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Visibility in Smoke Under different Extinction Coefficients

An experimental study on the visibility of exit signage types through several smoke characteristics

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Abstract

Visibility in smoke has since the 1970s gained some attention, mostly after Tadahisa Jin ran the experiments which helped him develop todays widely used visibility equation. By showing that visibility can be assumed to be inversely proportional to the extinction coefficient by a visibility constant (equal to 8 for light emitting sign and 3 for light reflecting), Jin opened up new doors for researchers who were testing out his theory by going around experimenting in different ways and also by showing that there is way for more research to be done. The visibility constant also allowed for easier modeling of visibility which is used in egress models. However, in recent years, his suggested values for the visibility constant have been thought to be lower, as claimed by the SFPE in their more recent Handbooks. Nonetheless, many factors come into play when studying the visibility of exit signs in smoke such as brightness, light color, signage type (reflecting/ emitting), smoke type (white/ black), and others. In this thesis, a literature review as well as an overview of the current standards of exit signs is presented in the first half. In addition, a small scale experiment was run for the purpose of this thesis. It included 20 participants going through 16 different scenarios where the previously mentioned factors are studied, and their effects on visibility are looked into. The results under black smoke conditions have exhibited an unexpected behavior, not following what the currently used equation dictates, nonetheless a clear performance superiority of red signs has been seen which agrees with the previous literature. It is speculated that this unexpected behavior suggests that for higher values of the extinction coefficient, Jin's equation does not stand. On the other hand, the results under white smoke conditions were more consistent, and showing that indeed as recently thought, the visibility constant is higher than what Jin had suggested. Finally, also in line with previous research, light emitting signs were shown to have a better performance than light reflecting ones.

خلاصة

حظيت الرؤية في الدخان ببعض الاهتمام منذ سبعينيات القرن الماضي، خاصة بعد أن أجرى تاداهيسا جين التجارب التي ساعدته على اقتراح معادلة الرؤية المستخدمة على نطاق واسع اليوم. من خلال إظهار أنه يمكن افتراض أن الرؤية تتناسب عكسياً مع معامل الانقراض من خلال ثابت الرؤية (يساوي ٨ لعلامة انبعاث الضوء و٣ لعكس الضوء)، فتح جين أبوابًا جديدة للباحثين الذين كانوا يختبرون نظريته من خلال التجريب بطرق مختلفة وأيضًا من خلال إظهار أن هناك طرق عديدة لإجراء المزيد من الأبحاث. سمح ثابت الرؤية أيضًا بنمذجة أسهل للرؤية والتي يتم استخدامها في نماذج الخروج. ومع ذلك، في السنوات الأخيرة، كان يُعتقد أن قيمة المقترحة لثابت الرؤية أقل مما هي عليه بالفعل. ومع ذلك، هناك العديد من العوامل التي تلعب دورًا عند دراسة مدى رؤية علامات الخروج في الدخان مثل السطوع، ولون الضوء، ونوع اللافتات (الانعكاس / الانبعاث)، ونوع الدخان (أبيض / أسود)، وغيرها. في هذه الأطروحة، يتم تقديم مراجعة الأدبيات بالإضافة إلى نظرة عامة على المعايير الحالية لعلامات الخروج في النصف الأول. بالإضافة إلى ذلك، تم إجراء تجربة على نطاق صغير لغرض هذه الأطروحة. تضمنت ٢٠ مشاركًا يمرون بـ ١٦ سيناريو مختلفًا حيث تمت دراسة العوامل المذكورة سابقًا، ويتم النظر في آثارها على الرؤية. أظهرت النتائج في ظل ظروف الدخان الأسود تبعثرًا كبيرًا، دون السماح بأي استنتاجات، ومع ذلك فقد لوحظ تفوق واضح للعلامات الحمراء وهو ما يتفق مع الأدبيات السابقة. من ناحية أخرى، كانت النتائج في ظل ظروف الدخان الأبيض أكثر اتساقًا، وتظهر أنه بالفعل كما كان يعتقد مؤخرًا، فإن ثابت الرؤية أعلى مما اقترحه جين. أخيرًا، تماشياً أيضًا مع الأبحاث السابقة، تم إثبات أن العلامات الباعثة للضوء تتمتع بأداء أفضل من الإشارات العاكسة للضوء.

Disclaimer

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read and approved
Lea Elhokayem

03/06/2022

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List of Abbreviations and Symbols

ABS	-	Acrylonitrile butadiene styrene
ANOVA	-	Analysis of Variance
CFD	-	Computational Fluid Dynamics
EN	-	European Standard
FDS	-	Fire Dynamics Simulator
IMO	-	International Maritime Organization
ISO	-	International Organization for Standardization
ITB	-	Building Research Institute
LED	-	Light Emitting Diode
NFPA	-	National Fire Protection Association
NIST	-	National Institute of Standards and Technology
VR	-	Virtual Reality
VTT	-	Technical Research Institute of Finland

1 Introduction

The aim of this chapter is to provide a brief introduction of the topic, through setting the background of the problem at hand, defining the problem statement as well as the objectives of the thesis and highlighting the outline of the report along with the limitations and delimitations of this study.

1.1 Background

There are numerous factors that can affect the success of evacuation from building in a fire situation, but one major factor is people's perception of the situation and their behavior during the evacuation in accordance with that perception. According to affiliation theory supported by (Sime, 1983), when evacuating, most people evacuate through a familiar exit or follow someone who is familiar to them such as a friend or a family member.

Affiliation theory in stressful situations was first talked about by (Schachter, 1959) where he compared people at a low-anxiety state to people at high-anxiety state and concluded that the latter have greater affiliation tendencies. A main conclusion of his study was that people would rather stick with others who have/ are experiencing the same distress as them. He then explained how doing so helps individual reduce their state of angst and stress.

Affiliation theory has been observed in several evacuation cases, such as the infamous Station Nightclub fire, where according to the National Institute of Standards and Technology (NIST, 2016), two-thirds of the attendees attempted to exit through the main entrance even though they were closer to a different exit. Evacuating through the main entrance might not always be possible due to the exit being blocked for example. Evacuees might also not be familiar with the building, nor surrounded by people who are, such as in an event center. Hence other alternatives must be available.

A successful evacuation is highly dependent on the people's ability to find the nearest accessible exit. Exit signs are a crucial part of people's capability to locate that safe exit. Most codes and standards, such as the National Fire Protection Association (NFPA), which is most commonly followed in the United States, require that all exit doors be marked by approved signage (NFPA 101, 7.10). While there are cases where a sign could be placed near the floor, the most common and required sign locations are above the door or hung on walls near the ceiling to point at the direction of the exit. Having the sign above the door allows for it to be in a wider field of vision, and less likely to be blocked by an obstacle. However, in a room filled with hot smoke rising to the ceiling and forming a smoke layer, exit signs will quickly be covered, and locating them could become a challenging task.

With authorities around the world agreeing on having the exit signs above head level, the design of the sign itself could widely differ from country to country. According to the NFPA 101 for example, an exit sign should clearly spell out EXIT (Figure 1). Whereas the International Organization for Standardization (ISO), most commonly followed in European countries as well as many other countries, requires the use of a pictogram of a person exiting through a door along with an arrow pointing in the direction of egress (ISO 7010). Pictograms make it easier to understand for a wider range of audiences, for example, children who might not be able to read yet or foreigners who do not speak the local language.

Another aspect that is covered by standards is the brightness of the sign, the European Standard (EN) for example (EN 1838:2013) states that “the luminance of any colored area of the safety sign shall be at least 2 cd/m^2”.

When it comes to the sign color, the NFPA 101 only states that signs must be distinctive and that there should be enough contrast with the background. This has led to exit signs color in the United States to differ from one state to another. In some states, red is the approved exit sign color, while in others it is green. In Europe on the other hand, green is the required color (92/58/EEC). Thus, when comparing an American exit sign to a European exit sign (Figure 1) for example, which one would be more visible in smoke?

To answer that question, it is first important to define visibility in the context of fire safety. Visibility in the context of fire safety is defined as the maximum distance from which an object can be seen through smoke.

There are several smoke and light characteristics that must be examined when it comes to visibility. Smoke characteristics such as the extinction factor, a way of expressing the smoke density and smoke type such as white or black also plays a role in visibility. White smoke has a scattering effect whereas black smoke has an absorbing effect. The light characteristics which affect visibility are, amongst others, brightness, and wavelength (in other words the light color). In addition, signage type (light-emitting signs and light-reflecting signs) plays an important role in a sign’s visibility. The importance of all these factors on visibility of exit signs in smoke is studied in this thesis. While it is highly unlikely for one to be evacuating a building filled with white smoke, the study of visibility under white smoke allows researchers to pick up on behaviors and patterns in a safer and more environmentally friendly way by using a smoke machine rather than burn materials to create black smoke.

Figure 1: Left: Red Exit sign (2018, October 5). [Photograph]. Connected Fire. https://connectedfire.com/index.php/blog/2018/10/05/emergency-lighting-and-exit-signs), Right: ISO Exit Sign (Source: Author)

1.2 Problem Statement

This thesis explores the relationship between the visibility of signs and the extinction coefficient for different smoke types and varying light characteristics.

1.3 Objectives

The main objectives of this thesis are to, through a literature review and experiments:

- Study the effects of light characteristics such as brightness and color on signage visibility in smoke,
- Study the effects of smoke characteristics such as smoke density and smoke color (black and white) on signage visibility in smoke,
- Study the effects of signage type on its visibility in smoke.

1.4 Outline

To achieve the above-mentioned objectives, the report will follow the below outline (Figure 2).

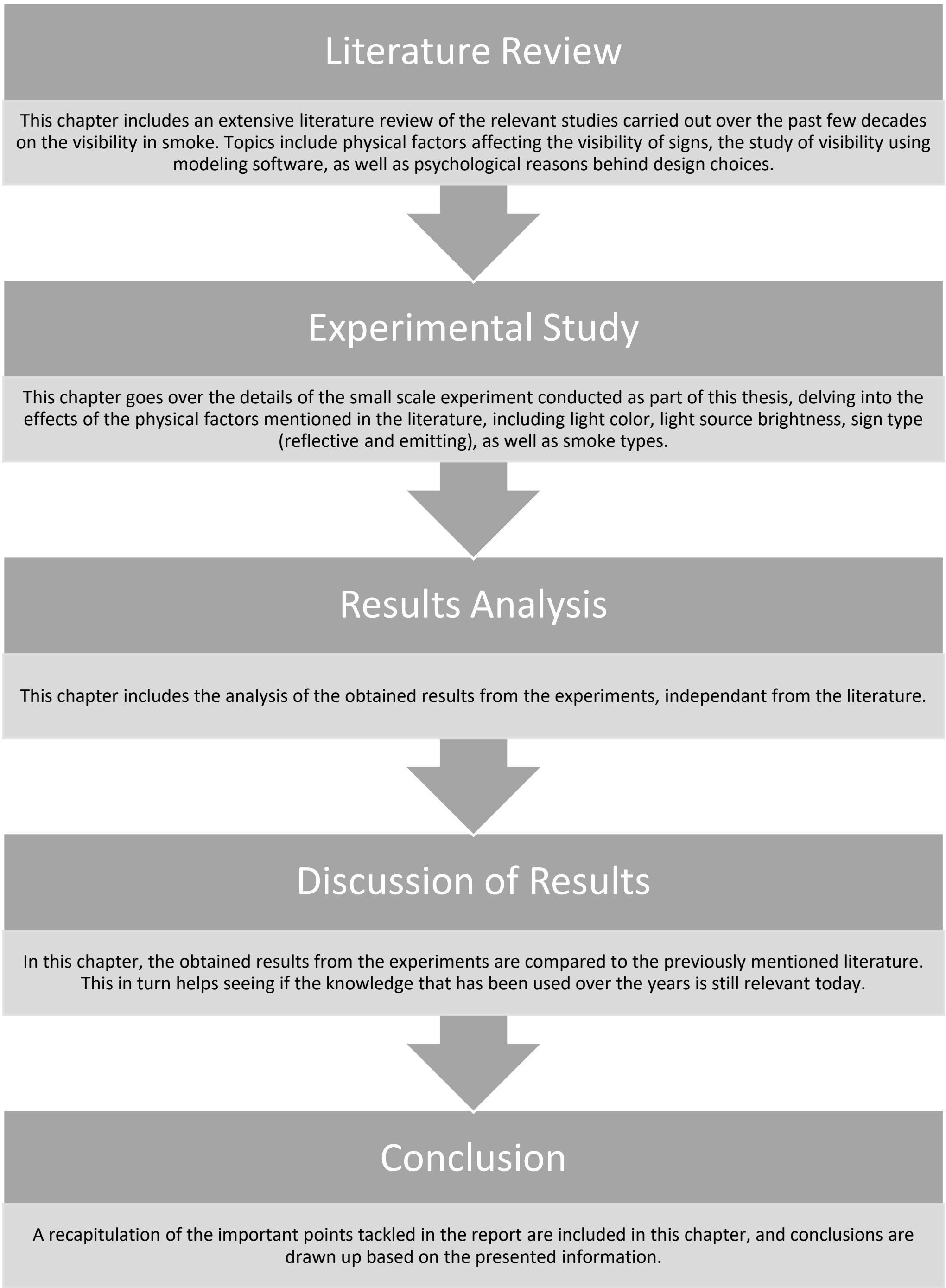

Figure 2 Thesis Outline

1.5 Delimitations

As this project entails experimental work, some delimitations were set to restrict the scope of the study. The main delimitations are:

- *Study of the psychological factor:* The psychology behind the perception of colors and identification of exits was not tested in the experiments but was touched upon in the literature review.
- *Scale of experiments:* It was decided to run small-scale experiments rather than life-scaled ones for this thesis due to logistical reasons.

