, a medium, a slightly conservative and a conservative correlation between movement speed and visibility should be used (see Figure 3).

Finally, Method III is intended to be used for calculations of movement through fire smoke when a probabilistic analysis is employed, i.e., an analysis including sufficient number of scenarios, with associated frequencies and consequences, that adequately represent the full scenario space. In these types of analyses, movement speed of occupants should be samples from representative distributions of movement speeds given in ISO/TS 21602.

B. Movement speed and irritant species concentration

In ISO/TS 21602, the influence of irritant species is considered in the same way independent of the method used for representing the reduction of movement speed as a function of visibility (Method I to III). The calculated value of fractional effective concentration (X_{FEC}), as defined in ISO 13571:2012, is used to determine when irritancy slows down the occupants. At $X_{FEC} > 0.1$, the movement speed of occupants reduces to 0.2 m/s (movement with very limited vision). ISO/TS 21602 also highlights that movement cannot continue beyond the point of incapacitation, i.e., the loss of ability to self-evacuate.

SUMMARY

The paper provides a summary of past research in the area of movement speed in smoke, and an insight into the current state of *ISO/TS 21602*, which is presently in the WD stage of the standards development process. The objective of the TS is to provide designers with the tools needed to consider the impact of fire smoke on movement speed in performance-based fire safety design.

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