



Reappraisal of Jin's visibility through fire smoke experiment: Insights into signage visibility and the impact of ambient light

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ABSTRACT

Jin's experiments in the 1970s contributed to fire evacuation research, but only examined relatively high ambient light levels. By replicating the Jin's experimental setup and varying ambient light level, we explore the relationship between smoke extinction coefficient, background illumination and signage emitting light intensity under low-light real-world emergency scenarios. Firstly, we confirm Jin's observation of a linear relationship between smoke extinction coefficient (σ) and visibility distance (V), although our measurements of σ are 7–11 % higher under equivalent signage luminance. Our findings on the σ versus normalized brightness $\pi L_t/E$ at a 15.5 m distance align with Jin's results, while a 20 % discrepancy is observed at 10.5 m and 5.5 m distances. At high ambient light (180 lx), the $K = \sigma V$ is comparable in Jin's experiment (from 5 to 8) and this work (from 4.7 to 9.5). However, at low ambient light (less than 22 lx), the signage remains visible in higher smoke extinction coefficients (with K from 6 to 11). The critical extinction coefficient decreases by nearly 40 % for every 5 m increase in visibility distance. This work deepens the understanding of smoke visibility under a dark fire environment, which may help guide fire signage design and inspire new fire evacuation research.

Nomenclature

Symbols	Greeks	
E Mean illuminance of ambient light (lx)	α	Scattering coefficient ratio
I Light intensity measured in smoke (cd)	δ_c	Contrast ratio
I_0 Initial light intensity (cd)	σ	Extinction coefficient (m^{-1})
K $K = \sigma V$ Dimensionless fitting coefficient	σ_s	Scattering extinction coefficient (m^{-1})
L_b Luminance of background (cd/m^2)	σ_{abs}	Absorption extinction coefficient (m^{-1})
L_t Luminance of a signage or target (cd/m^2)		
l Optical length (m)	Abbreviation	
V Visibility (m)	PBD	Performance-based design
	ASET	Available safe egress time

1. Introduction

In the event of a fire, massive smoke is produced after the condensed fuels, pyrolysis gases and combustion products mix with fresh air [1]. Fire smoke is often toxic and has various colour of white, brown and black, so it can significantly hinder the evacuation of occupants due to reduced visibility [2–4]. Therefore, exit signs are designed to be clearly observed in a smoke-free environment (Fig. 1(a)) and guide occupants' evacuation in a fire emergency [5–7]. The smoke reduces visibility in the environment and obstructs exit signs and evacuation routes [7–11].

In case of a fire, it is difficult to distinguish the lights and exit signs in a smoky indoor environment, and in some cases, the exit signs may be completely obscured (see Fig. 1(b)). Consequently, visibility in smoke is a critical parameter in fire safety engineering design practices [3,12]. However, the physical visibility in smoke is influenced not only by smoke density, but also greatly by the ambient lighting (or background light), the brightness of signage, the size of signage, and the type of

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smoke present [9,13–19]. Therefore, assessing smoke visibility is challenging when considering all these factors in a dynamically changing fire environment.

From the collective experience of firefighters dating to the 1960s (Tables 2–4.3 of [20]), a rule of thumb was determined, that is, smoke exposure is safe, as long as the fire escape exits or evacuation signs are visible from a safe distance (usually 5–20 m). This approach has gained traction, as it could be explained to laymen, and the authorities found it fairly easy to assign a threshold value to this parameter and incorporate it in law. In the 1970s, Tadahisa Jin from the Fire Protection Equipment & Safety Centre of Japan [13,14,16] expressed concern about the consequences of loss of visibility in a fire environment, as a causal factor for fire fatalities.

Following a series of large-scale experiments, Jin has developed a simple empirical model to estimate the visibility of signage in smoke. This model was later introduced into zone models and computational fluid dynamics (CFD) codes, becoming a default and staple tool in contemporary fire safety engineering. Jin's model was based on experiments in which an observer viewed an illuminated signage in a smoke chamber under varying smoke concentrations, signage brightness levels, ambient light conditions, and observation distances. From the visibility experiments, a correlation was established between the smoke extinction coefficient, smoke visibility, signage luminance, and ambient light illuminance. However, several limitations have been identified in Jin's smoke visibility model [13], including main issues with the measurement accuracy of key parameters and the fact that the experiment considered relatively high ambient light illuminance.

Although Jin's smoke visibility model is an empirical model, it is widely applied to current fire safety design codes and performance-based design (PBD) to estimate the available safe egress time (ASET) and design the smoke extraction systems for buildings [21–24]. International and local codes of practice, such as NFPA [25], BS [26], Hong Kong Code of Practice for Fire Safety in Buildings [27], set a 10-m visibility tenability limit threshold. This 10-m visibility ensures that building occupants can see exit signs and evacuate the building safely in the event of a fire. It is important to note that smoke visibility calculated by CFD is often the primary criterion to reach the tenability limit among other criteria, such as temperature, heat flux, and toxicity, during a fire [4,28].

This study first reproduces Jin's smoke visibility experiment from the 1970s [13] by using modern setups and equipment. Jin's data from plots shown in Ref. [13] was scrapped, and re-plotted in a different arrangements with SI-units, revealing some discrepancies which will be discussed further. After defining the data points obtained by Jin, experiment was performed to obtain new measurements in the same parametric space. Furthermore, the investigated background lighting

conditions were extended to be broader than Jin's ambient light conditions (from 1 lx to 22 lx) and different signage brightness to represent the modern building emergency scenarios.

2. Smoke visibility and Jin's experiments

Modern fire safety science recognizes that simple observation of an evacuation sign does not yet mean that the sign is recognized, and the information successfully processed by the observer [11,29]. However, in Jin's approach the visibility was simplified to (1) the obscuration of the sign, and (2) the resulting observed contrast ratio between the sign and its background. In this approach an object or signage can be identified by the human eye mainly based on the brightness or luminance of the signage (L_t) and the background (L_b), as shown in Eq. (1) [13,17]. The signage becomes visible when the brightness contrast δ_c exceeds a certain threshold (see Fig. 1). In meteorology, a contrast value of $\delta_c = 0.02$ is defined as the visibility threshold [17,30]. For the signage under fire smoke conditions, the contrast threshold δ_c ranges from 0.01 to 0.05 [17]. It is important to note that the visibility of the signage is also influenced by an individual's visual acuity [31,32], and in case of the experimental work – the observer's knowledge about the sign presence, location and expected shape.

$$\left| \frac{L_t - L_b}{L_b} \right| = \delta_c \quad (1)$$

Then, Lambert-Beer law can be used to describe the light obscuration caused by an aerosol or smoke (Eq. (2)) [33]. The ratio of the light intensity measured in a smoke condition (I) to the light intensity measured in a clean smoke-free environment (I_0) over a fixed constant optical distance (l) indicates the obscuration caused by smoke. The extinction coefficient (σ) accounts for the size of smoke particles, their density, distribution, absorption coefficient, scattering coefficient [34] and the wavelength of the light being measured. This extinction coefficient represents the combined effects of these parameters on the obscuration of light as it passes through the smoke.

However, the Lambert-Beer law only describes how light (i.e., usually from a strong laser light) passes through and attenuates in smoke over a specific measurement distance (l). The extinction coefficient (σ) is used to estimate the signage visibility under smoke conditions, which can be measured by a smoke densitometer (Fig. 2(a)).

$$\frac{I}{I_0} = e^{-\sigma l} \quad (2)$$

Based on contrast theory, extinction coefficient, and the characteristics of light from signage and background, Jin developed a mathematical visibility model for evacuation signage in fire smoke in the

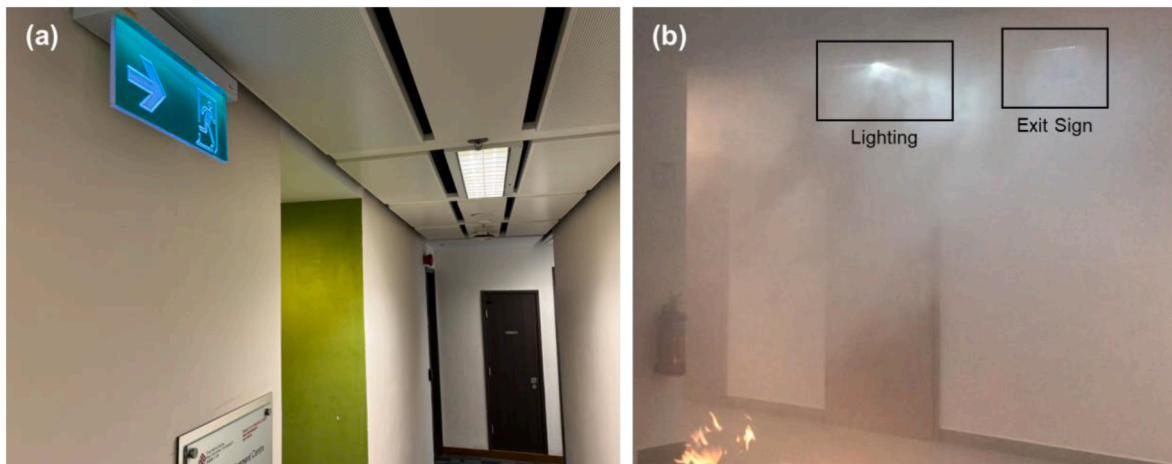


Fig. 1. (a) An illuminated exit sign in a smoke-free environment, and (b) obstructed by white smoke.