Both these delimitations are important for getting more realistic results which reflect reality. The design of exit signs, as will be shown later in this thesis, is not only linked to the physical properties but also to the psychological reaction of people to the design. Additionally, small scale experiments can not be easily translated into real life scenarios, and results from these experiments could sometimes not reflect reality. For example, in this situation, a small scale experiment takes out the physical aspect of evacuation where people would walk through smoke.

1.6 Limitations

Below are the limitations faced when conducting the experiments:

- *Participants Safety:* Due to limitations imposed by the participant's safety, further investigations on the effect of smoke irritation on visibility were not made. The importance of those effects is further discussed in the literature review and should not be taken lightly. This limitation reduces the scope of the results to be valid only for non-irritative environments.
- *Time limit:* Due to the restrictions imposed by the time span of the semester, the experiments had to be done over the period of a week, reducing the number of participants.
- *Participants' demographic:* due to the limited number of participants, the age range was rather young, and included people within the same background of Fire Safety. Results could differ for older people as eyesight reduces over age and is not as sharp even with the use of corrective lenses. Additionally, none of the participants was colorblind which is also a factor that should be taken into consideration.

Similar to the delimitations, these limitations have a direct effect on the results. The bigger the number of participants, the more valid the results would be, as well as a mixed demographic, which would help extrapolate the results for different ages, ethnicities, etc…. An attempt to get as many participants as possible was made and taking into consideration the time limit, the number of participants was optimized.

2 Literature Review

This chapter summarizes the literature around visibility in smoke, going over the origins of the commonly used formula to calculate visibility, to more recent studies on the effects of the different light characteristics as well as smoke properties on the visibility and the validity of the visibility constant. Furthermore, the use of the smoke constant in modeling is tackled, and finally the psychological and behavioral aspect of visibility is discussed.

2.1 Research Methods

The research starting point was the three literature pieces provided by the thesis supervisor in the thesis brief: Visibility through fire smoke by Jin, T (1978), Smoke production and properties chapter by Mulholland, G. W. in the 3rd edition of SFPE handbook (1995), and Modelling the Impact of Emergency Exit Signs in Tunnels by Ronchi et al. (2012). It quickly became noticeable that Jin's papers were the basis of more recent papers as both Mulholland and Ronchi cited him in their papers. Hence the research that started with Jin's papers lead to go more in-depth in experimental studies focused on testing the visibility of different signage designs, as well as the effect of smoke irritation on visibility. On the other hand, reading Ronchi's paper, two other aspects of the topic of visibility in fire smoke were decided on: visibility in modeling and the psychological and behavioral aspect of visibility. The details of the flow of the thought process can be seen in Figure 3.

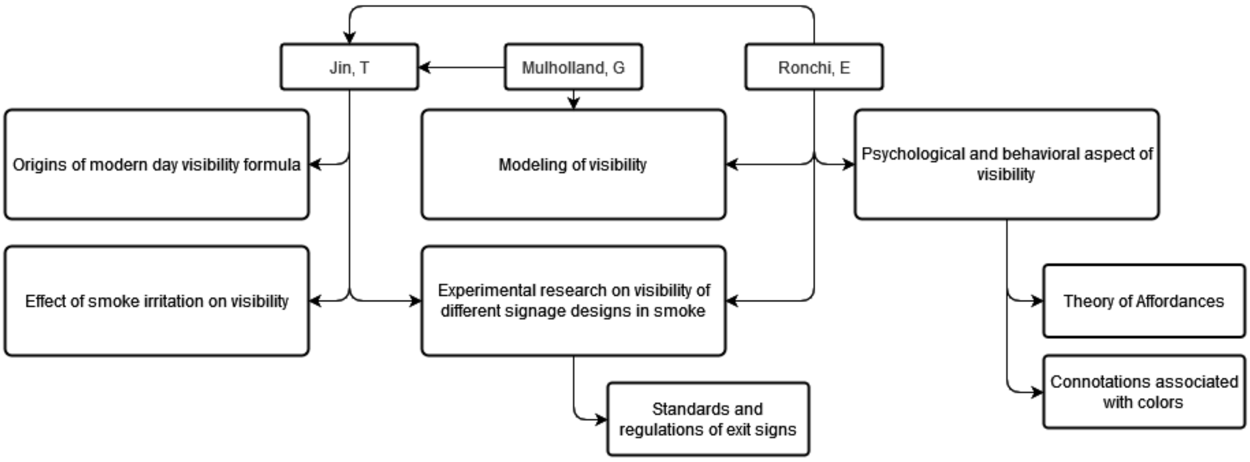

Figure 3 Flow of thought process

As for the main research tools, scholar.google.com was the main website used for this research, as well as www.researchgate.net. As for the most frequent keywords used to search: visibility, smoke, exit signs, human behavior, color, evacuation, modeling; with the most relevant combinations of: visibility in smoke, modeling of evacuation in smoke, modeling of visibility, human behavior during evacuation, perception of colors, visibility of exit signs in smoke. The research was further refined by setting the time of publication between 1975 and 2022. The research did not only involve the mentioned keywords, but also searching commonly cited researchers in papers around this topic, as well as searching for papers citing Jin.

2.2 Relevant Literature

2.2.1 The origins of the modern-day visibility formula

Visibility in smoke has been a relatively recent matter of concern with not much research around the topic. Even though a better understanding of visibility in smoke would greatly help improve existing egress models and lead to more accurate egress simulations, the correlations and values used today primarily rely on experiments led by Tadahisa Jin in the 1970s. In this thesis work, the results obtained by Jin are challenged and an attempt to see the extent of their validity is made.

In his paper (Jin, 1978), the author explains how for a person to separate the sign from its background in a smoky environment, the difference between the intensity of light coming from the sign itself and that of the background must exceed a certain threshold value (1).

$$\left|\frac{B_E - B_B}{B_B}\right| \geq \delta_C \tag{1}$$

Where,
B_E is the brightness of the sign [cd/m^2],
B_B is the background brightness [cd/m^2],
δ_C is the contrast threshold of signs in smoke at the obscuration threshold which is almost constant and in the range of 0.01-0.02. It must be noted however, that these values are not applicable in very dark environments.

The original formula for visibility of a light-emitting sign in smoke is in function of the extinction coefficient C_s [m^{-1}], the sign brightness B_{Eo} [cd/m^2], the mean illuminance of illuminating light from all directions in smoke L [m/ m^2], the previously seen δ_C, and the ratio of the scattering coefficient to the extinction coefficient k, equation (2).

$$V = \frac{1}{C_s} \ln \frac{B_{Eo}}{\delta_C k L} \tag{2}$$

And for reflective signs the formula could be written as:

$$V = \frac{1}{C_s} ln \frac{\alpha}{\delta_C k} \tag{3}$$

Where α is the reflectance of the sign.

However, through his experiments, Jin was able to propose a simplified version of the equation. The experiments entailed that participants be seated behind a glass window, looking through the window to a smoke-filled chamber where the lit signs were placed. As seen in Figure 4, it was observed that the visibility increased as the extinction coefficient decreased for all cases of a light-emitting sign. The same behavior was observed for light reflecting signs as well. It was also observed that the visibility in black smoke was slightly better than that in white smoke. Jin then concluded from the obtained results that for low smoke densities, the visibility at the obscurity threshold and the extinction coefficient are inversely proportional following equation (4).

$$V = \frac{C}{C_s} \tag{4}$$

Where,
C is a constant which depends on the sign type [-],
and C_s is the extinction coefficient which can be expressed using the following equation (5):

$$C_s = \frac{2.3}{\mathrm{L}}\log\frac{I_0}{I} = \frac{1}{\mathrm{L}}\ln\frac{I_0}{I} \quad (5)$$

Where,
L is the light path length [m],
I_0 the intensity of the incident light without smoke,
I the light intensity after having passed through the smoke.

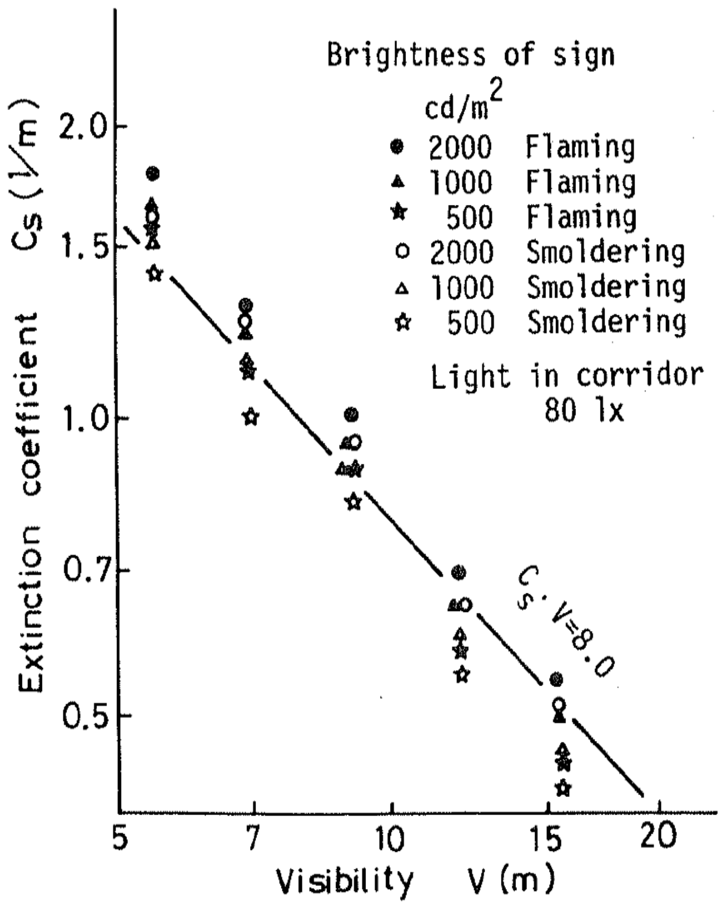

Figure 4 Jin, T. (1977, July 18). Relation between the visibility of light-emitting signs at the obscurity threshold and smoke density (Extinction coefficient) [Graph]. In Visibility Through Fire Smoke.

Through his experiments, Jin concluded that, for a light-emitting sign, C is in the range of 5 to 10 (Figure 4); while for light reflecting signs it is in the range of 2 to 4 (Figure 5). This indicates that light-emitting signs are more visible than light-reflecting ones when put in the same environment.

The experimental results also pointed that red light is 20 to 40% more visible in smoldering smoke (white smoke) and 20 to 30% more visible in flaming smoke (black smoke) than blue lighted signs when both blue and red signs were at the same brightness.

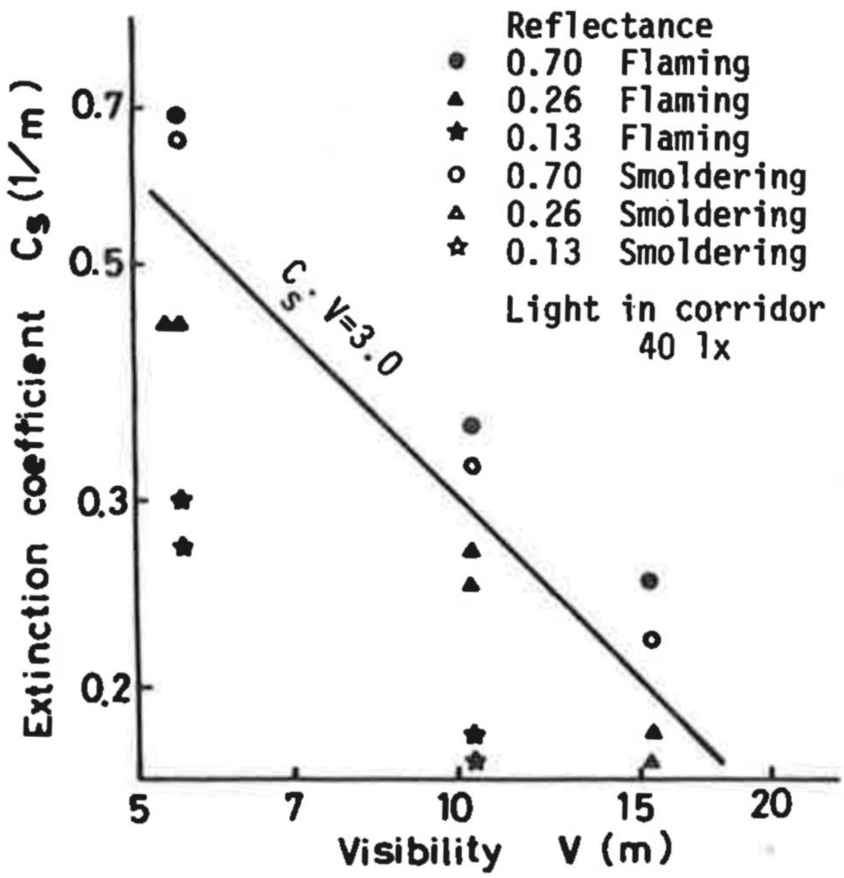

Figure 5 Jin, T. (1977, July 18). Relation between the visibility of reflecting signs at the obscuration threshold and smoke density (Extinction coefficient) [Graph]. In Visibility Through Fire Smoke.

2.2.2 Experimental studies on visibility in smoke

In this section, a summary of the relevant experiments that have been led on visibility in smoke will be presented by chronological order.

It must be noted that some notations differ from literature to another depending on where the papers were published (Paulsen Husted, 2004). While the extinction coefficient is the most widely used term to describe the smoke density, the optical density (od) is also used (6).

$$\text{od} = \ln\frac{I_0}{I}\ [-] \tag{6}$$

The optical density could also be referring to the value of:

$$\text{od} = \log\frac{I_0}{I}\ [\text{Bel}] \tag{7}$$

And od per meter would be the same as the extinction coefficient (8).

$$C_S = \text{od per meter} = \frac{1}{L}\ln\frac{I_0}{I}\ [m^{-1}] \tag{8}$$

After the experiments run by Jin in the 1970s, many researchers have investigated the visibility in smoke under different conditions. As the results obtained in (Jin, 1978) did not apply for very dark environments, researchers in Canada set-up their own experiments to define the readability and detectability threshold limits of different exit sign types in not only highly illuminated environments but also darkened ones. In their paper (Clark et al., 1985), highlight the importance of exit signs in modern fire protection systems. The authors shed light on the difference in guidelines found in standards and regulations in Canada when it comes to sign characteristics from luminance to color as well as letter size.

During their experiments, 13 different signs were used, and they differed by color, script, field luminance and light source. The details of the signs can be seen in Table 1. The signs were hung in a smoke chamber, where cosmetic oil smoke was injected at two different points. The smoke density was continuously measured. Two of the signs were reflective (tritium) and the other 11 were lit from behind. The participants were sat one by one in a dark viewing room separated from the smoke room by a transparent plastic window.

Table 1 Exit Sign Characteristics (Clark et al., 1985)

Sign No	Colors	Script, glyph	Large field luminance (lights on, lights off) (cd/m^2)	Light source
1	red, white	EXIT/ SORTIE	292, 291	2 x 25 w incandescent
2	green	EXIT, triangle	18, 14	2 x 15 w incandescent
3	red, white	EXIT, triangle	51, 46	2 x 15 w incandescent
4	green	EXIT	12, 0.18	tritium
5	green	arrow EXIT, triangle	19, 0.61	tritium
6	red	EXIT, triangle	170, 170	7 w, 9 w fluorescent
7	red	EXIT	36, 22	2 x 15 w incandescent
8	white, red	EXIT, triangle	38, 29	2 x 15 w incandescent
9	red	EXIT, SORTIE	231, 232	2 x 25 w incandescent
10	green	EXIT, triangle	391, 391	1 x 9 w fluorescent
11	red, white	Triangle, EXIT	1272, 1277	1 x 9 w fluorescent
12	red	EXIT	342, 281	1 x 9 w fluorescent
13	white, red	EXIT, triangle	506, 498	1 x 9 w fluorescent

The 16 participants evaluated the visibility threshold for each of the signs in the presence of smoke. It is important to note that out of the 16 participants, four had protanomaly[1], and two had deuteranomaly[2] , the rest had normal vision or put on corrective lenses if needed.

By slowly and homogeneously increasing smoke densities in the room, the smoke density thresholds were determined. This was determined at several sign illuminations.

The data was analyzed using the analysis of variance method (ANOVA). Three variables were input: exit sign, ambient illumination, and threshold criterion. The results can be seen in Table 2)

Table 2 Analysis of Variance for Critical Smoke Density (Clark et al., 1985)

Source of Variation	Sum of Squares	df	Mean Square	F	P
S	20.7	12	1.73	286	0.000
R	16.0	1	16.0	2653	0.000
C	1.34	1	1.34	223	0.000
S×R	1.54	12	0.128	21.3	0.000
S×C	0.182	12	0.015	2.52	0.003
R×C	0.085	1	0.085	14.1	0.000
S×R×C	0.076	12	0.006	1.05	0.404

Results of the experiments showed a significant difference between the 13 signs. Notably, a linear relationship was observed between the averaged critical smoke density and the log of the general luminance. Nonetheless a variation is seen about the line hence the luminance cannot be considered as the sole requirement for sign visibility. Sign 4 had the lowest critical smoke density while sign 11 the highest.

When it came to the effect of ambient light on smoke densities, the authors noted that the critical smoke density was considerably lower when the ambient lights were on rather than off (Figure 6). As (Clark et al., 1985) explain it, the lower smoke density threshold in ambient light is due to the ambient illumination further scattering the light emitted by the sign.

According to the results obtained in this study, people with normal vision and deutans had comparable results whereas protans had significantly different results than the previous two. According to the authors, the order of magnitude of the difference between protans and the other participants is coherent with previous literature (Wyszecki & Stiles, 1982). The difference is highlighted in Figure 7 where the dashed line (representing the values given by protans) follows the same trend as the solid line (representing normal and deutans) but is constantly lower throughout. When investigating the wavelength dependance scatter, (Clark et al., 1985) found results which agreed with what (Jin, 1978) had found as well, longer wavelengths (i.e.: red) exhibited less scattering by the smoke while shorter wavelengths (i.e.: green) was more susceptible to scatter.

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[1] "Protans are people with protanomaly, a type of red-green color blindness in which the red cones do not detect enough red and are too sensitive to greens, yellows, and oranges. As a result, greens, yellows, oranges, reds, and browns may appear similar, especially in low light". Definition from: https://enchroma.com/pages/protan

[2] "Deutan color blindness (also known as deuteranomaly) is a type of red-green color blindness in which the green cones in the eye detect too much red light and not enough green light. As a result, red, yellow, green, and brown can appear similar, especially in low light". Definition from https://enchroma.com/pages/deutan

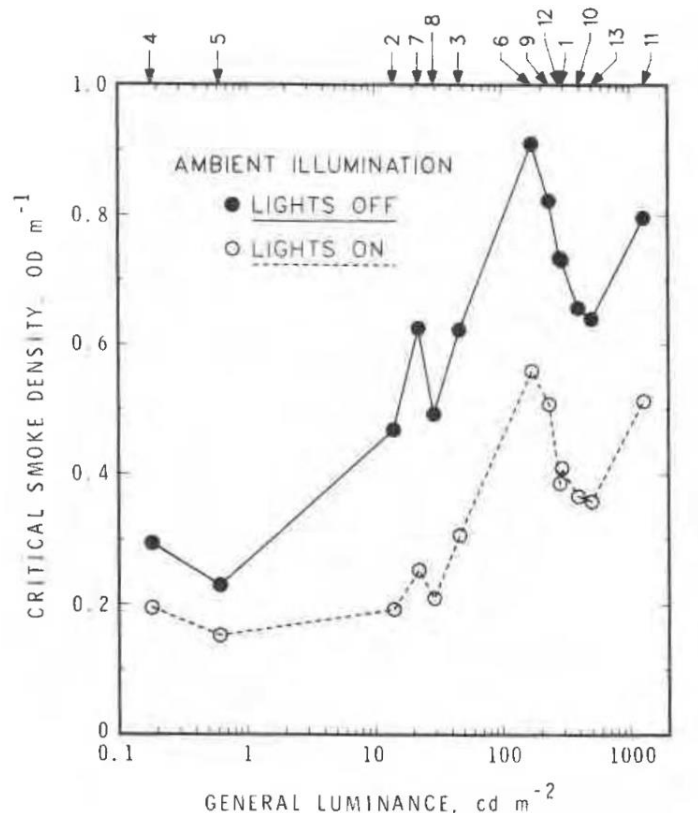


Figure 6 Critical smoke density as a function of general luminance for both levels of ambient illumination (sign numbers on top) (Clark et al., 1985).

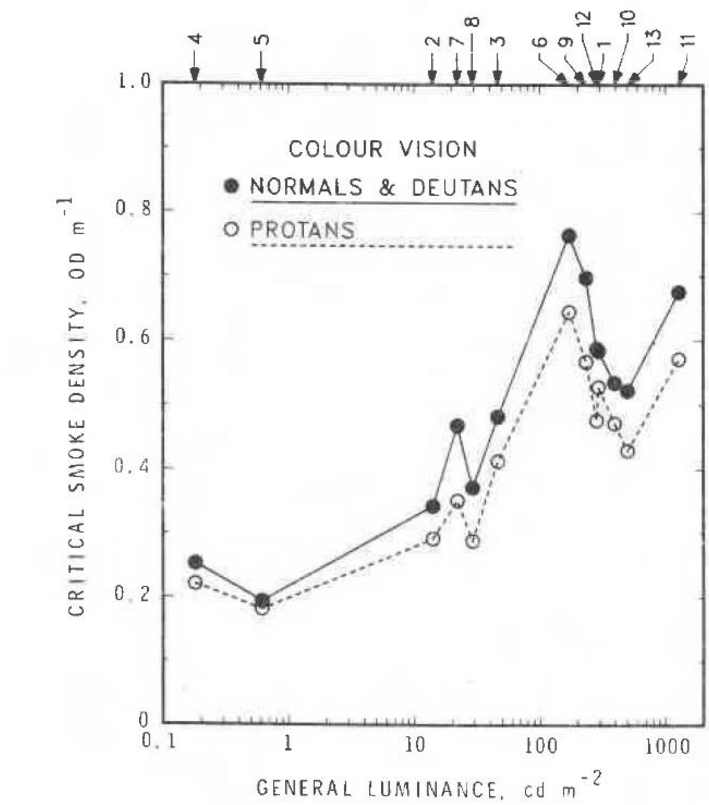


Figure 7 The effect of color vision on sign visibility (sign numbers on top) (Clark et al., 1985).

Another set of experiments were led by (Jouellette, 1988) with the aim of testing visibility of existing signs under different conditions. Similar to the previous experiment, subjects were sat behind a transparent window looking into a smoke room where three different signs (Table 3) were hung. Participants were asked to change the sign brightness until it was readable. The experiment was repeated for various levels of smoke density, and with and without ambient illumination. The signs were all identical in all aspects except for the mentioned differences in the table.

Table 3 Features of signs under test (Jouellette, 1988)

Sign type	***Letters***	***Background***
A	Red transilluminated	Black Opaque
B	Black Opaque	Red transilluminated
C	Red transilluminated	White transilluminated

There were 12 participants involved in the experiment, aged between 22 and 48, and none of them had any sort of colorblindness. Naturally, the results showed that higher smoke densities required higher back illuminance. For each log unit increase of smoke density, sign illuminance had to be increased by 1.7log units. The authors highlighted that the maximum set sign luminance by the British standard at that time was not enough for the smoke densities measured, which are easily surpassed during a fire.

When it came to ambient illumination, results went hand in hand with what we previously saw in (Clark et al., 1985). The stronger the ambient light, the higher the sign illuminance must be, to counter the scattering effect in smoke.

As for sign type, two criterion were looked at. The first, illuminance threshold, sign type C performed the best, and was about 5 times more energy efficient than A and B. The second, luminance, did not necessarily affect sign efficiency as they were all more or less on the same level of performance. Nonetheless, the authors shed light on some differences which made a significant performance distinction between the signs. Signs with a white transilluminated background such as sign C require higher luminance, the reason being their generation of a more luminous blanket in smoke (due to scattering) leading to a reduced readability. Also agreeing with previous research, a lower ambient light leads to higher readability of the signs, especially at elevated smoke densities.

In their paper (Collins et al., 1992) the authors focus on the visibility in smoke of internally illuminated conventional and electroluminescent signs. The information on the observers can be seen in Table 4. And the details of the different signage designs can be seen in Table 5.

Table 4 Participants' information

#participants	***Male***	***Female***	***18-30 y/o***	***31-40 y/o***	***41-50 y/o***	***56-60 y/o***	***Deutans***
21	14	7	5	6	9	1	2

The signs were examined in two aspects: Photometrically, by comparing their individual luminance; and psychophysically, by comparing their visibility at a fixed distance of 18.9m in clear and smoke filled environments.

The 12 signs were hung in an array form of 3 by 4, in a room where smoke could be ejected. The signs with the highest luminance were placed at the top while those with the lowest luminance were placed at the bottom. Additionally, the smoke room did not have any ambient light.

As in previous experiments, the participants looked through a transparent window into the smoke room. In this case, participants rated the visibility of each sign on a scale of 1 to 7. The mean rating of each sign can be seen in the Table 5. In addition to the rating, the time until the sign disappeared in the smoke was also measured.

Smoke was produced using a 100kW diffusion flame propane gas burner which was a cylinder open from the top and contained sand that was covered by fibrous materials, and on top an expanded metal.

Results showed that signs that have a mean luminance greater than 70 cd/m^2 required double the amount of smoke density to reach the obscuration threshold, the smoke density for these signs were in the range of 0.07-0.16 od m^{-1}. Another conclusion that the authors got to, was that transilluminated signs (stencil-faced) were the most visible in smoke even if their luminance was not as high as other signs. Hence signs where letters are luminated and which the background is opaque tend to be more visible, as participants noted that they were less blurry and easier to read in comparison to the background lit panel-faced signs which might form a veiling luminance over its lettering. Finally, red signs also tended to be more visible than green signs as the data showed.

Table 5 Signage details (Collins et al., 1992)

Sign	***Design***	***Rating***	***Time [s]***
1	*Inc Green*	*4.7*	*220.7*
2	*Inc Red*	*5.2*	*433.0*
3	*Fl Green*	*5.6*	*469.2*
3	*Fl Red*	*6.2*	*497.8*
4	*Fl Red*	*5.6*	*571.8*
5	*El Red*	*6.2*	*262.5*
6	*El Green*	*6.0*	*281.6*
7	*El Red on Green*	*5.7*	*250.1*
8	*El Blue-Green*	*6.0*	*277.8*
9	*El Red on Green*	*2.9*	*206.2*
10	*El Red*	*6.0*	*298.5*
11	*El Green*	*5.9*	*300.3*
12	*El Green*	*5.3*	*297.5*

Key: El= Electroluminescence, Inc= Incandescent, Fl= Fluorescent

Performed in 2004 but presented in 2012 by (Ronchi et al., 2012), the experiment aimed at studying sign visibility in smoke. The experiment was done at Lund University and involved 49 participants averaging 23 years of age, 35 of which were men and 14 were women. The experiment was run in a room where ambient light from the outside could not infiltrate, artificial smoke was injected into the room and to add the irritating effect of smoke, acetic acid was added. At the other end of the room, three different signs were hung, one back-lit emergency exit sign, and two lights one green and the other orange. Participants were asked to move in the smoke filled room one at a time and inform the experimenters when they noticed one of the previously mentioned signs. Once one of the signs was seen it would be shut down and the participants would continue until they've seen all 3 signs. The distances (otherwise referred to as visibility) required to see the different signs was logged and the results can be seen in the table below.