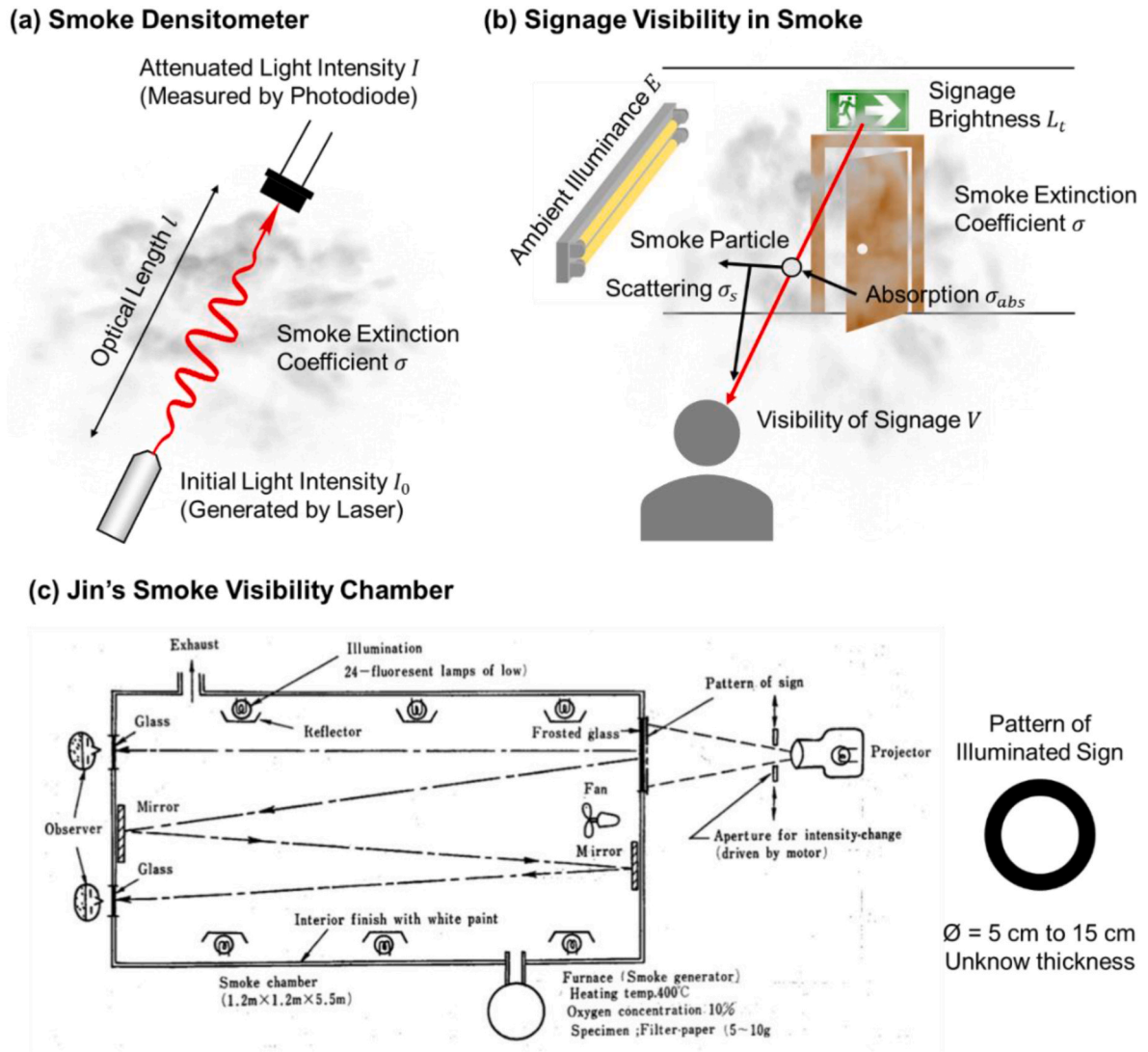


Fig. 2. (a) Mechanism of smoke densitometer based on Lambert-Beer law, (b) illustration of signage visibility in a smoky environment, and (c) Jin's smoke visibility experiment setup [13].

1970s [13,14,16]. His mathematical visibility model defined the visibility of signage (V [m]) as

$$V = \frac{1}{\sigma} \ln \frac{\pi L_t}{\delta_c a E} \quad (3)$$

that is influenced by the smoke extinction coefficient (σ) and its normalized value $\alpha = \sigma_s / \sigma = 0.4\text{--}1.0$, the contrast threshold of the signage (δ_c), the brightness or luminance of the signage (L_t [cd/m^2]), and the illuminance of external light from all directions (E [lx]), as illustrated in Fig. 2(b). However, this mathematical model is not directly adopted for current fire safety engineering applications due to its complexity.

To simplify Eq. (3), Jin [13] conducted an experiment in a small smoke chamber filled with white smoke generated from smouldering furnace paper (Fig. 2(c)). An observer (characteristics of the observer are unknown) viewed a projected circular "O" shape sign of varying sizes (5 cm–15 cm diameter but the thickness is unknown) at different observation distances through a smoke layer under controlled smoke densities and lighting conditions, as illustrated in Fig. 2(c). The observer could interact with the sign, changing its illumination until the sign is barely visible. As a critical contrast was reached, the sign illumination and smoke density were noted, and the distance, at which the observation

was made, was considered as the critical visibility distance. It is important to note, that the visual angle of the sign was maintained at different distances. This means that the observer viewed a 5 cm sign from a 5.5 m distance, a 10 cm sign from a 10.5 m distance, and a 15 cm sign from a 15.5 m distance. Observations revealed that the product of smoke concentrations (expressed as extinction coefficient σ) and the critical visibility distance (V) remains constant for standardized sign to background illumination.

Based on the experimental results, the variables from Eq. (3) were combined into a dimensionless empirical fitting coefficient K as

$$V = \frac{K}{\sigma} \quad (4)$$

The K coefficient mainly depends on the luminance of the signage (L_t), and the illuminance of external light (E). It was concluded that the K coefficient ranges from 5 to 10 for illuminated signage and from 2 to 4 for reflecting signage [20]. In current fire safety engineering applications, a K value of 3 for light reflecting signs and 8 for light emitting signs. These values are widely used to estimate the visibility tenability limit for the ASET assessment to ensure the redundancy of the fire safety designs.

Careful study of Jin's research reveals three major practical issues with implementation of his empirical model:

- (I) His experiments applied very powerful light sources for the signage (about 3000 asb or 955 cd/m^2), which were significantly stronger than the commonly used evacuation signage in buildings. As a result, the signage was observed at very high smoke extinction coefficients (up to 1.8 m^{-1}).
- (II) All experiments were conducted in high ambient light levels environment and the suggested K values are related to a single illuminance level of 180 lx ambient light. However, in real fire scenarios, weaker light sources, lower ambient light levels and lower smoke concentrations are more common.
- (III) The assumption that the sign size was different at different observation distances makes the practical value of this model questionable, because the perceived size of the sign obviously changes with increasing distance.

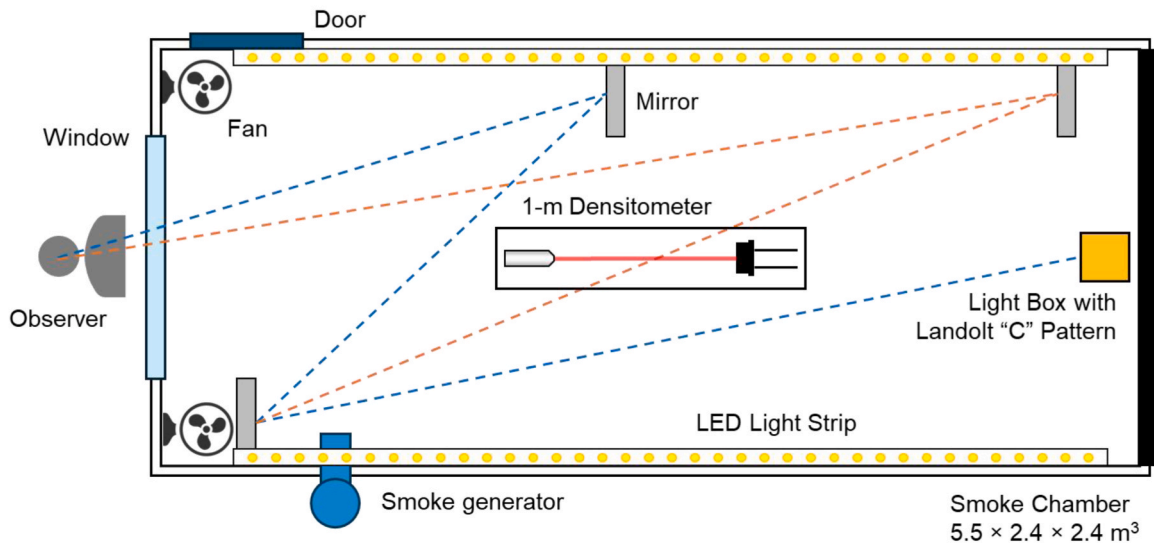
All these three issues lower reliability of Jin's model and recommended K values for fire safety engineering design practices. This work will address Issues (I) and (II) with a new experimental design, and Issue (III) will be studied in future research.

3. Methodology

To replicate Jin's visibility experiment [13], a full-scale smoke chamber is constructed, as shown in Fig. 3(a). The chamber structure consists of an aluminium frame, wooden boards, and gypsum boards. The inner surface of the chamber is coated with white paint to ensure uniform illumination distribution. The dimensions of the chamber are 5.5 m (length) $\times$ 2.4 m (width) $\times$ 2.4 m (height), having larger cross-section than Jin's smoke chamber (1.2 m width $\times$ 1.2 m height). The increase in size was due to requirements of further experiments planned with this setup. A door on the side provide access to the interior of the chamber for experimental configuration.