Table 6 Visibility Distance for the Back-lit emergency exit sign, the green light, and the orange light (Ronchi et al., 2012)

	Visibility [m]		
	Back-lit exit sign	*Green Light*	*Orange Light*
Average (range)	5.2 (2.5-7.4)	7.7 (4.0–10.5)	9.6 (5.0–13.5)

As seen, orange light has proven to be the most visible under the same conditions. The reason for that is the scattering of light due to small particles such as water droplets or soot. Lights with shorter wavelengths are easier to scatter than longer wavelengths according to (Ronchi et al., 2012). Using the obtained results, and on the basis of the results showcased by (Jin, 1978) for back-lit exit signs, a value for the visibility constant was derived for green lights (value of 12) and orange lights (value of 15). The visibility constant values derived for the lights were calculated with the assumption that the extinction coefficients during the trials was constant throughout and for all participants. In the section on Visibility in Modeling, it will be explained how (Ronchi et al., 2012) used the obtained values to configure evacuation calculations in two different evacuation models.

When it comes to modeling visibility, (Węgrzyński & Vigne, 2017) explain that it is done by modeling the transport of combustion products, focusing on the production of soot particles, as well as the previously discussed visibility factor and extinction coefficient. The produced soot is directly related to the fuel's effective heat of combustion and its soot yield (Y_s). (Węgrzyński & Vigne, 2017) argue that while past research has shown that when comparing the effects of extinction coefficient, visibility factor and soot yield on visibility, soot yield has the highest impact; however little focus is given to the soot yield by engineers while inputting different parameters while modeling, as the focus is on the other two factors. Hence in their paper, (Węgrzyński & Vigne, 2017), aimed at investigating the impact of the soot yield on visibility in smoke. As part of their research, they ran full scale experiments in the Building Research Institute (ITB) in Warsaw. The experiments were done in a $10 \times 10\ m$ room of height 4m, and included fuels with different soot yields, ranging from 0.001 g/g to 0.178 g/g. The results obtained, showed an exponential decrease in visibility with an increased soot yield. More on the results will be seen in Visibility in Modeling as the authors compare their experimental results to numerical ones.

2.2.3 Effect of smoke irritation on visibility

In continuation of his initial paper on visibility in smoke, Jin further investigates the effects of eye irritation due to smoke on visibility. In their paper (Jin & Yamada, 1985), participants were asked to walk along a 20m corridor filled with irritating white smoke produced by burning wood cribs or a less irritating black smoke produced from burning kerosene. Participants were then asked to mark the distance at which they saw the lit exit sign at the other end and then again when they could read what it spells out.

Participants had difficulties keeping their eyes open due to the irritation inflicted from the smoke, leading to a significant decrease in visibility as seen in Figure 8.

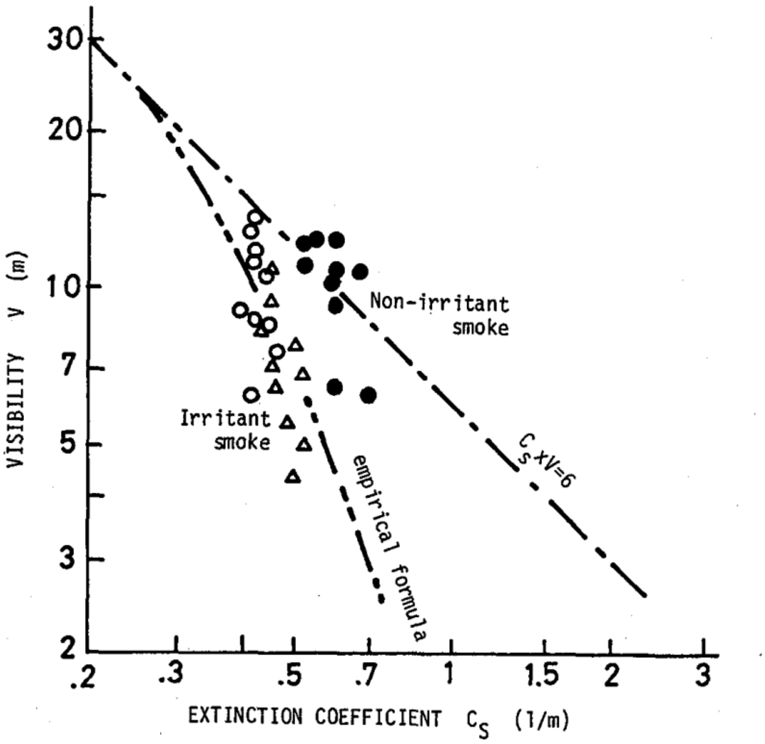


Figure 8 Jin, T. & Yamada T. (1985, July 8). Visibility of the FIRE EXIT sign at the legible threshold of the words in an irritant or non-irritant smokes. [Graph]. In Irritating Effects of Fire Smoke on Visibility.

In the same paper, (Jin & Yamada, 1985) ran another experiment where they measured the eye blink rate which was taken as an indicator of eye annoyance as well as tear flow rate. In this second experiment, irritating white smoke produced through the combustion of wood cribs, was introduced into an 18 m^2 room, with the smoke density increasing at a rate of 0.05 $(m.s)^{-1}$. The experiment included 12 subjects aged between 20 and 30 and included only one female. It included two scenarios, one where participants would wear well sealed goggles and another where the goggles were none-sealed and had holes in the frame to represent no-goggles. A wet towel was used to protect their noses from the irritant smoke. Participants were asked to push a button when the light became visible, this was repeated with both goggles.

The results showed that visibility dropped by more than 15% for the cases with the non-sealed goggles. In addition, the eye blink rate increased with the increasing smoke density for the non-sealed goggles scenario while it remained constant for the sealed goggles scenario. The authors argued that the irritating factor of smoke must be taken into account when calculating visibility for smoke densities above 0.25 m^{-1} and proposed a set of equations for visibility, using Weber-Fechner's law to take into account the effects of irritant smoke.

Through experiments where 32 participants were exposed to different types of smoke in their different stage, (Weber et al., 1979) concluded that the response of human sensitivity follows a logarithmic path in function of the impact intensity (9).

$$S = A - B\ logC_s \tag{9}$$

Where,
S is the visual acuity,
A the impact,
B an experimental constant.

The set of equations obtained by (Jin & Yamada, 1985) is as follow:

$$V_1 = \frac{C}{C_S} \qquad for\ 0.1 \leq C_S < 0.25 \tag{10}$$

$$V_2 = \frac{C}{C_S}\ (0.133 - 1.47 \log C_S) \qquad for\ (C_S \geq 0.25) \tag{11}$$

Both the equations in this set of equations point that with an increasing smoke density, visibility drops.

2.2.4 Visibility in Modeling

With the emergence of performance-based design, fire simulators and evacuation models have witnessed a rise in popularity. A tenability criterion for these types of simulations and depending on the model, is often and amongst others, visibility at 2m height from the floor. Fire Dynamics Simulator (FDS) for example, according to the FDS User Guide (McGrattan et al., 2021) uses the visibility equation developed in the first discussed paper by (Jin, 1978), to calculate visibility in the domain, with C=8 for light emitting signs and C=3 for light reflecting signs. However, while previous SFPE Handbook versions mentioned these values when it came to visibility (DiNenno et al., 2002), the most recent versions (Hurley et al., 2016) explicitly suggest that the values of the constant C in the visibility formula are in reality higher than previously thought. Similar to FDS, Autodesk's CFD package solves for the visibility the same way, also setting the visibility constant C as 8 and 3 for illuminated signs and reflecting signs respectively (AUTODESK, 2021). Although higher values of C entail higher visibility hence a more conservative approach when it comes to life safety, it defeats the purpose of performance-based design which is used to reduce costs and get results that are representative of real life.

In their paper, (Rubini et al., 2007) present results from a CFD study on visibility in smoke. In the simulations, they accounted for different configurations for direct and scattered illumination. They tracked the smoke movement through a transient CFD simulation and then put the results in a post processor where they determined the visibility of an exit sign. The goal of that paper was to set basis for a post processing plug in for already existing CFD packages, which would simulate visibility.

In the section 2.2.2 Experimental studies on visibility in smoke the results from experiments on evacuation run at Lund University were presented from (Ronchi et al., 2012). In the same paper, (Ronchi et al., 2012) uses those results, coupled with previous data on the probability of signage choice from (Nilsson, 2009) to calibrate two different simulation models of smoke filled tunnel evacuation. In his paper (Ronchi et al., 2012) highlights the fact that engineers face a problem when modeling evacuations in smoke filled environments, as little research has been done on sign visibility in smoke (under different designs) and the interaction of individuals with these signs, as well as the probability of the respective exits being used. Hence, (Ronchi et al., 2012) sets out to compare results from simulations differing in modeling approaches and complexity when it comes to visibility and exit choice. Different visibility constants were modeled and compared, as well as different sign designs.

The two models used were FDS+Evac which was created by the Technical Research Institute of Finland (VTT) and the National Institute of Standards and Technology (NIST), and buildingEXODUS created by the University of Greenwich's fire safety engineering group. In their paper, (Ronchi et al., 2012) presented three different approaches for simulating the evacuation. The approaches were as follows:

- Approach A (Implicit - Imposed): Impose pre-known information about agent (person in the simulation) behavior in the model, the information inputted was derived from a literature review. No direct interaction between the agent and the exit sign, rather the probability of the sign being seen and used, independent of its visibility. Information about the design of the signs were also inputted.
- Approach B: The use of default values of the models, but there is an explicit interaction between the agent and the exit sign. No information on signage type/color/… was inputted in the model. By default, FDS+ Evac assumes all exits are known, hence the choice of exit is exclusively dependent on how visible the exit is (visibility criteria 3m). In addition, the default setting for the signs is light-reflecting with the visibility constant set as 3. As for buildingExodus, four main elements are used: a) the visibility of the sign within a physical area, b) the probability of the agent seeing the sign based on the viewing angle, c) the probability of understanding the given information in the sign, and d) the probability of using that information. The sign properties in (a) were based on British and US standards, the probability in (b) was calculated using a simple equation, the probability of (c) and (d) was based on data provided by a previous study.
- Approach C: The information about signage was inputted, and their visibility constants were altered to be more representative of reality. In FDS, the simulated visibility constants were 8, 12, and 15. Effects of visibility reduction due to smoke was considered. In addition, the probability of the exit being used after being seen was introduced to the model. Finally, the walking speeds were altered to fit with the experimental results obtained by (Jin & Yamada, 1985) (as was seen in the previous section).

The results of the different approaches can be seen in Table 7.

Table 7 Summary of Simulated Evacuation Times (Ronchi et al., 2012)

Approach	***Evacuation time [s]***	
	buildingExodus	*FDS+Evac*
A	278–295	122–140
B	304–309	125–144
C	273–297	292–328

The results obtained by (Ronchi et al., 2012) highlight the impact of the several signage systems when running evacuation simulations through the varying results across models used and approach taken. It was concluded by (Ronchi et al., 2012) that the more information fed to the model, the closer the results were to the benchmark results. In addition, (Ronchi et al., 2012) stated that setting-up the explicit representation of agent-sign interaction was very time consuming and required a lot of data and expertise which may not always be available. He then affirmed that when these information are available, they may allow for an accurate model and a high level of confidence. Nonetheless, (Ronchi et al., 2012) warned that evacuation simulations could be misrepresented if the model is not set-up correctly, and that one should understand the default settings as well as be careful what third party data to use when changing them.

Going over another previously mentioned paper, (Węgrzyński & Vigne, 2017) clarify that while the behavior of light in smoke is dependent on the absorption, scattering and refracting effects of smoke as well as the properties of the light itself, modeling visibility simplifies this intricate phenomenon into a basic equation, i.e. the equation derived by Jin. In the same paper, (Węgrzyński & Vigne, 2017) also highlight a common misconception when interpreting visibility slices while modeling. They explain that the colored contours seen in Figure 9 mean that if someone were to be located in a room filled with a homogeneous smoke density of that represented by yellow for example, then they would have a visibility of 20m.

But a common mistake is believing that the color contours seen in the visibility slice represent the actual visibility at that point due to the different smoke densities in the room at that time stamp, when it is not the case. A more detailed explanation about the misconception can be read in the description of the caption of Figure 9.