Two dimmable LED light strips are mounted on the ceiling to provide different ambient light conditions inside the chamber. Two fans are installed in the ceiling to facilitate air circulation and ensure even smoke distribution within the chamber. Additionally, three mirrors are mounted on the walls to create different optical path lengths: 5.5 m (directly look at the signage), 10.5 m (blue path, Fig. 3(a)), and 15.5 m (orange path, Fig. 3(a)). Please note that it is unclear how the 10 m observation distance was obtained in Jin's experiment. The detailed comparison of Jin's setup (Fig. 2(c)) and the new setup (Fig. 3(a)) is

(a) New Smoke Visibility Chamber



(b) Front View of Chamber



(c) Back View of Chamber

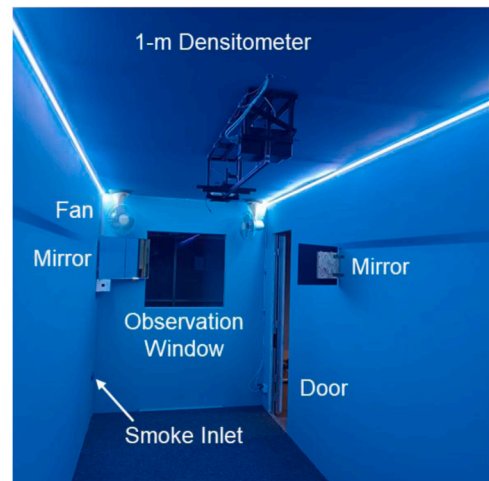


Fig. 3. (a) New experimental setup for signage visibility experiment: (b) front view of the chamber and (c) back view of the chamber.

listed in Table 1.

To test visibility in smoke, an illuminated signage box, designed based on the Jin's experiment, is placed at the end of the chamber while observers view the box through a glass window. An important note is that the observer is familiar with the sign shape and location before the experiments, possibly influencing their perception of the sign through smoke. The design of the illuminated signage box is shown in Fig. 4(a). A 3D-printed plastic box measuring 18 cm (length) $\times$ 18 cm (width) $\times$ 18 cm (height) serves as the housing of the LED lights and the sign. Aluminum foil is adhered to the inside of the box to ensure even light distribution (Fig. 4(b)). A Landolt "C" shape with diameters of 5 cm, 10 cm, and 15 cm are placed on the front face of the box. The "C" shape is covered with aluminium tape to block the light from inside, while a sheet of transparent projection paper is used to diffuse the light, creating the appearance of a sign. The Landolt "C" shape was chosen as a standard tool used in visual acuity tests [17,35].

An observer focuses on the 5 cm diameter circle when the observation distance is 5.5 m, the 10 cm diameter circle at a 10.5 m distance, and the 15 cm diameter circle at a 15.5 m distance (Fig. 4(c)). To change the brightness of the sign, the observer can adjust the intensity of the LED lights inside the signage box by a variable resistor, so that the critical visibility limit of the illuminated sign in different smoke extinction coefficients can be assessed. The signage box is placed at the end of the chamber with a height of 1.7 m, as shown in Fig. 3(a). The box is equipped with a lux meter, which was calibrated to a range of surface light intensities, as described further in the paper. This way we were able to monitor the brightness of the sign during the entire experiment.

For smoke generation, Jin heated furnace paper with an electric furnace to generate uniform white smouldering smoke. In contrast, an industrial white smoke generator (Concept Smoke Vulcan 5000) is selected to generate white smoke for the current experiment. The smoke is injected into the chamber from the side, and two fans are used to ensure even smoke distribution throughout the entire chamber. The

injection of smoke continues slowly until the desired smoke extinction coefficient is reached. After each test, the smoke is extracted from the chamber.

A lab-made smoke densitometer with a 1-m optical length is utilized to measure the smoke extinction coefficient inside the chamber [28]. The light source of the densitometer is a 10-mW red laser with a wavelength of 638 nm. The smoke densitometer is positioned in the middle of the ceiling. For the measurement of ambient light illuminance, a Sonopan L-100 luxmeter is placed in the centre of the chamber at a height of 1 m to measure the ambient light illuminance in the smoke-free environment. The level of ambient light illuminance is controlled by adjusting the luminance of the LED light strips.

Regarding the measurement of signage luminance, a TES-137 contact luminance meter is used to assess the surface luminance. The meter is placed on top of the transparent projection paper to take measurements. However, it cannot be mounted during the experiment as it would obstruct the signage and affect observation. To address this issue, a pre-calibration test is conducted. Assuming that the light inside the signage box with the aluminium foil is evenly distributed, another Sonopan L-100 luxmeter is positioned on top of the box facing inward, to measure the illuminance inside (Fig. 4(a)–(b)). Simultaneously, the luminance on the surface of the transparent paper is measured. It is observed that the illuminance inside the box is linearly proportional to the luminance of the paper's surface, see Appendix. Therefore, the illuminance inside the box is recorded during the experiment, and the illuminance (lx) is subsequently converted into the signage luminance (cd/m^2).

Regarding the procedure for the visibility experiment, the door of the smoke chamber is closed, and the smoke generator is activated to fill the chamber with white smoke. Once the smoke chamber reaches the desired smoke extinction coefficient, an observer with a visual acuity of 1, as confirmed by a visual acuity test, attempts to observe the illuminated signage under smoke conditions. The observer adjusts the brightness of the signage until the observer can barely see the Landolt sign shape ("O", as in the work of Jin [13]) and the gap in the Landolt sign ("C"), and for both point the luminance of the signage is recorded. Afterward, the chamber door is opened to exhaust the smoke, and the process is repeated with different smoke extinction coefficients, ambient light illuminances, and observations distances. Each set of measurements repeats two times.

4. Results

4.1. Comparison to Jin's experiment

Jin [13] examined the visibility limits of illuminated signage under various smoke extinction coefficients and different ambient light conditions. It is important to note that Jin measured the luminance of the signage L_t in a unit of apostilb (asb), which is not commonly used in modern measurement. To convert the unit from apostilb (asb) to the SI unit of candela per square meter (cd/m^2), the luminance of the signage L_t is presented as

$$L_t = \frac{L_{t, \text{asb}}}{\pi} \quad (5)$$

The results of the effect of ambient lighting on visibility at a distance of 5.5 m are shown in Fig. 5. Note that Jin used a circular "O" shape as the signage, while in the new measurements, the luminance of the signage is recorded when the observer can distinguish the "O" shape for replication. It is observed that a higher luminance L_t is required for the signage to be visible in environments with a higher smoke extinction coefficient σ or increased smoke concentration. Considering the effect of ambient light, it significantly affects the visibility of the signage under the smoky conditions. As the ambient light illuminance E increases, the critical smoke extinction coefficient σ for signage visibility decreases. The smoke extinction coefficient demonstrates a linear increase

Table 1
Comparison of Jin's experimental setup and the new experimental setup.

Feature	Current Smoke Chamber	Jin's Smoke Chamber [13]
Smoke chamber size	2.4 m $\times$ 2.4 m $\times$ 5.5 m	1.2 m $\times$ 1.2 m $\times$ 5.5 m
Chamber structure	Gypsum and wood boards with an aluminium frame	Not mentioned
Chamber coating	White paint	White paint
Ambient lighting	2 LED light strips	24 units of 10 W fluorescent lamps
Fan	2 fans	1 fan
Mirror	3 mirrors	2 mirrors
Observation distance	5.5 m, 10.5 m, and 15.5 m	5.5 m, 10.5 m, and 15.5 m
Display of the object	A box with LED lights inside to reproduce the Jin's setting	Combination of frosted glass, aperture, and projector
Observe object	A Landolt "C" shape with diameters of 5, 10, and 15 cm	A circular "O" shape with diameters of 5, 10, and 15 cm
Smoke generation	An industrial white smoke generator (Concept Smoke Vulcan 5000), mineral oil 180 heated at 360 °C in a pressurized stream of CO ₂	Heating 5–10 g dry furnace papers with an electric furnace (white smouldering smoke) Heating temperature: 400 °C O ₂ Concentration: 10 %
Smoke filling	Until reaching target smoke extinction coefficient	2–4 min
Smoke exhaust	Open door until reaching 0 m ⁻¹ extinction coefficient	10–15 min
Smoke measurement	1-m smoke densitometer with a 638 nm, 10 mW red laser	1-m smoke densitometer
Ambient light measurement	Sonopan L-100 luxmeter	Not mentioned
Signage brightness measurement	Sonopan L-100 luxmeter (measurement calibrated to TES-137 contact luminance meter)	Not mentioned

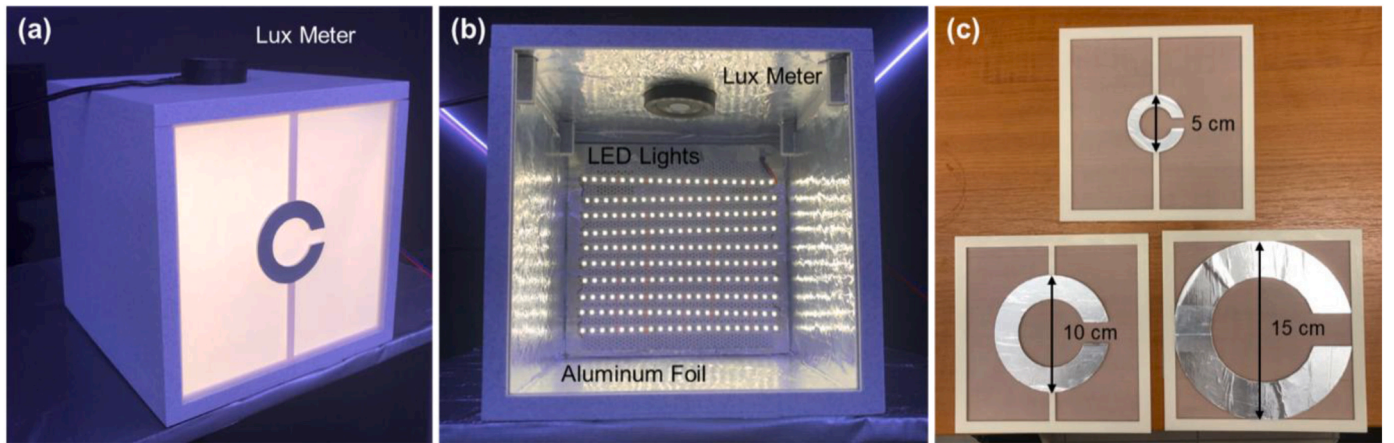


Fig. 4. (a) Lab made signage box inspired by Jin's experiment [13], (b) interior design of the signage box, and (c) Landolt "C" shapes with different diameters for different observation distances.

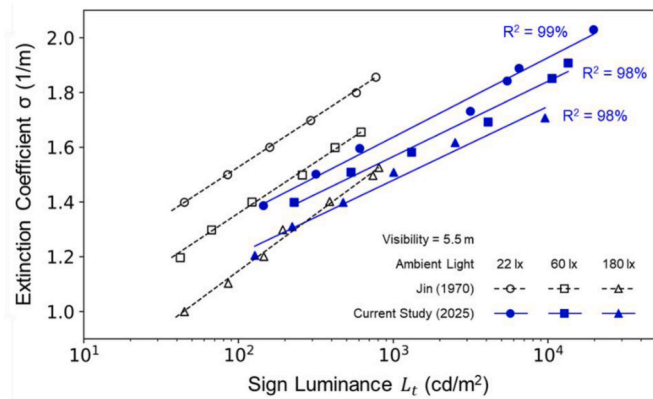


Fig. 5. Critical smoke extinction coefficients for visible illuminated signage at 5.5 m visibility distance under different ambient light conditions.

corresponding to the exponential increase in signage luminance. This indicates that the signage is easier to observe in lower ambient light conditions for the same smoke extinction coefficient. For Jin's measurements, when the smoke extinction coefficient σ is 1.4 m^{-1} , the critical signage luminance under ambient light conditions of 22 lx, 60 lx, and 180 lx is 45 cd/m^2 , 122 cd/m^2 , and 389 cd/m^2 , respectively.

The minimum and maximum signage luminance levels for Jin's experiment are 42 cd/m^2 and 808 cd/m^2 , respectively, while this study finds them to be 128 cd/m^2 and $22,500 \text{ cd/m}^2$. Note that the luminance of illuminated exit signage used in buildings ranges from approximately 100 cd/m^2 to 500 cd/m^2 . The range of signage brightness has been extended in this study, and it is observed that the relationship between the smoke extinction coefficient and the exponential signage luminance remains a linear correlation (Fig. 5). At an ambient light level of 180 lx, the results from Jin's and the new measurements are similar when the signage luminance is less than 1000 cd/m^2 . However, as the smoke extinction coefficient continues to increase, a much higher luminance is required for the signage to remain visible. For the ambient light levels of 22 lx and 60 lx, a deviation is observed between Jin's results and the new results. With the same signage luminance, the critical smoke extinction coefficient is higher in Jin's measurements, indicating that signage with the same luminance is visible at approximately 7 % and 11 % higher smoke concentrations in Jin's measurements for ambient light levels of 60 lx and 22 lx, respectively.

The differences observed between Jin's results and the new results might primarily be attributed to the ambient light conditions within the smoke chambers. Although the walls of both chambers were coated with

white paint to ensure the uniform illumination distribution, the ambient lighting arrangement is different. Jin changed the ambient light illumination by adjusting the number of fluorescent lamps turned on, while the new measurements adjusted ambient light levels by dimming LED strips. The new setup likely provides a more uniform illumination distribution across different ambient light conditions within the smoke chamber than Jin's setup, resulting in more accurate assessments of signage visibility. It is also unclear if Jin measured sign and ambient light illuminance during the experiment with smoke or referred to calibration carried out before an experiment.

Based on Eq. (3), signage visibility V is a function of signage luminance L_t and ambient light illuminance E . Jin introduced a term called "dimensionless brightness" $\pi L_t/E$, which represented as a variable for the critical smoke extinction coefficient σ to eliminate the effects of ambient lighting, but this term is not actually dimensionless and retains units of $\text{cd/m}^2 \cdot \text{lx}$. Therefore, we introduced a term, "normalized brightness" $\pi L_t/E$, to replace "dimensionless brightness" and avoid confusion. Fig. 6 replots the extinction coefficient σ from Fig. 5 using $\pi L_t/E$, as the variable. It is important to note that there is a discrepancy between Figs. 5 and 6 in Jin's paper [13], and Fig. 6 is replotted based on the data from Fig. 5 in Jin's paper.

As shown in Fig. 6, data from both Jin's measurements and the new measurements collapse into a linear correlation after introducing the variable $\pi L_t/E$, although Jin's data deviates less from the regression line. Introduction of this parameter means that the influence of ambient lighting has been removed. Besides, it is observed that when the extinction coefficient ranges from 1.2 m^{-1} to 1.4 m^{-1} , both measurements

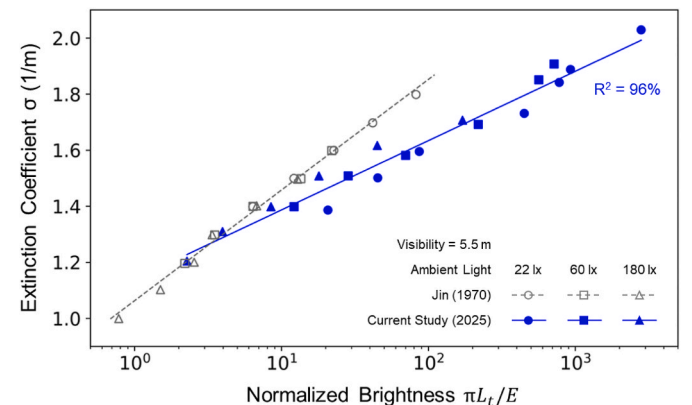


Fig. 6. Relationship between the normalized brightness and the critical smoke extinction coefficient at 5.5 m visibility distance under different ambient light conditions.

yield a similar $\pi L_t/E$ value for an ambient light level of 180 lx. However, as the smoke extinction coefficient continues to increase, the $\pi L_t/E$ value from the new measurements is higher than that from Jin's measurements. This suggests that a brighter signage is required for visibility in the new measurements under the same smoke extinction coefficient.

In addition to investigating visibility at 5.5 m distance, Jin also examined the relationship between the normalized brightness $\pi L_t/E$ (or signage luminance L_t) and the critical smoke extinction coefficient σ at observation distances of 10.5 m and 15.5 m at an ambient light level of 180 lx. It is important to note that Jin reported an ambient light level of only 180 lx for various observation distances and did not consider other ambient light levels at these distances. To achieve these observation distances, Jin installed two mirrors at the end of the chamber (Fig. 2(c)), while measurements can be taken at 15.5 m, how the measurements were carried out at 10.5 m is unknown.

The new experimental setup has been improved by mounting three mirrors on the side walls, allowing for measurements at three observation distances (Fig. 3(a)). The diameters of the observation signage or target for distances of 5.5 m, 10.5 m, and 15.5 m are 5 cm, 10 cm, and 15 cm, respectively, in order to maintain a consistent visual angle, following Jin's experiment. It is important to note that another discrepancy is observed in Jin's results. The Jin's 5.5 m visibility results (grey data in Fig. 7) are different from the results from Fig. 5. The Jin's 5.5 m visibility results in Fig. 7 are plotted based on Fig. 7 in Jin's paper [13].

The effect of observation distances on the critical smoke extinction coefficient is shown in Fig. 7. As the observation distance increases, the critical smoke extinction coefficient significantly decreases. In Jin's measurements, the signage is visible with a critical smoke extinction coefficient as low as 1.0 m^{-1} at a distance of 5.5 m, while it becomes visible only at extinction coefficients of 0.5 m^{-1} and 0.3 m^{-1} at distances of 10.5 m and 15.5 m, respectively. In the new measurements, the result at 15.5 m aligns with Jin's findings. However, considering the lowest normalized brightness $\pi L_t/E$, there is approximately a 20 % difference in the extinction coefficient at distances of 5.5 m and 10.5 m. This suggests that illuminated signage is visible at a slightly higher extinction coefficient, despite having the same signage brightness, at the distances of 5.5 m and 10.5 m in the new measurements.

Fig. 8 illustrates the relationship between the normalized brightness $\pi L_t/E$ and the dimensionless number σV at an ambient light level of 180 lx. This is the foundation of K value (Eq. (4)) used in the current fire safety industry and research for the illuminated signage. The dash black curve in Fig. 8 represents the theoretical curve of Eq. (3) when $\delta_c = 0.01$ based on Jin's measurements and $\alpha = \sigma_s/\sigma = 1$ based on Jin's

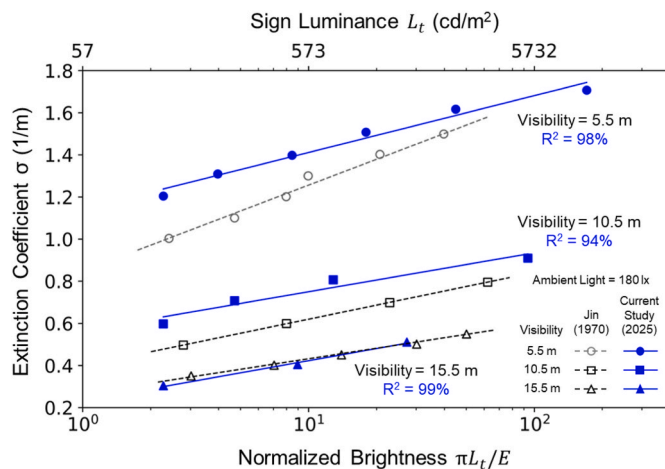


Fig. 7. Relationship between the normalized brightness and the critical smoke extinction coefficient at a 180-lx ambient light condition with different observation distances.