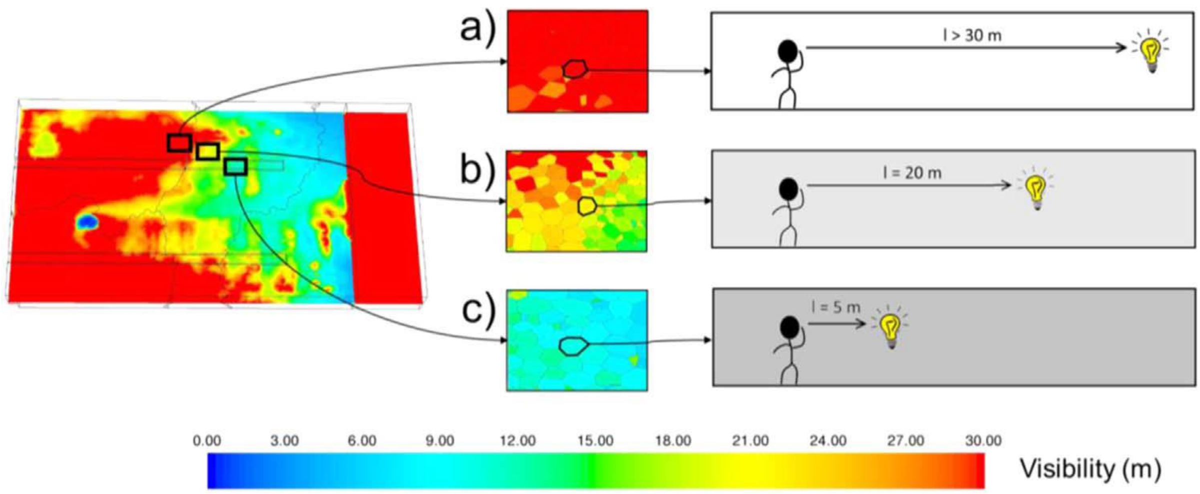


Figure 9 The local visibility range plot (most left, range from 0 to 30 m and more, for K =3) is created as an array of visibility values from individual cells (middle clips). Value within each of the cells represents the distance, from which a certain object (e.g., Sign, light) would be seen, in a room (right side drawings) with uniform smoke corresponding to the mass concentration of the smoke withing that cell. (Węgrzyński & Vigne, 2017)

The Warsaw experiments previously seen in their paper, was replicated in both FDS and ANSYS Fluent. The details on how FDS and ANSYS numerically differ will not be covered in this report as it is out of the scope of the thesis.

To assess the validity of the models, the temperatures measured during the test were compared to the values obtained in the simulation and were deemed representative. The results obtained numerically in comparison to the experimental ones can be seen in Figure 10. While the behavior of the curves is similar for the numerical and experimental results, the values themselves are not quite the same. For both K=3 and K=8, the predicted visibility is lower than the experimental one. However, (Węgrzyński & Vigne, 2017) explained that comparing the values of visibility is not as straightforward since the visibility measurement technique is flawed.

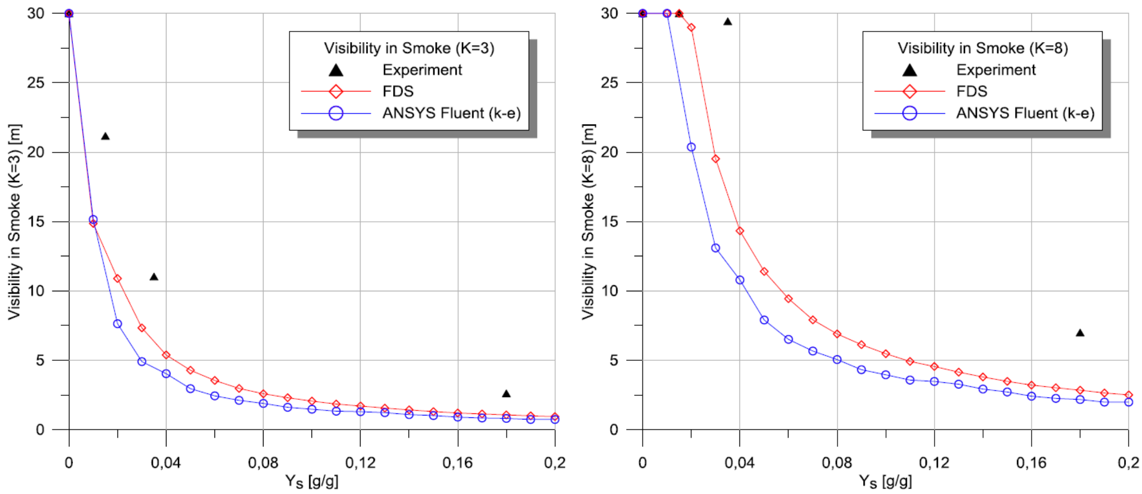


Figure 10 Visibility range vs Soot Yield for K=3 and K=8 (Węgrzyński & Vigne, 2017).

2.2.5 Psychological and behavioral aspect of visibility

Despite previous research having established that red light is more visible in smoke than green light, green exit signs are still the standard in most countries. This is highly linked to the human behavior aspect and how colors and other qualities are perceived. When it comes to the design of exit signs, the end goal is not to only be seen but to be understood and used by the evacuees.

Like any product design, the design of exit signs follows the theory of affordances. To quote (Hartson, 2003) "We also think that sensory affordance is necessary to support cognitive and physical affordance throughout the user's Interaction Cycle". Throughout his paper (Hartson, 2003) explains the different types of affordances and their importance with how people interact with products based on these affordances. He summarizes the several types of affordances in Table 8 below.

Based on the information provided in the table, we can extrapolate the reason behind different design choices for an exit sign. The use of pictograms along with an arrow pointing in the way of egress could be explained with the cognitive affordance. Sign brightness could be associated with physical affordance as the higher the brightness the more visible it would be. And the sensory affordance could be linked to the green color of the sign which could be perceived by the evacuees as "safe" (Nilsson et al., 2005).

Table 8 Summary of affordance types (Hartson, 2003)

Affordance Type	Description	Example
Cognitive affordance	Design feature that helps users in knowing something	A button label that helps users know what will happen if they click on it
Physical affordance	Design feature that helps users in doing a physical action in the interface	A button that is large enough so that users can click on it accurately
Sensory affordance	Design feature that helps users sense something (especially cognitive affordances and physical affordances)	A label font size large enough to read easily
Functional affordance	Design feature that helps users accomplish work (i.e., the usefulness of a system function)	The internal system ability to sort a series of numbers (invoked by users clicking on the Sort button)

In 1999, as part of his paper, (Heskestad, 1999) compiled a series of Norwegian experiments conducted in the early 1990s which focus on the human behavior in smoke. The five experiments included more than 300 participants who were all unfamiliar with the set-up of the layout and in all but one experiment (the MS Polarlys), participants navigated individually. The results of these experiments showed that green signs with large pictograms and arrows were the most efficient in a human behavior perspective. It was also concluded that in high smoke densities, signages were reduced to useless regardless of their light intensity, size or color as it becomes nearly impossible to locate them and a tactile system was proven to perform better. When comparing the probability of "making a correct choice", (Heskestad, 1999) found that the highest probability (98%) was attributed to a combination of systems, consisting of tactile system with electrically powered systems, and the lowest probability (between 69% and 79%) for electrically powered and photoluminescent low location lighting systems following International Maritime Organization (IMO) design guidelines.

It is important to note that people's perception of which color refers to safety could also be dependent on the environment they grew up in. As previously mentioned, some states in the United States of America mandate red exit signs while others green, hence even Americans could have contradicting perceptions when it comes to exit sign color. This difference in design, amongst not only states but countries as well, could cause problems for travelling people not familiar with the country's regulations. For a European visiting a state where the standard is "EXIT" in red, it could lead to them interpreting the information as meaning "no exit", since red might be perceived as "danger" or "not allowed" (Pravossoudovitch et al., 2014). However, a study by (Or & Wang, 2014) which included both Americans and Chinese participants, concluded that most participants associated green with "go" or "safe" and red with "danger" and "stop", regardless of their origins.

Another set of experiments was run as part of a thesis with the purpose of evaluating the difference in human behavior based on nationality. (Troncoso, 2014) set out to see if perception of colors as well as decision making during evacuation is different between Chinese and European people. The experiments showed that all but one participants considered the color green to mean safe and red to be danger. The results also showed that participants would rather take a further exit if they perceived it as safer or if they were familiar with that exit. Nonetheless it is important to keep in mind that these experiments were ran individually and that the decisions of the individuals were not affected by other people evacuating as well, which could occur during a real scenario. In a study presented by (Nilsson & Johansson, 2009), it was shown that during the early phases of evacuation, people are influenced by other people's decisions which is a phenomena known as "Social Influence". Social Influence was also proven to be stronger when people are closer to each other and when the available information about what is happening was limited (Nilsson & Johansson, 2009).

In an attempt to evaluate how colors are perceived during evacuation, (Kinateder et al., 2019) ran an experiment that involved 24 participants, half of which were female, and a mean age of 19.79 years. (Kinateder et al., 2019) challenged the validity of previous research such as the above mentioned (Heskestad, 1999), (Troncoso, 2014), and (Ronchi et al., 2016), and which pointed the same outcome as (Or & Wang, 2014), and argued that there could have been bias as they were mostly led in countries where exit signs were green and linked it to the "local exposure hypothesis". The participants in their experiment were from Rhode Island in the United States where the law mandates red exit signs. Additionally, the authors highlighted that participants passed by many red exit signs on their way to the experiment. The authors were to prove that if these participants had a tendency to associate the color green with exit signs, then color interpretations as previously proven are caused by semantic associations rather than local exposure.

The participants were asked to take part in a virtual reality (VR) experiment where they had to choose between two doors equally distant from them, with each door having a different colored sign. The colors tested were green, red, magenta, and blue and all colors were alternating equally between left and right so that there is no bias for a certain side. After the VR experiment, the participant had to answer a questionnaire.

Results showed that participants were more likely to go for the door with the green sign while in the VR. However, in the questionnaire which followed the VR experiment, participants answered that exit signs must be red. This contradiction between what participants chose during the simulation and what they answered in the questionnaire is worrying and important to be further looked into. Nonetheless, it further validates previous research on the association of the color green with safety regardless of the social constructs the person grew up surrounded with.

This chapter has included the different literature, explaining how visibility in smoke is calculated today whether in engineering calculations or modeling software. The literature also included experiments that compared different sign designs. Some of the main findings include: the dominance of light emitting signs over light reflecting signs, the better performance of red light in comparison to green light in black smoke, the clear correlation between higher sign luminance with higher visibility and the reason behind some design decisions. However as previously mentioned, while Jin's equation along with his suggested values for visibility are used as default settings, these values have been criticized by the SFPE as lower than what they should be. As no recent experimental study investigating the real values of the visibility constant has been found, the following experiment is an attempt at doing so.

3 Experiment

Inspired by the work done in the above mentioned literature and seeing the need to gather more data on signage visibility in smoke, the current chapter includes a detailed overview of the experiments which were conducted to further investigate the validity of previous results with the technology offered today. The chapter will include a description of the experimental set-up and the multiple scenarios tested, as well as information on the participants.

The experiments took place in the fire safety engineering laboratory in Lund University's technical faculty, during the week of February 28th, 2022.

3.1 Experimental Set-Up

The set-up consisted of six main components: the extraction hood, a duct, a smoke source, smoke density measuring device, a moveable target, and a structure to hold things together (Figure 11).

The main idea of the set-up was to have the participant stood at the stool, looking through the smoke-filled duct at a moveable target. Attached to the moveable target is a light source which can be set-up put in two positions, representing two signage types.

- Position 1: Representing a light-emitting sign, the light source mounted facing the participant.
- Position 2: Representing a light-reflecting sign, the light source illuminating a high contrast sign (Figure 12) from a lower angle.

The moveable target was a wooden rod at the end of which was a plate holding the light source and the reflective sign.

The light source could be remotely controlled to change both color and brightness. The colors green and red were used in this experiment, as well as the maximum and minimum brightness. Prior to conducting the experiments, the brightness of the light source at different settings was measured in the duct in a non-smoky environment, the values can be read in the table below.

Table 9 Brightness Measurements of various light source settings

Setting	***Brightness [cd/m²]***
Green, High Brightness	315
Green, Low Brightness	35
Red, High Brightness	130
Red, Low Brightness	16

In order to generate smoke, two sources were used, a smoke machine for the generation of white smoke, and the burning of blocks of Acrylonitrile butadiene styrene (ABS) to generate black smoke. The ABS placed in a metal container with heptane at the bottom then ignited with a burner. Due to buoyancy, the smoke went up the duct and came out the other side where it was extracted by the mechanical extraction hood. After ignition, participants were asked to wait a few minutes before starting the experiment as enough smoke had to fill the duct before conducting the experiments. The smoke level in the duct was constantly monitored and more plastic was added to the fire if needed.

The duct was 1.8m long, with a cross-section of 23×15 cm. Furthermore, the entire set-up was placed under the extraction hood, collecting all the generated smoke.