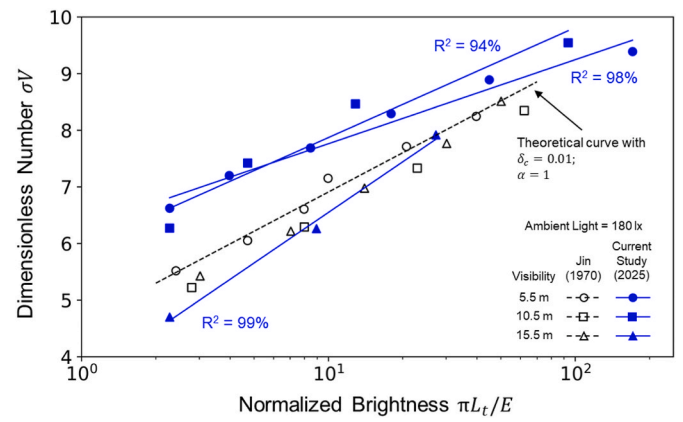


Fig. 8. Relationship between the normalized brightness $\pi L_t/E$ and the dimensionless number σV with different visibilities under an ambient light level of 180 lx.

assumption for white smoke [13]. Jin's results align with the theoretical curve for visibility from 5.5 m to 15.5 m at an ambient light level of 180 lx. When the normalized brightness $\pi L_t/E$ increases exponentially, the dimensionless number σV increases linearly. Based on Jin's results, the dimensionless number σV or the K value for the illuminated signage ranges from 5 to 8 for calculating and modelling visibility, according to Eq. (4). However, a difference is observed between the new measurements and Jin's results. For visibility at 5.5 m and 10.5 m, the dimensionless number σV or the K value ranges between 5.3 and 9.5, which is higher than Jin's results. In contrast, the K value for 15.5 m visibility ranges from 4.7 to 8, which is lower than in Jin's results. Furthermore, the new measurement results do not align with the Jin's theoretical solid black curve, indicating that the assumptions of $\delta_c = 0.01$ and $\alpha = \sigma_s/\sigma = 1$ may not be accurate.

In this experiment, the illuminated signage with adjustable brightness is viewed in different smoke extinction coefficients under three observation distances and different relatively high ambient light illuminances (i.e., $>60 \text{ lx}$). Differences are observed between Jin's measurements and the new measurements. In current fire safety assessments and research, K value from Jin's smoke visibility experiment is often used to estimate the smoke visibility, which ranges from 5 to 8 for illuminated signage. However, the reference ambient light illuminance for the K value is 180 lx (Fig. 8), which is significantly higher than the ambient light conditions during emergency or power outage. Therefore, it is important to consider low ambient light illuminances for the visibility of the signage under smoky environment.

4.2. Effect of lower ambient light

Jin conducted the experiment under relatively high ambient light conditions between 22 lx and 180 lx. However, according to international codes and standards, the minimum illuminance for spaces ranges from 1 lx to 15 lx during emergencies [36–39]. Therefore, this study also investigates ambient light illuminance below 22 lx to better reflect real-world scenario. Besides, the pattern of the signage used in Jin's experiment was a simple circular "O" shape with different diameters for varying observation distances. In this study, this pattern is changed to a Landolt "C" shape, which is a standard optotype for visual acuity measurement (Fig. 4(b)). In smoky environment, evacuees can either identify the light from the exit sign or emergency lighting (Fig. 1(b)), recognize the presence of an exit sign, or distinguish the information from the exit sign. With the "C" pattern, both the critical visibility of the signage and the signage details (e.g., arrows, logos, words) can be examined. However, in smoky conditions, smoke scatters and absorbs the light, making the gap in the "C" indistinguishable and causing it to resemble an "O" shape.

The relationship between the signage luminance and the smoke extinction coefficient over a range from 1 lx to 222 lx is shown in Fig. 9 (a). At the same signage luminance, the critical extinction coefficient for signage visibility is higher in lower ambient light conditions. For example, the critical extinction coefficient is approximately 1.5 m^{-1} for an ambient light illuminance of 1 lx and 0.9 m^{-1} for 222 lx (Fig. 9(a)). Under lower ambient light condition, the signage is much more visible to evacuees. For the clarity of the signage, an increased signage luminance is required for clear visibility of the signage information (e.g., arrows and words).

When the ambient light level is 1 lx and the extinction coefficient is 1.6 m^{-1} , the critical signage luminance is 170 cd/m^2 to barely see the “O” shape (i.e., identifying it as an “O”) and 440 cd/m^2 to barely see the “C” shape (i.e., identifying the gap in the “C”) (Fig. 9(a)). It is important to note that the signage visibility may be further diminished under stressful conditions, such as during a fire evacuation, due to human psychological factors [2,17]. Or physiology of the observer. Therefore, signage luminance should be brighter than the measured critical signage luminance in real fire scenarios to ensure it can be observed clearly by evacuees.

In Fig. 9(b), it is shown that the signage remains visible in smoke extinction coefficient as high as approximately 1.4 m^{-1} to 1.7 m^{-1} when the signage luminance is below 500 cd/m^2 at a 5.5 m observation distance, depending on the level of the ambient light. During a fire scenario, when the smoke layer obscures the exit sign, evacuees may still be able to see the exit sign under low ambient light conditions. However, in high ambient illumination conditions (e.g., $>200 \text{ lx}$), visibility of the exit sign becomes impossible.

4.3. Effect of observation distance

Although the signage is visible in a relatively high smoke extinction coefficient (i.e., $>1.4 \text{ m}^{-1}$) under ambient light levels below 22 lx at a 5 m observation distance, increasing the observation distance (but preserving the angular dimension of the sign) significantly decreases signage visibility. Fig. 10(a)–(b) illustrates the relationship between the normalized brightness $\pi L_t/E$ and the critical smoke extinction coefficient at different observation distances under low ambient light levels. At an ambient light level of 22 lx (Fig. 10(b)), the signage remains visible

with the extinction coefficients of 1.4 m^{-1} (224 cd/m^2), 0.7 m^{-1} (135 cd/m^2), and 0.4 m^{-1} (220 cd/m^2) at observation distances of 5.5 m, 10.5 m, and 15.5 m, respectively. Similarly, at an ambient light level of 1 lx (Fig. 10(a)), the signage is visible with the extinction coefficients of 1.5 m^{-1} (189 cd/m^2), 0.8 m^{-1} (202 cd/m^2), and 0.5 m^{-1} (492 cd/m^2) at observation distances of 5.5 m, 10.5 m, and 15.5 m, respectively. The lower the ambient light illuminance, the higher the extinction coefficient at which the signage remains visible. Moreover, the critical extinction coefficient decreases by nearly 40 % or more for every 5 m increase in visibility distance, which means that observing an exit sign becomes significantly more difficult at longer distances.

According to building regulations and codes, sufficient exit signs shall be installed to ensure that all evacuation routes are clearly indicated within the building. However, there is no regulation that specifies a minimum observation distance for exit signs. Considering a long corridor scenario, evacuees may be able to see an exit sign from a considerable distance. While it is true that the exit sign is likely to be visible in clear environments, its visibility in smoky environments at long observation distances is uncertain.

4.4. Dimensionless number σV in low ambient light conditions

Based on Jin's results, the suggested dimensionless number σV equals a constant and ranges between 5 and 8 at an ambient light level of 180 lx for illuminated signs (Fig. 8). However, as mentioned above, the ambient light level in emergency scenarios ranges from 1 lx to 15 lx with reference to the building regulations. The relationship between the normalized brightness $\pi L_t/E$ and the dimensionless number σV at low ambient light levels of 1 lx and 22 lx is presented in Fig. 11(a)–(b). The results show that the dimensionless number σV for 1 lx ambient light ranges from 7.5 to 11 (Fig. 11(a)), whereas for 22 lx ambient light, it ranges from 6 to 11 (Fig. 11(b)). Besides, the dimensionless number σV at 15.5 m observation distance is lower compared to distances of 5.5 m and 10.5 m. It is observed that the dimensionless number σV is slightly higher at lower ambient light levels.

This implies that using Jin's dimensionless number σV of 5 to estimate the visibility of illuminated signage may result in overestimation. Considering the low ambient light conditions, the actual visibility of the

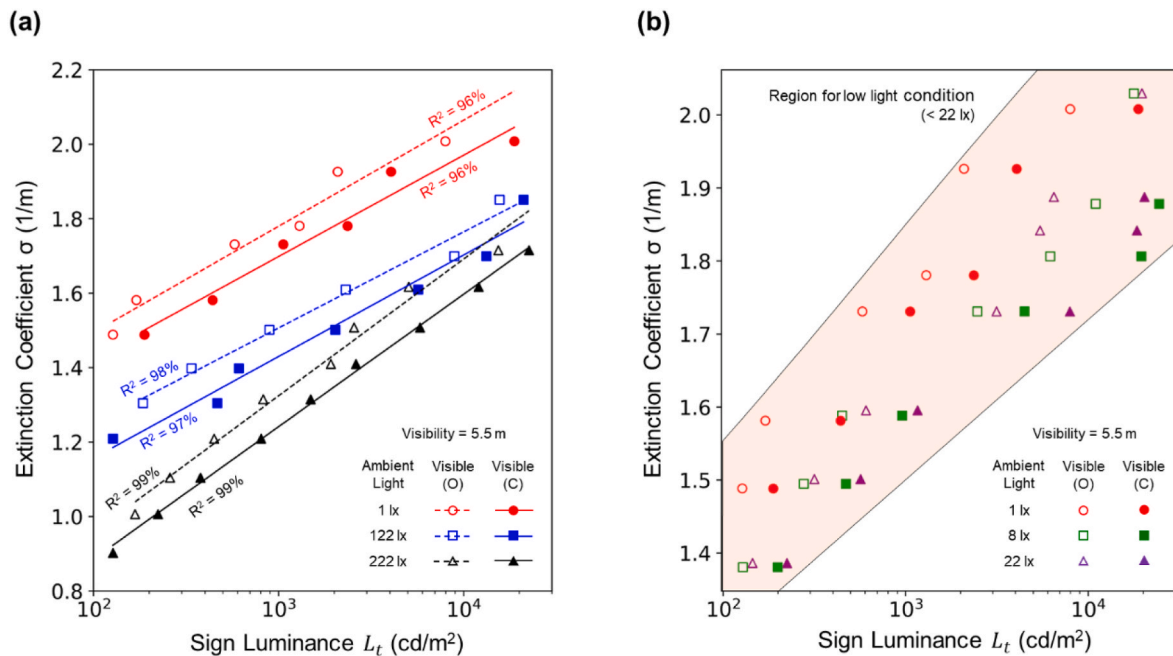
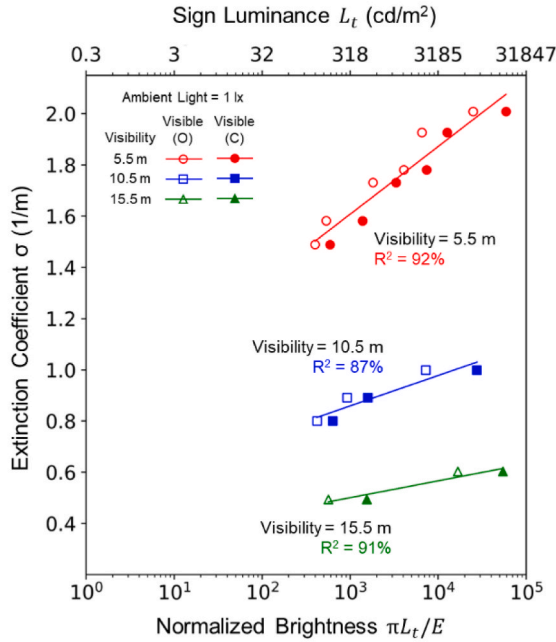
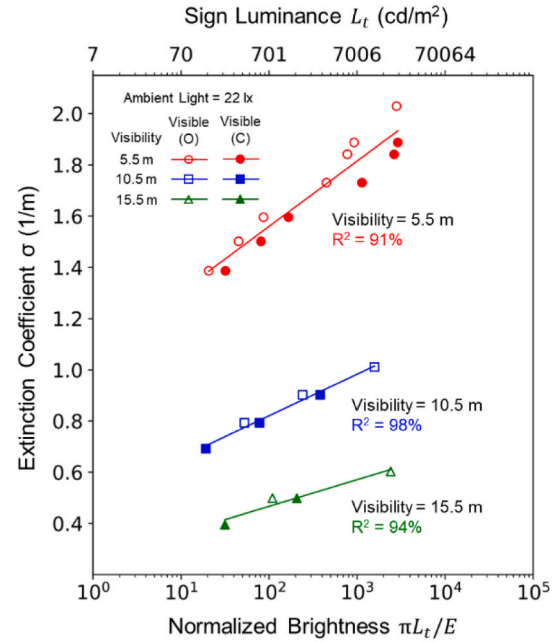


Fig. 9. Relationship between signage luminance and smoke extinction coefficient at 5.5 m visibility with ambient light illuminance ranges (a) from 1 to 222 lx and (b) from 1 to 22 lx.

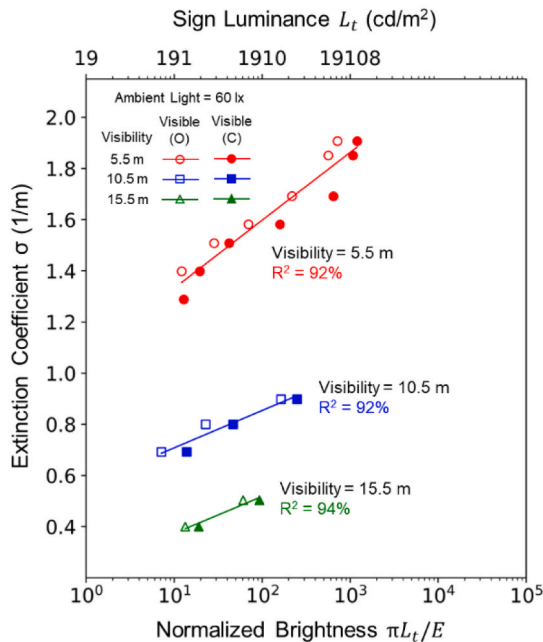
(a) 1 lx Ambient Light



(b) 22 lx Ambient Light



(c) 60 lx Ambient Light



(d) 180 lx Ambient Light

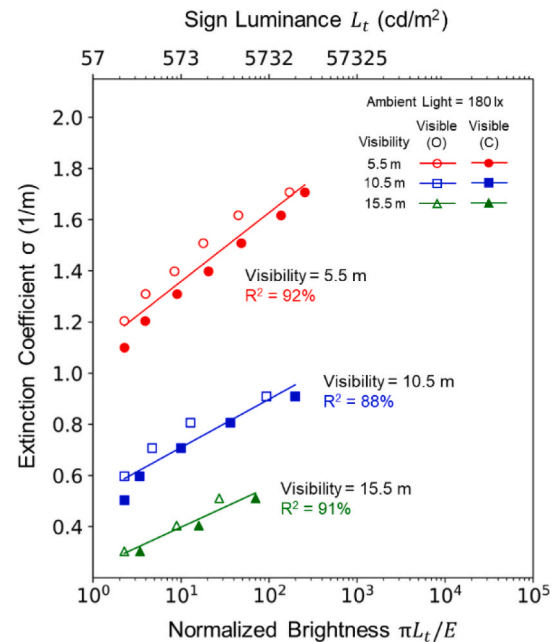


Fig. 10. Relationship between the normalized brightness and the critical smoke extinction coefficient at different observation distances under low ambient light levels of (a) 1 lx, (b) 22 lx, (c) 60 lx, and (d) 180 lx.

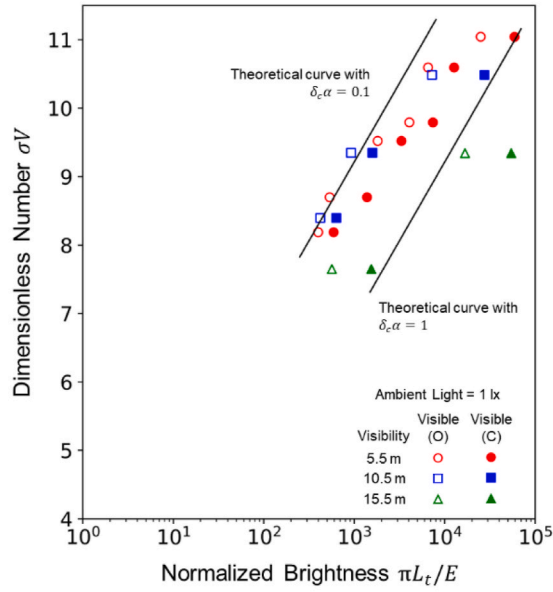
illuminated signage should be higher. Additionally, the theoretical curves derived from the new experiment from 1 lx to 180 lx are shown in Fig. 11. Jin suggested that the results were consistent with the theoretical curve where $\delta_c \alpha = 0.01$, see Section 4.1 and Fig. 8. However, the theoretical curves based on the new results do not match Jin's assumptions and exhibit different values for each ambient light level: (1) the scattering coefficient ratio α may not be 1 and could be lower; and (2) the contrast ratio δ_c may not be 0.01 and could vary depending on different ambient light levels and signage brightnesses. For instance, with fixed signage brightness, the lower the ambient light level, the lower the contrast ratio. It is also stipulated, that the critical contrast

ratio may be linked to the visual acuity of the observer.

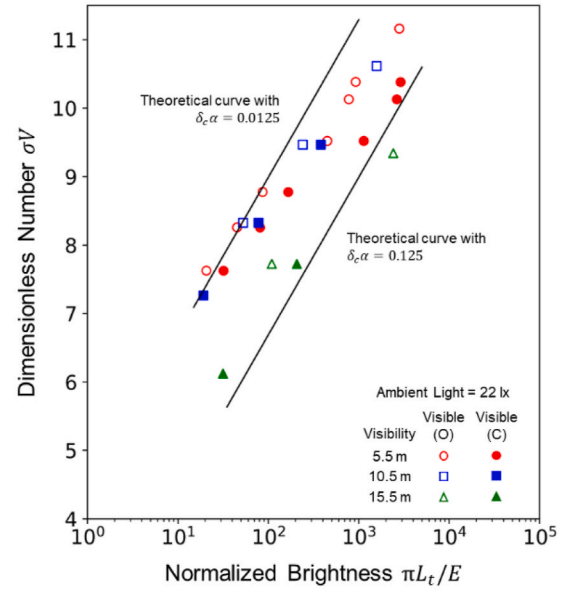
5. Discussion

The experiments discussed in this paper are the foundation of the visibility in smoke model, which is a core concept of modern fire safety engineering. The loss of visibility in fire is usually not directly causal to the fatality or injury but rather becomes a contributing factor. Loss of visibility may cause a victim to be slowed down along an evacuation route or completely trapped in smoky environment for excessive amount of time, eventually leading to damage from toxic products. This was also