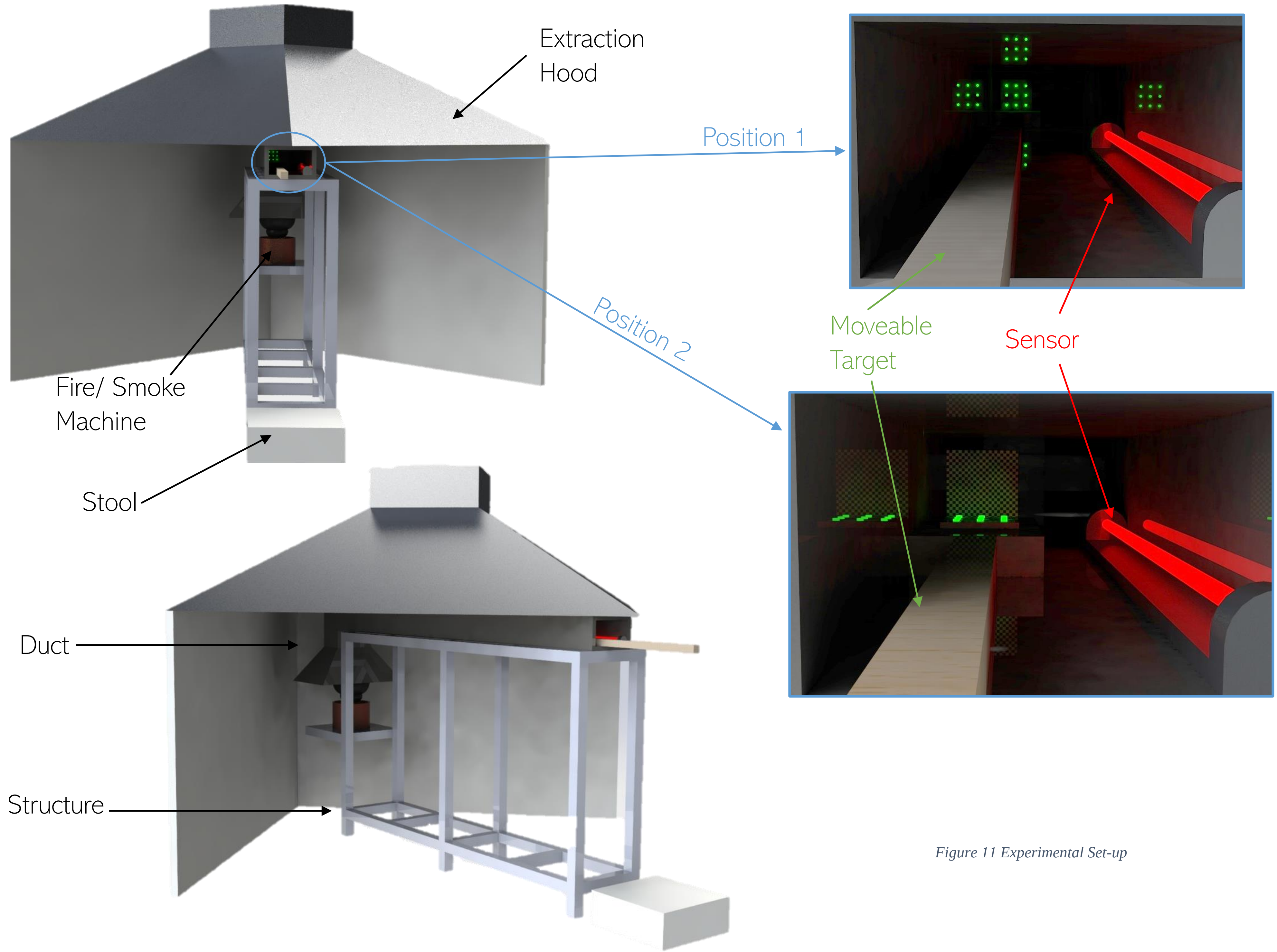


Figure 11 Experimental Set-up

The sensor seen at the inlet of the duct was a device continuously measuring the smoke density, which was connected to a data logger, saving the values at each second.

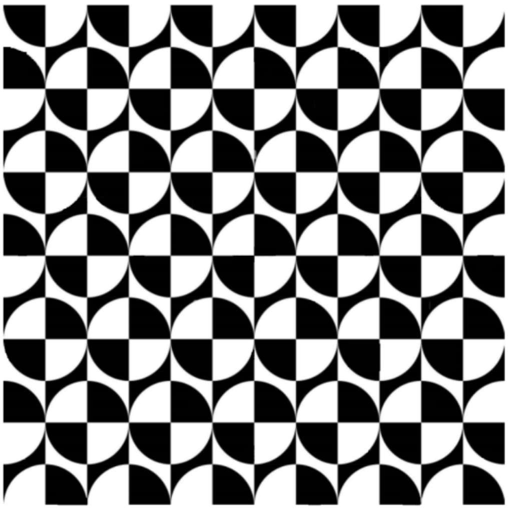


Figure 12 High Contrast Sign

Machinery used in the experiments:

- Mechanical Smoke extraction,
- Smoke density meter: CW Laser Diode Module with Line Generator with Receiver,
- Light intensity meter: Hagner Digital Luxmeter EC1,
- Data logger: DT85 Serie 2,
- Controllable light source: 30cm 8W LED Strip (9 LEDs used),
- White smoke machine: Magnum Pro 2000.

For more pictures on the actual set-up, go to Appendix B Pictures of Experimental Set-up.

3.2 Procedure

3.2.1 Overview

There was a total of 14 scenarios, throughout which the participants were asked to each come in each at a time and do one thing: “move the target until you can no longer see the light source or the reflective sign”.

While the participant stood on the stool at a small distance from the opening, they manipulated the rod so that they toggled with the distance at which the light source/ sign was placed within the duct. As the duct was filled with smoke, at some point, the target became unrecognizable, and the participant was asked to stop moving it. The distance at which the target was placed was measured with the help of a measuring tape which was previously taped along the rod. At the same time, the value of the smoke density was retrieved at the moment at which the participant made their decision.

The speed at which the participants moved the rod was up to each person. It was observed however that participants tended to initially displace the target in big increments at a relatively fast speed until they got closer to the distance they would eventually stop at. The closer they got to their final distance, the slower they would move the target and the smaller the displacement would be.

The smoke density was actually retrieved by doing the following: The voltage reading on the data logger was manually taken note of, along with the time at which a participant's decision was made. In post-processing of the data, the smoke density value was averaged over the 3 seconds around the time it was logged to accommodate for different factors (delay in reaction time of the participant; and the placement of the sensor at the opening of the duct and not at the indicated visible distance, so an extra second for the smoke displacement was added.)

3.2.2 Scenarios

The scenarios differed by light color, brightness, sign positioning, and smoke type. While participants repeated the same thing 14 times, each time one of those three variables changed. The light color could either be red or green, the brightness set at high or low, sign positioning as position 1 or 2 as previously seen, and smoke could be either black or white.

Each participant was asked to come in on two days, the first day the 8 first scenarios were conducted under white smoke, and the second day the 6 other scenarios were conducted under black smoke. Due to the maximum brightness being too bright in comparison to this small scale experiment, coupled with the smoke not being thick enough, 2 of the tasks for black smoke were not evaluated. Making the smoke thicker would require a bigger fire which would put the participants at danger hence the decision was to not go through with it. For the different settings for each scenario consult Table 10.

Table 10 The 14 different Scenarios (Name: Brightness/Color/Smoke type/position, with H=High brightness, L= Low brightness, G= Green, R=Red, W= White smoke, B=Black Smoke, 1= Position 1, and 2=Position 2)

Day	*Part*	*Scenario*	*Distance*	*Brightness*	*Light color*	*Smoke Type*	*Light set-up*
Day 1	*Part 1*	HGW1	Variable	High	Green	White	Position 1
		LGW1	Variable	Low	Green	White	Position 1
		HRW1	Variable	High	Red	White	Position 1
		LRW1	Variable	Low	Red	White	Position 1
	Part 2	HGW2	Variable	High	Green	White	Position 2
		LGW2	Variable	Low	Green	White	Position 2
		HRW2	Variable	High	Red	White	Position 2
		LRW2	Variable	Low	Red	White	Position 2
Day 2	*Part 1*	~~HGB1~~	~~Variable~~	~~High~~	~~Green~~	~~Black~~	~~Position 1~~
		LGB1	Variable	Low	Green	Black	Position 1
		~~HRB1~~	~~Variable~~	~~High~~	~~Red~~	~~Black~~	~~Position 1~~
		LRB1	Variable	Low	Red	Black	Position 1
	Part 2	HGB2	Variable	High	Green	Black	Position 2
		LGB2	Variable	Low	Green	Black	Position 2
		HRB2	Variable	High	Red	Black	Position 2
		LRB2	Variable	Low	Red	Black	Position 2

3.3 Participants

A call for participants was sent out to fire engineering students at Lund University through their instructors. Final participants were asked to fill in a form (Appendix A) with some questions regarding personal information which could influence the results.

In total, 20 participants took part in the experiments. Amongst those, 8 were female and 12 male. In addition, 50% of all participants wore corrective glasses while the rest did not need them, 3 of which were male and 7 female. None of the participants was colorblind. The average age was 26 with the youngest being 22 years old and the oldest 31 years old, the distribution can be seen in (Figure 13).

Out of the participants, 12 participated in the white smoke experiments, out of which 11 also participated in the black smoke experiments, having 19 participants taking part in the black smoke experiments in total.

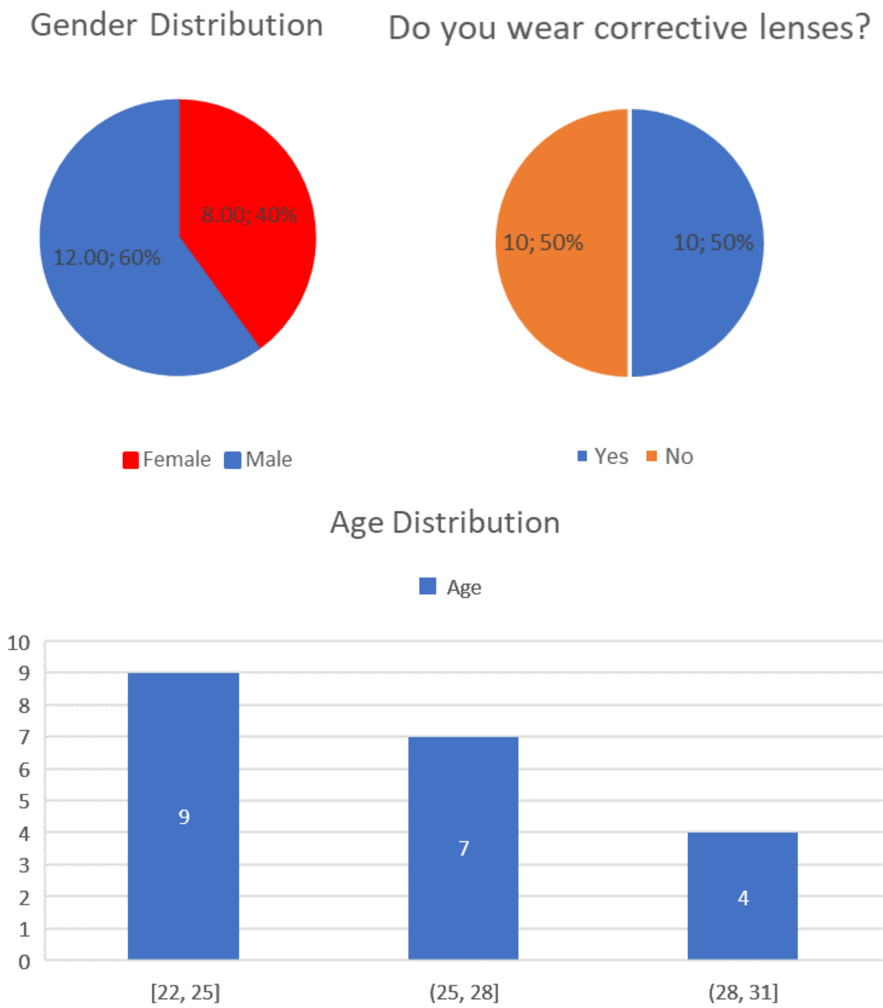


Figure 13 Participants Distributions: Gender (top left), Need for corrective glasses (top right), and Age distribution amongst ranges of 22-25, 25-28, and 28-31 (bottom)

3.4 Risk and Safety

As the experiments were run in the fire safety engineering laboratory, participants were not subject to any type of foreseeable risks. Nonetheless, extra safety measures were taken, including:

- The extraction of smoke by the mechanical system at maximum setting.
- Providing participants with protective glasses to protect their eyes from any smoke irritation, as well as face masks to prevent the inhaling of smoke.
- The placement of participants outside of the extraction hood, at a distance from the smoke.
- The set-up of blinds on the circumference of the extraction hood with only the duct opening being seen, for smoke containment.
- The presence of an external person at all times during the running of the experiments.

A detailed report on safety was submitted to the laboratory engineer and the thesis supervisor prior to the initiation of the experiments.

4 Results

This chapter will present the results obtained from the previously described experiment which was conducted as part of this thesis. The results will be presented in form of tables and graphs. Also included in this chapter is the mathematics behind the results and how they were obtained from the raw data.

4.1 Data Transformation

As previously mentioned, two main values were measured during the experiments. The first measurement is the voltage read by the smoke density meter and the second is the distance read on the measuring tape along the movable target. Both these two values were measured at the time for each observation made during the scenarios. To be able to compare the experimental results in this experiment to the literature, these results must be turned into "Visibility" and "Extinction Coefficient".

4.1.1 Visibility

For the light reflecting setting, *6cm* were added to the initially logged distance, which is the distance separating the sign from the beginning of the measuring tape (Figure 14 top). For the light emitting setting, no distance was added as the measuring tape started at the point of origin of the light (Figure 14 bottom).

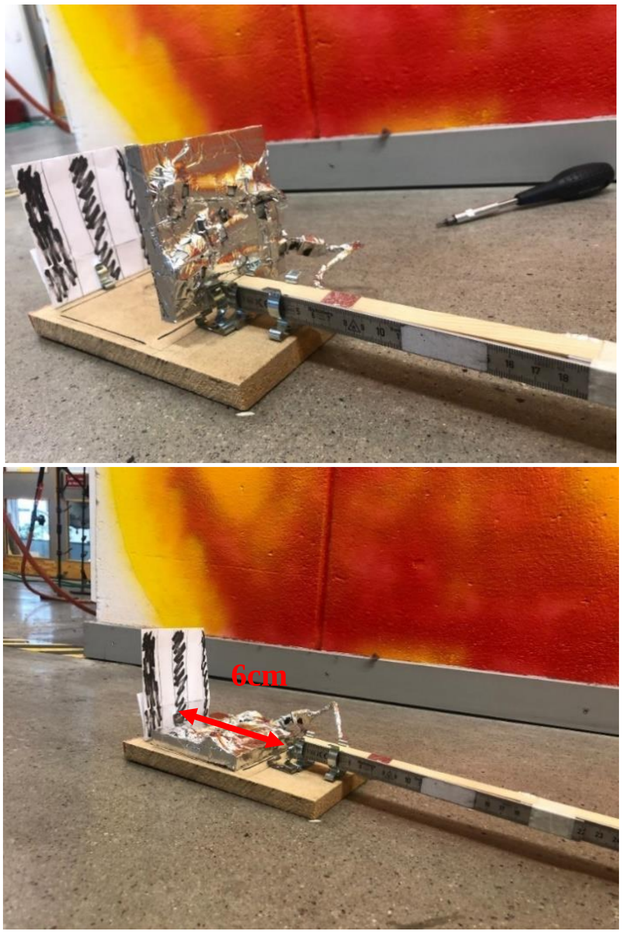


Figure 14 Position 1 (top) and Position 2 (bottom)

Additionally, a supplementary *3cm* were added to represent the smoke thickness at the outside of the duct before it is completely removed from the level of sight (Figure 15). It is important to note that that thickness is not constant but a value of 3cm is a good representation of the average that was observed, and that the thickness seen in (Figure 15) is the maximum reached for a few seconds. For black smoke, this distance was also observed to be more constant and around the value of 3cm. As there was no means of measuring the thickness of the smoke outside of the duct for each scenario conducted the average value of 3cm was used. This final distance value obtained is what is called "Visibility".