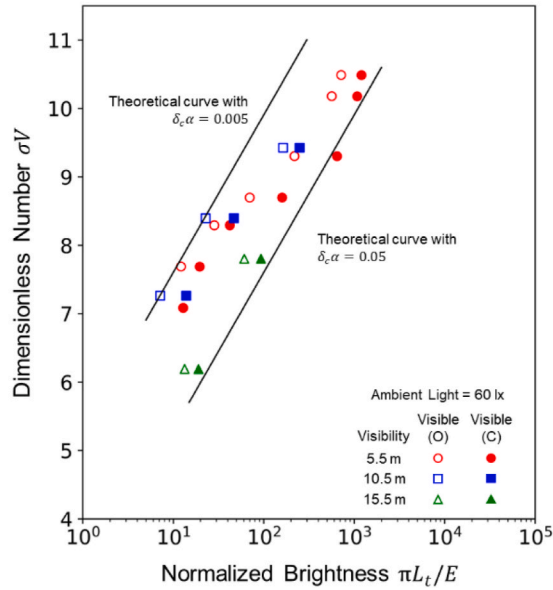
(a) 1 lx Ambient Light



(b) 22 lx Ambient Light



(c) 60 lx Ambient Light



(d) 180 lx Ambient Light

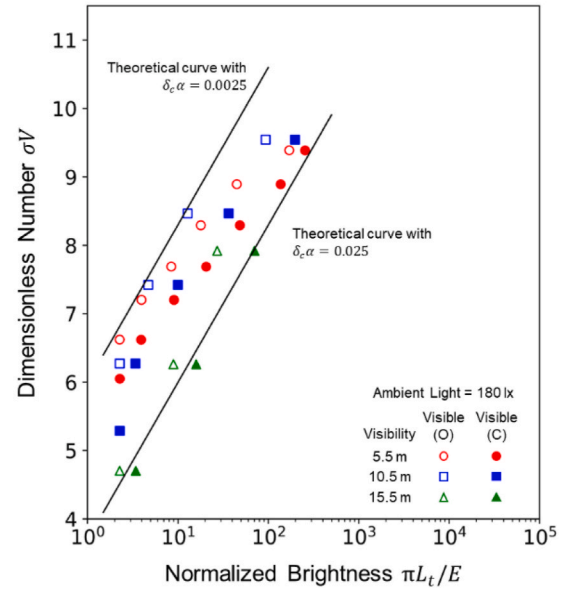


Fig. 11. Relationship between the normalized brightness $\pi L_t/E$ and the dimensionless number σV with different visibilities under ambient light levels of (a) 1 lx, (b) 22 lx, (c) 60 lx, and (d) 180 lx.

the original rationale of Jin's research, expressed in his first paper on the subject [13]. With this in mind, the application of the visibility in smoke in modern fire safety engineering does not necessarily follow the same logic. Typically, evaluation is on whether a certain smoke density (visibility) threshold is met, and the consequences are not further evaluated. As the criterion may be satisfied by low extinction coefficient (thin) smoke, the visibility in smoke is usually the first tenability criterion to cross its acceptance criterion (typically before temperature or toxicity criteria are reached). Therefore, the visibility in smoke becomes the critical environmental variable determining the choices and design of fire safety features of the buildings [12]. We that the consequences of loss of visibility should be recognized by practitioners using the model, and considered in the Fire Safety Engineering decisions based on the outcomes of the model.

In Section 4.1, notable differences are observed between Jin's results and the new results. These discrepancies can be mainly attributed to variations in measurement methods. Jin's paper reveals a lack of detailed information on the measurement methods used for ambient light illuminance, signage luminance, and smoke extinction coefficients. Although Jin mentioned that he used a 1-m smoke densitometer to measure the smoke extinction coefficient, the design of the meter in the 1970s and its placement remain unknown.

Furthermore, the measurement procedures for ambient light illuminance and signage luminance were not even mentioned in Jin's paper, despite these parameters significantly influence the measurement results. The measurement point for signage luminance is crucial, as readings near the projector (i.e., the light source), outside the glass of the smoke chamber, and inside the glass of the smoke chamber can yield

different values. Similarly, in the new measurement, it reveals that different locations, heights, and facing angles can affect the readings of the ambient light illuminance. The detailed experimental setup for the new measurement and the comparison between the Jin's and new measurements are discussed in Section 3 and Table 1. Therefore, the absence of detailed measurement information in Jin's paper is likely contributed to the discrepancies between Jin's results and the new results.

On the other hand, Jin's visibility experiment may not accurately represent real fire scenarios. The experiment employed relatively high ambient illuminances between 22 lx and 180 lx and high signage luminance from 36 cd/m² to 810 cd/m². However, in emergency scenarios, ambient light illuminance can be as low as 1 lx–15 lx and illuminated exit signs typically have a fixed luminance of 100 cd/m² to 300 cd/m². In this study, we investigate low ambient light illuminance, ranging from 1 lx to 22 lx. Similar to Jin's findings, our results show that the dimensionless number σV increases with the logarithm of normalized brightness $\pi L_t/E$. Nevertheless, the dimensionless number σV in our results ranges from 6 to 11 for ambient light levels between 1 lx and 22 lx, whereas Jin's results fell between 5 and 8 at an ambient light level of 180 lx. It is worth noting that Jin's experiment used a circular "O" shape illuminated signage, whereas our study employs a Landolt "C" shape illuminated signage as the observation target. Future work will focus on testing the visibility of illuminated exit signs and photoluminescent exit signs commonly used in buildings.

Observation distances of 5.5 m, 10.5 m, and 15.5 m were tested in the visibility experiment. Based on the new results, the illuminated signage is visible at high smoke extinction coefficients of 1.2 m⁻¹ and 1.5 m⁻¹ under ambient light conditions of 180 lx and 1 lx, respectively, at a 5.5 m observation distance. However, the critical extinction coefficient decreases by 40 % for every 5 m increase in observation distance. This implies that exit signs become harder to see with low extinction coefficients at longer observation distances. Therefore, early warning systems for fire detection are crucial to facilitate early evacuation. Evacuating in conditions of clear or low smoke concentrations is important. As smoke concentration increases, exit signs may become obscured, reducing the chances of finding the evacuation route. It is important to note that a smoke layer can easily form near the ceiling and spread rapidly, blocking emergency lighting and exit signs, which hinders effective evacuation.

This study has several limitations that will be considered in future work. First, this experiment utilizes white smoke from an industrial smoke generator, which may not accurately represent the varying visibility conditions posed by white smoldering smoke, black, and grey flaming smoke in real fire scenarios. Black smoke could have different absorption and scattering characteristics for light, resulting in different K factors, as confirmed by Refs. [14,17,40]. Further studies are needed with focus on evaluating visibility in different types of sooty smoke from real fires. Additionally, the observations are conducted by an observer with a visual acuity of 1.0, which is not representative to the entire population. Furthermore, the observer was familiarized with the sign shape, size and location within chamber, potentially positively reinforcing their ability to observe the sign. To increase the validity of the findings, future research will involve a larger randomized group of observers with diverse visual acuities, unfamiliar with the evacuation signage shown to them. Lastly, the signage used in the experiment is a lab made Landolt "C" pattern signage, which differs from the exit signs typically used in buildings. This was chosen to maintain link to the original Jin's research and is considered another significant limitation of the current visibility in smoke model. In future work, illuminated exit signs and photoluminescent exit signs will be tested in different types of smoke environments and observed by a diverse group of people with varying visual acuities.

6. Conclusions

This work attempted to replicate Jin's visibility experiment using an identical setup in a smoke chamber, while providing detailed measurements and setup information. Additionally, the visibility measurements are extended to low ambient light conditions, which are more representative of real building scenarios during emergency situations. Regarding the effect of ambient light conditions, under the same signage luminance, the measured critical smoke extinction coefficient is approximately 7 %–11 % higher in Jin's results than in the new results.

As the extinction coefficient increases, the normalized brightness $\pi L_t/E$ also increases, with the new results yielding higher values than Jin's results. For the effect of observation distances, the results at 15.5 m align with Jin's findings. However, at distances of 10.5 m and 5.5 m, the extinction coefficient differs by approximately 20 %. Furthermore, Jin's measurements showed that the dimensionless number σV falls between 5 and 8, whereas the new results have a broader range of 4.7–9.5 at an ambient light level of 180 lx.

For low ambient light conditions, ranging from 1 lx to 22 lx, the signage remains visible in smoke extinction coefficients as high as approximately 1.4 m⁻¹ to 1.7 m⁻¹, depending on the level of signage luminance. Furthermore, the illuminated signage is more easily observable at a shorter distance (i.e., 5.5 m). However, the critical extinction coefficient decreases by nearly 40 % for every 5 m increase in visibility distance. Additionally, the range of the dimensionless number σV in low ambient conditions from 1 lx to 22 lx is from 6 to 11. The revised values of σV may find direct use in fire safety engineering, enabling more accurate estimates of signage visibility. However, their application requires careful considerations of the signage type and size, as well as considerations of the background ambient lighting, which should preferably be agreed with the Authority Having Jurisdiction.

Future research will focus on evaluating the visibility of commercial illuminated and photoluminescent exit signs in various smoke environments including black, sooty smoke from real fires, and observed by a diverse group of people with differing visual acuities. An unbiased evaluation of visibility of real evacuation signage through various layers of fire smoke will allow for definition of novel visibility in smoke models, accounting for sign shape, colour and size, as well as the ambient background illumination, hopefully initiating a paradigm shift needed for the fire safety engineering profession.

CRedit authorship contribution statement

Wai Kit Cheung: Writing – original draft, Methodology, Investigation, Formal analysis. **Jakub Bielawski:** Writing – review & editing, Resources, Investigation. **Lukas Arnold:** Writing – review & editing, Methodology, Funding acquisition, Formal analysis. **Xinyan Huang:** Writing – review & editing, Supervision, Formal analysis, Conceptualization. **Wojciech Węgrzyński:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. – Sign luminance calibration procedure

The signage luminance is determined from the inner signage box illuminance, which was measured during the experiment. Two measurements were taken – an illuminance measurement with a sensor installed inside the box, and an illuminance measurement in the front of the box (the luminous surface observed by the Observer). The reason for the calibration was that we are unable to continuously monitor the luminance of the surface, as the luminance meter itself is a significant obstruction on the path of sight. Therefore, a pre-calibration was carried to verify if a linear relationship exists between inside and surface luminance measurements, and the results are shown in Fig. A1. It is observed that the illuminance inside the signage box is linearly proportional to the signage surface luminance. The illuminance (lx) inside the box, recorded during the experiment, is subsequently converted into signage luminance (cd/m^2) using the fitting equation: $y = 0.45x - 24.9$.