Figure 15 Smoke thickness formation at duct outlet

4.1.2 Coefficient

Prior to conducting the experiments, two base values of the voltage were measured. The voltage reading representing a no smoke environment (0% opacity), and the voltage representing complete blockage of the receiver (100% opacity) (Table 11).

Table 11 Base Voltage Values for smoke density

Environment	***Voltage [mV]***
No smoke	1672.4
Full smoke	62

These base values will be used to interpolate the opacity in the duct at the time of interest. The relation between the smoke density and voltage of the sensor was previously proven to be linear and hence why a direct interpolation is possible. However, soot deposition on the receiver could affect this relationship, nonetheless the sensor was wiped clean between each participant to ensure that the linear relationship stands.

As seen in the previous literature, equation (5):

$$C_s = \frac{2.3}{\mathrm{L}} \log \frac{I_0}{I}$$

Here L is the distance over which the measuring device is doing its readings, which for the one we have is a fixed value of 0.5m. As for $\frac{I_0}{I}$, according to (Tu et al., 2011):

$$Opacity = 1 - \frac{I}{I_0} \tag{12}$$

And $Opacity$ here can be extrapolated from the measured voltage, where 62mV is 100% Opacity and 1672.4mV is 0%.

Example:
If the participant found the "no visibility" point of the light source at 09:00:00 for a distance of 70cm, then the visibility is V=70+3=73 cm. The voltage reading at that time is 200mV, at 08:59:59 205mV, and at 09:00:01 203mV

$$\rightarrow U_{average} = \frac{(200+205+203)}{3} = 202.67\ mV$$

$$\rightarrow opacity = \frac{(U_{avg} - U_{no\ smoke})}{(U_{full\ smoke} - U_{no\ smoke})} = \frac{(202.67-1672.4)}{(62-1672.4)} = 0.912$$

$$\rightarrow \frac{I_0}{I} = \frac{1}{1-opacity} = \frac{1}{1-0.912} = 11.36$$

$$\rightarrow C_s = \frac{2.3}{\mathrm{L}} \log \frac{I_0}{I} = \frac{2.3}{0.5} log(11.36) = 4.85\ m^{-1}$$

$$\rightarrow C = V.C_s = 4.85 \times 0.73 = 3.54$$

4.2 Presentation of Results

In the below presented information, the scenarios will be referred to by the nomenclature presented previously in Table 10. It is also important to note that the initial intentions were to have all participants partake in both black and white smoke experiments, but due to unforeseen equipment damage, the experiments had to be terminated earlier. Nonetheless, the data is enough to get some preliminary results that could be representative of this youthful age group.

In Table 12, the values for the average visibility constant of each scenario along with their mean, standard deviation, minimum value, and maximum value are presented. The results exhibit quite a scatter, with a significant standard deviation in comparison to the range for all scenarios.

Table 12 Distribution of the visibility constant representing $V.C_s$

		Visibility Constant							
		Light Emitting				Reflective			
		HGW1	**LGW1**	**HRW1**	**LRW1**	**HGW2**	**LGW2**	**HRW2**	**LRW2**
WS	Average	11.48	9.98	10.86	8.94	5.67	4.90	5.47	4.18
	Std dev	2.38	2.02	2.93	2.64	1.21	1.26	1.54	1.33
	Max	16.04	13.95	14.31	11.81	7.49	7.07	7.61	6.37
	Min	6.88	6.67	4.05	3.99	3.28	3.24	2.12	2.16
	Average	10.32				5.05			
	Std dev	2.69				1.46			
	Max	16.04				7.61			
	Min	3.99				2.12			
			LGB1		**LRB1**	**HGB2**	**LGB2**	**HRB2**	**LRB2**
BS	Average		7.91		8.28	6.00	3.07	6.43	3.15
	Std dev		1.77		2.38	1.97	1.39	2.37	1.45
	Max		11.08		13.37	9.88	6.28	11.12	7.24
	Min		3.83		3.87	2.79	1.38	2.62	1.15
	Average	8.10				4.66			
	Std dev	2.11				2.41			
	Max	13.37				11.12			
	Min	3.83				1.15			

Comparing the average, minimum, and maximum value of the visibility constant of HGW1 to HRW1, LGW1 to LRW1, HGW2 to HRW2, and LGW2 to LRW2, the values for the green colored light scenarios slightly surpass those of the red colored ones, which shows a tendency for green signs to perform better under white smoke conditions for both emitting and reflective signs. However, the contrary is seen when comparing the results of LGB1 to LRB1, HGB2 to HRB2, and HGB2 to LRB2. Under black smoke conditions, red colored signs are seen to perform better. Nonetheless, the slight advantage in numbers is still very minimal, especially when comparing results with a significant scatter, yet the trend of green advantage in white smoke and red advantage in black smoke can be concluded.

Looking at Figure 16, a few tendencies in performance can be observed. First, light emitting signs exhibit a significantly higher visibility constant than light reflecting signs. Second, for light emitting signs, the visibility constant is higher in white smoke than black smoke conditions for both scenarios LG1 and LR1. Finally, for light reflecting signs, at low brightness, the signs had a higher visibility constant value in white smoke in comparison to black smoke. While at high brightness, these signs have had a higher value of the visibility constant in black smoke than white smoke.

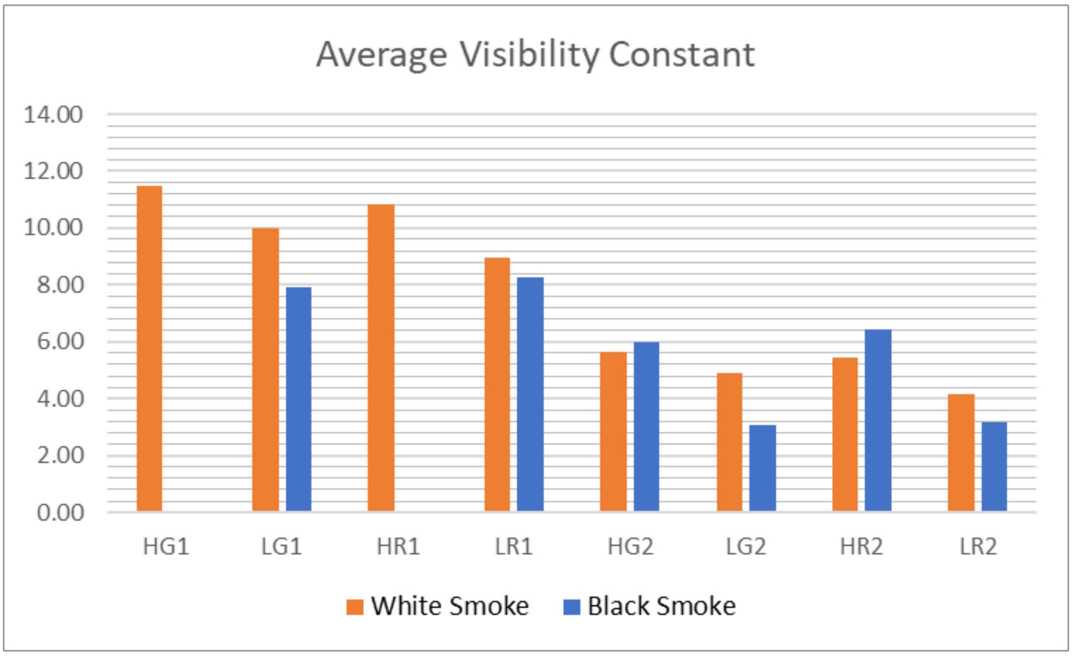


Figure 16 Column Chart of the average visibility constant of each scenario.

Looking at the graphs in Figure 18, and Figure 20 through Figure 24, there is a clear scatter in the results pertaining to the black smoke experiments, with the data points being spread out all over the graph instead of being around the line representing the average visibility constant of their respective scenario (blue dots in respect to the blue line). Hence making a strong conclusion from these results is not feasible and cannot be made with confidence.

It was not foreseen that for such a small range of the extinction coefficient, the reported values of visibility would differ so drastically among participants within the black smoke scenarios. While the extinction coefficient was relatively high, and a slight increase of it could make a large impact, a range of visibility between 30cm and 160cm for more or less the same value of the extinction coefficient (Figure 20) was not expected and comes to show how sensitive and unpredictable it could be to assume visibility values when doing engineering calculations.

On the other hand, through the graphs in Figure 17 to Figure 24, it can be seen that the results of the experiments under white smoke conditions somewhat follow their respective visibility constant line, with an acceptable amount of scatter regardless of having a few points be an exception (yellow dots in respect to the yellow line). It seems to be that assuming V.Cs is equal to a constant is not a bad assumption to make when it comes to white smoke, and a higher value of the visibility constant may be more representative for both light emitting and light reflecting signs than the ones suggested by Jin.

The reason behind the unexpected behavior pertaining to data points of black smoke experiments could not be identified. The fact that the behavior of the results from the white smoke experiments is as expected, suggests that it is not an error in the experimental set-up as it was the same for both types of experiments. However, it could still be human error that has went unnoticed. Another explanation could be that the equation that Jin suggested is limited to lower values of the extinction coefficient, as his tests included a range of 0-2 m^{-1} for the extinction coefficient. Further experiments should be carried out to assess whether this behavior is the result of an error or the actual behavior for higher smoke densities. More on the comparison to Jin's experiments will come later.

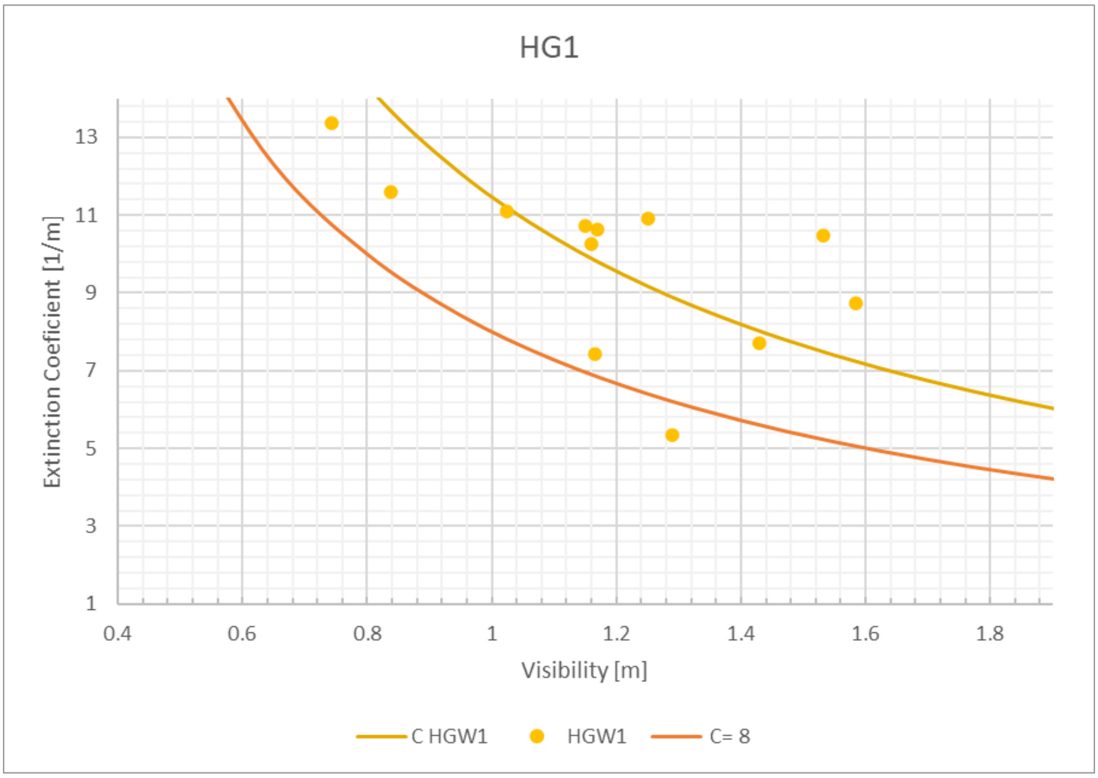


Figure 17 Results for Scenario including: High Brightness, Green Light position 1, under white smoke conditions.