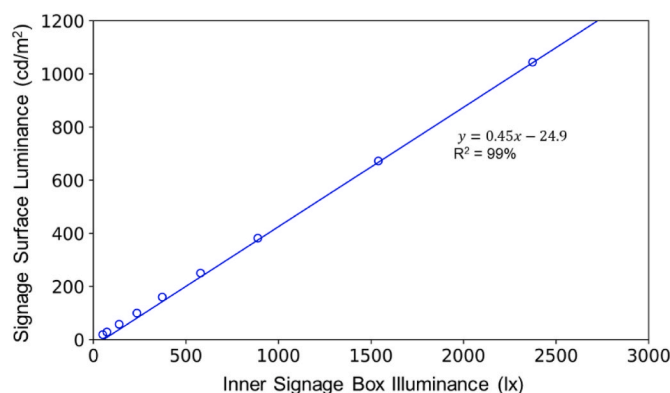


Fig. A1. Conversion of inner signage box illuminance to signage surface luminance.

Data availability

Data will be made available on request.

References

- [1] D. Drysdale, An Introduction to Fire Dynamics, third ed., Wiley Blackwell, 2011 <https://doi.org/10.1002/9781119975465>.
- [2] J. Tadahisa, Studies on human behavior and tenability in fire smoke, *Fire Saf. Sci. Proc. Fifth Int. Symp.* (1997) 3–21.
- [3] D.A. Purser, J.L. McAllister, Assessment of hazards to occupants from smoke, toxic gases, and heat. SFPE Handb. Fire Prot. Eng., fifth ed., 2016, pp. 2308–2428, https://doi.org/10.1007/978-1-4939-2565-0_63.
- [4] W.K. Cheung, Y. Zeng, S. Lin, X. Huang, Modelling carbon monoxide transport and hazard from smouldering for building fire safety design analysis, *Fire Saf. J.* 140 (2023) 103895, <https://doi.org/10.1016/J.FIRESAF.2023.103895>.
- [5] E. Ronchi, D. Nilsson, S.M.V. Gwynne, Modelling the impact of emergency exit signs in tunnels, *Fire Technol.* 48 (2012) 961–988, <https://doi.org/10.1007/s10694-012-0256-y>.
- [6] W. Węgrzyński, G. Vigne, Experimental and numerical evaluation of the influence of the soot yield on the visibility in smoke in CFD analysis, *Fire Saf. J.* 91 (2017) 389–398, <https://doi.org/10.1016/J.FIRESAF.2017.03.053>.
- [7] M. Jouellette, Exit signs in smoke: design parameters for greater visibility, *Light. Res. Technol.* 20 (1988) 155–160, <https://doi.org/10.1177/096032718802000402>.
- [8] Y. Akizuki, Evacuation route design based on visibility for reducing evacuation delays, *Fire Saf. J.* 144 (2024) 104099, <https://doi.org/10.1016/J.FIRESAF.2024.104099>.
- [9] B.L. Collins, M.S. Dahir, D. Madrzykowski, Visibility of exit signs in clear and smoky conditions, *Fire Technol.* 29 (1993) 154–182, <https://doi.org/10.1007/BF01038537/METRICS>.
- [10] Y. Akizuki, S. Okuda, M. Iwata, T. Tanaka, Evaluation method for easy wayfinding of escape routes by configuration factors, *J. Environ. Eng.* 77 (2012) 231–239, <https://doi.org/10.3130/AJJE.77.231>.
- [11] K. Fridolf, E. Ronchi, D. Nilsson, H. Frantzich, Movement speed and exit choice in smoke-filled rail tunnels, *Fire Saf. J.* 59 (2013) 8–21, <https://doi.org/10.1016/J.FIRESAF.2013.03.007>.
- [12] W. Węgrzyński, N. Spodyniuk, M. Zimny, W. Jahn, G. Vigne, L. Arnold, Survey on the use of tenability criteria in CFD analyses for performance-based fire safety engineering, in: 5th Eur. Symp. Fire Saf. Sci., 2025.
- [13] T. Jin, Visibility through fire smoke (I), *Bull. Japan Assoc. Fire Sci. Eng.* 19 (1970) 1–8, <https://doi.org/10.11196/KASAI.19.2.1>.
- [14] T. Jin, Visibility through fire smoke (II), *Bull. Japan Assoc. Fire Sci. Eng.* 21 (1971) 17–23, <https://doi.org/10.11196/KASAI.21.17>.
- [15] T. Jin, Visibility through fire smoke (III), *Bull. Japan Assoc. Fire Sci. Eng.* 22 (1972) 11–15, <https://doi.org/10.11196/KASAI.22.11>.
- [16] T. Jin, Visibility through fire smoke, *J. Fire Flammabl.* (1978).
- [17] T. Yamada, Y. Akizuki, Visibility and human behavior in fire smoke, SFPE Handb. Fire Prot. Eng. Fifth Ed (2016) 2181–2206, https://doi.org/10.1007/978-1-4939-2565-0_61/FIGURES/29.
- [18] K. Börger, L. Sichma, T. Schultze, A. Belt, S. Orzel, L. Arnold, Photometric Measurement of Visibility in Case of Fire, IAFSS, 2021.
- [19] H.Y. Wong, M. Wang, X. Zhang, Y. Zhang, M.C. Wong, X. Huang, Safe evacuation framework with intelligent dynamic exit sign system and demonstration in tunnel fire, *J. Saf. Sci. Resil.* 6 (2025) 100183, <https://doi.org/10.1016/j.jnlsr.2024.12.001>.
- [20] T. Jin, Visibility and human behavior in fire smoke, in: SFPE Handb. Fire Prot. Eng., 3rd Edition, 2002, pp. 2–42–2–53.
- [21] M. Luo, Y. Zeng, L.-C. Su, X. Huang, Review and application of engineering design models for building fire smoke movement and control, *Emerg. Manag. Sci. Technol.* 4 (2024), <https://doi.org/10.48130/EMST-0024-0001>, 2024 1e001, 0–0.
- [22] M. Kohno, T. Okazaki, Performance based fire engineering in Japan, *Int. J. High-Rise Build.* 2 (2013) 23–30, <https://doi.org/10.21022/IJHRB.2013.2.1.023>.
- [23] C.M. Fleischmann, Is prescription the future of performance-based design? *Fire Saf. Sci.* 10 (2011) 77–94, <https://doi.org/10.3801/IAFSS.FSS.10-77>.
- [24] L.C. Su, X. Wu, X. Zhang, X. Huang, Smart performance-based design for building fire safety: prediction of smoke motion via AI, *J. Build. Eng.* 43 (2021) 102529, <https://doi.org/10.1016/J.JOBE.2021.102529>.
- [25] NFPA, NFPA 92 Standard for Smoke Control System, 2024.
- [26] BSI British Standards, BS 9999:2017 Fire Safety in the Design, Management and Use of Buildings, 2017.
- [27] Hong Kong Building Department, Code of practice for fire safety in buildings 2011. <https://www.bd.gov.hk/en/resources/codes-and-references/codes-and-design-manuals/fs2011.html>, 2023. (Accessed 28 February 2024).
- [28] W. Węgrzyński, P. Antosiewicz, J. Pangrat, Multi-wavelength densitometer for experimental research on the optical characteristics of smoke layers, *Fire Technol.* 57 (2021) 2683–2706, <https://doi.org/10.1007/S10694-021-01139-5/FIGURES/16>.
- [29] D. Nilsson, H. Frantzich, E. Ronchi, K. Fridolf, A. Lindgren Walter, H. Modig, Integrating evacuation research in large infrastructure tunnel projects - experiences from the Stockholm Bypass project, *Fire Saf. J.* 97 (2018) 119–125, <https://doi.org/10.1016/J.FIRESAF.2017.07.001>.
- [30] Z. Yu, J. Wang, X. Liu, L. He, X. Cai, S. Ruan, A new video-camera-based visiometer system, *Atmos. Sci. Lett.* 20 (2019), <https://doi.org/10.1002/ASL.925>.
- [31] Y. Akizuki, Y. Inoue, The concept of visual acuity ratio to the maximum level of individual visual acuity —the evaluation method of background luminance and

- visual distance on visibility taking into account of individual visual acuity—, J. Light vis, Environ. Times 28 (2004) 35–49, <https://doi.org/10.2150/JLVE.28.35>.
- [32] Y. Akizuki, T. Tanaka, K. Yamao, Calculation model for travel speed and psychological state in escape route considering luminous condition, smoke density and Evacuee's visual acuity, Fire Saf. Sci. 9 (2008) 365–376, <https://doi.org/10.3801/IAFSS.FSS.9-365>.
- [33] W.C. Hinds, *Aerosol Technology : Properties, Behavior, and Measurement of Airborne Particles*, Wiley, New York, 1999.
- [34] C. Gnendiger, T. Schultze, K. Börger, A. Belt, L. Arnold, Extinction coefficients from aerosol measurements, Fire Saf. J. 146 (2024) 104110, <https://doi.org/10.1016/J.FIRESAF.2024.104110>.
- [35] International Organization for Standardization, ISO 8596:2017 - ophthalmic optics — visual acuity testing — standard and clinical optotypes and their presentation. <https://www.iso.org/standard/69042.html>, 2017. (Accessed 30 June 2025).
- [36] BSI British Standards, BS 5266 Emergency Lighting Code of Practice, (n.d.).
- [37] BSI British Standards, BS EN 1838:2013 lighting applications. Emergency Lighting, 2013.
- [38] The chartered institution of building services engineers CIBSE, LG12: emergency lighting, n.d. <https://www.cibse.org/knowledge-research/knowledge-portal/lg12-emergency-lighting-2022/>, 2022. (Accessed 28 January 2025).
- [39] National Fire Protection Association, NFPA 101 life safety code. <https://www.nfpa.org/product/nfpa-101-code/p0101code>, 2024. (Accessed 28 January 2025).
- [40] L. Elhokayem, Visibility in Smoke with Different Extinction Coefficients, Lund University, 2022. <http://lup.lub.lu.se/student-papers/record/9084340>. (Accessed 6 October 2025).