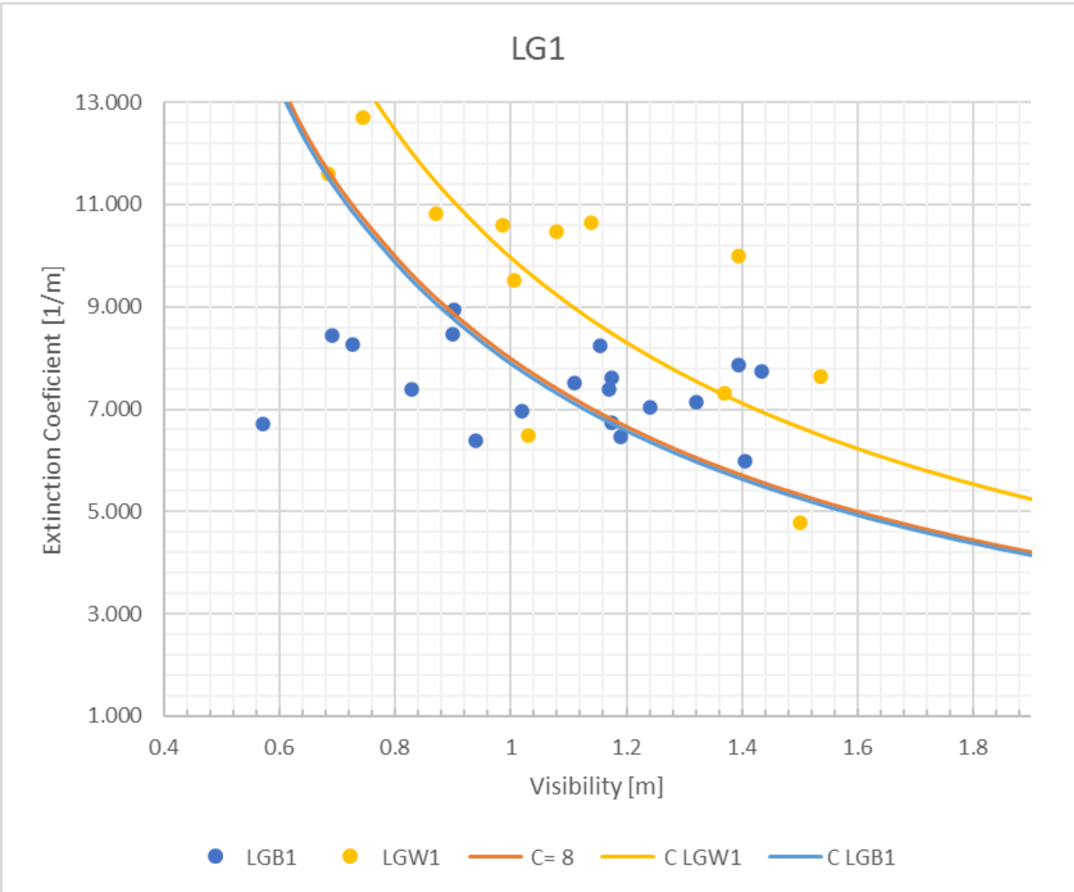


Figure 18 Comparison of results for Scenarios including: Low Brightness, Green Light position 1, under white and black smoke conditions.

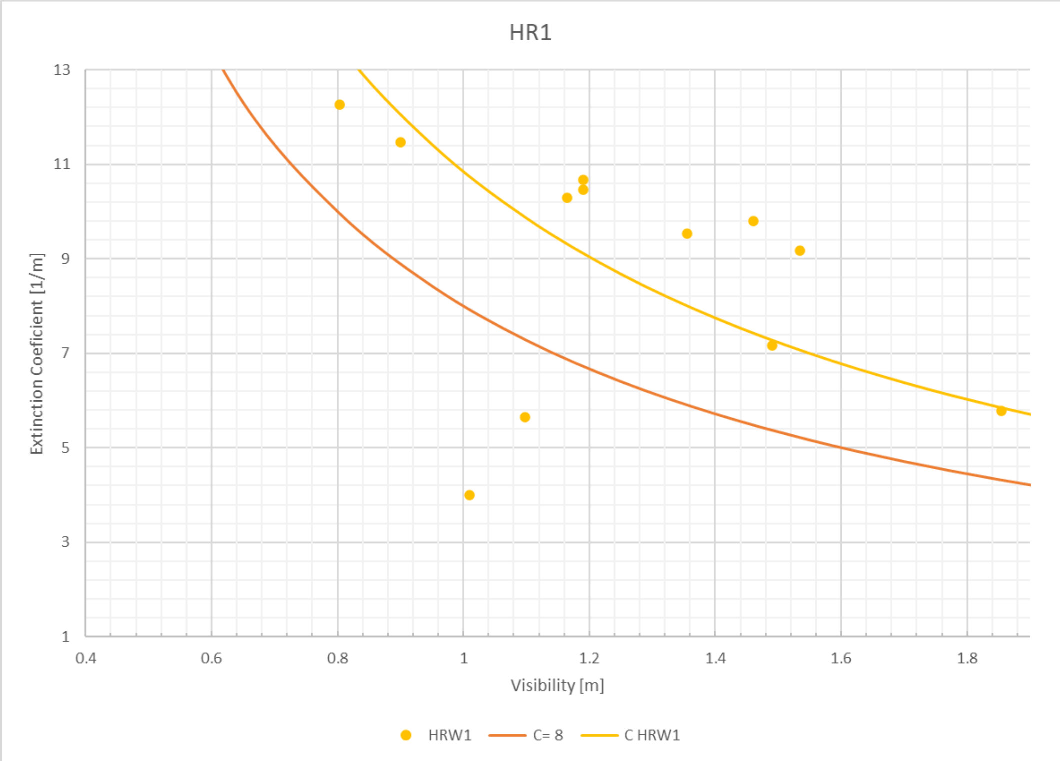


Figure 19 Results for Scenario including: High Brightness, Red Light position 1, under white smoke conditions.

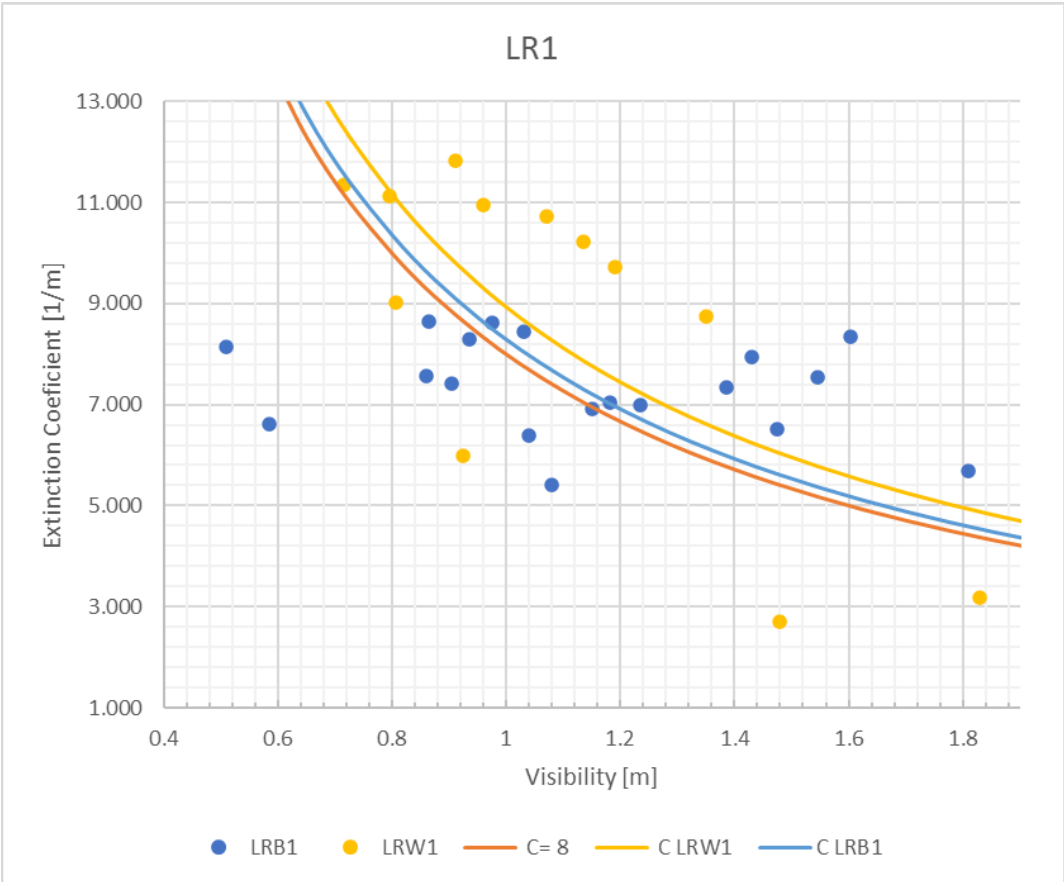


Figure 20 Comparison of results for Scenarios including: Low Brightness, Red Light position 1, under white and black smoke conditions.

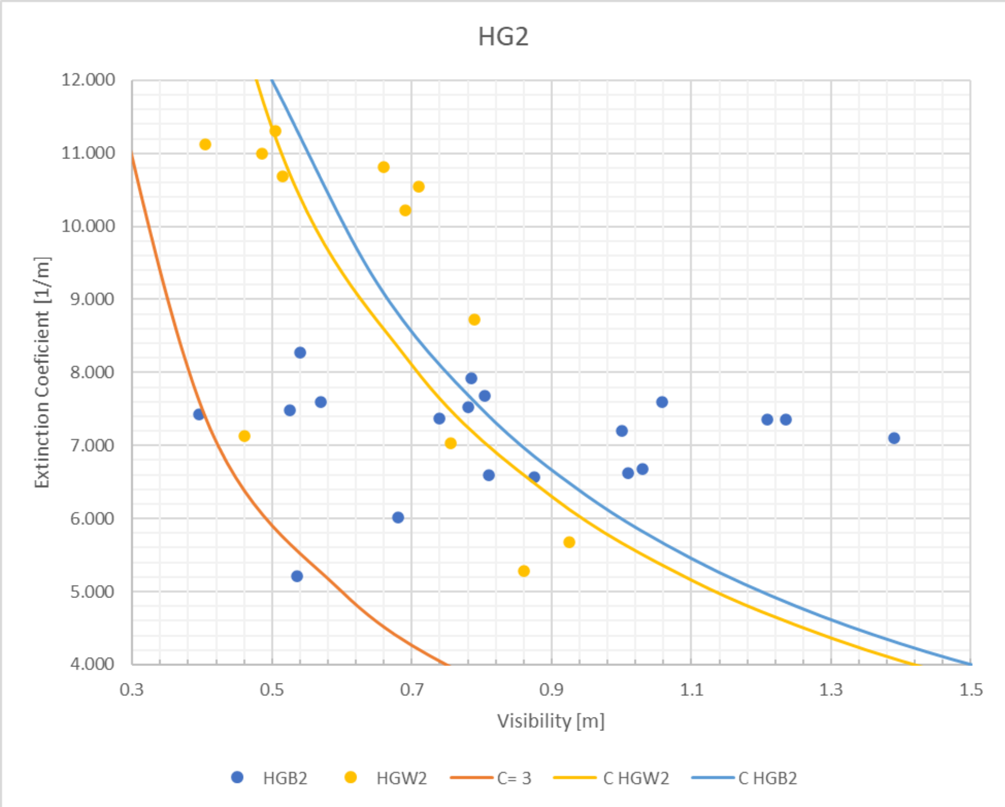


Figure 21 Comparison of results for Scenarios including: High Brightness, Green Light position 2, under white and black smoke conditions.

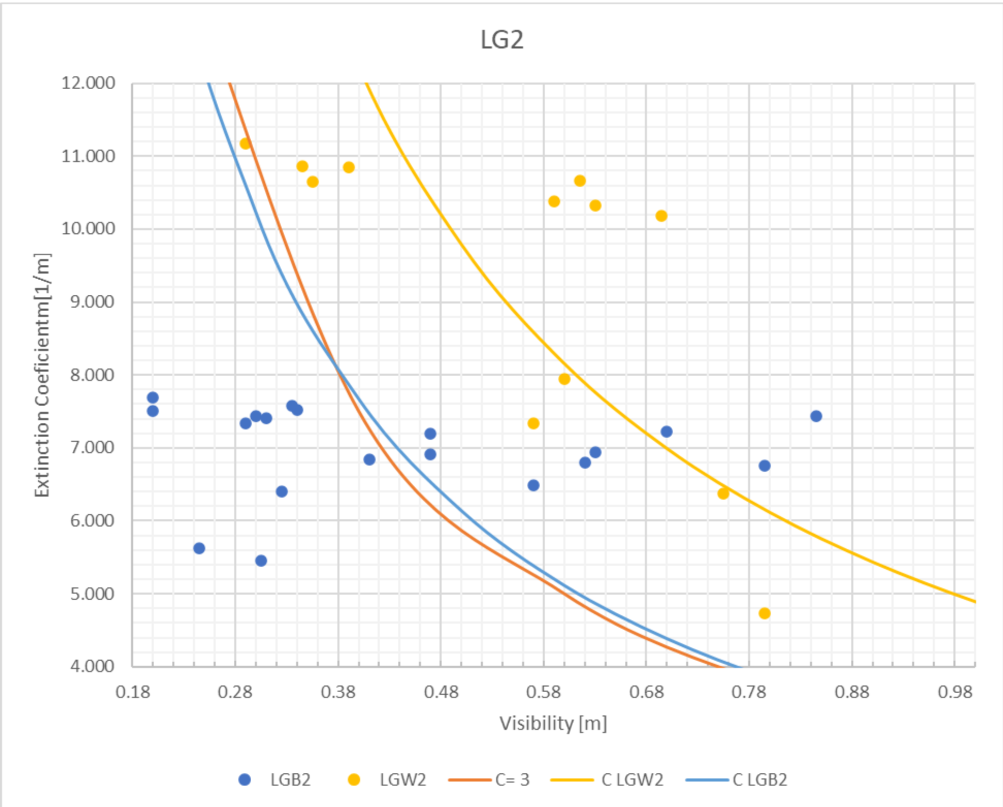


Figure 22 Comparison of results for Scenarios including: Low Brightness, Green Light position 2, under white and black smoke conditions.

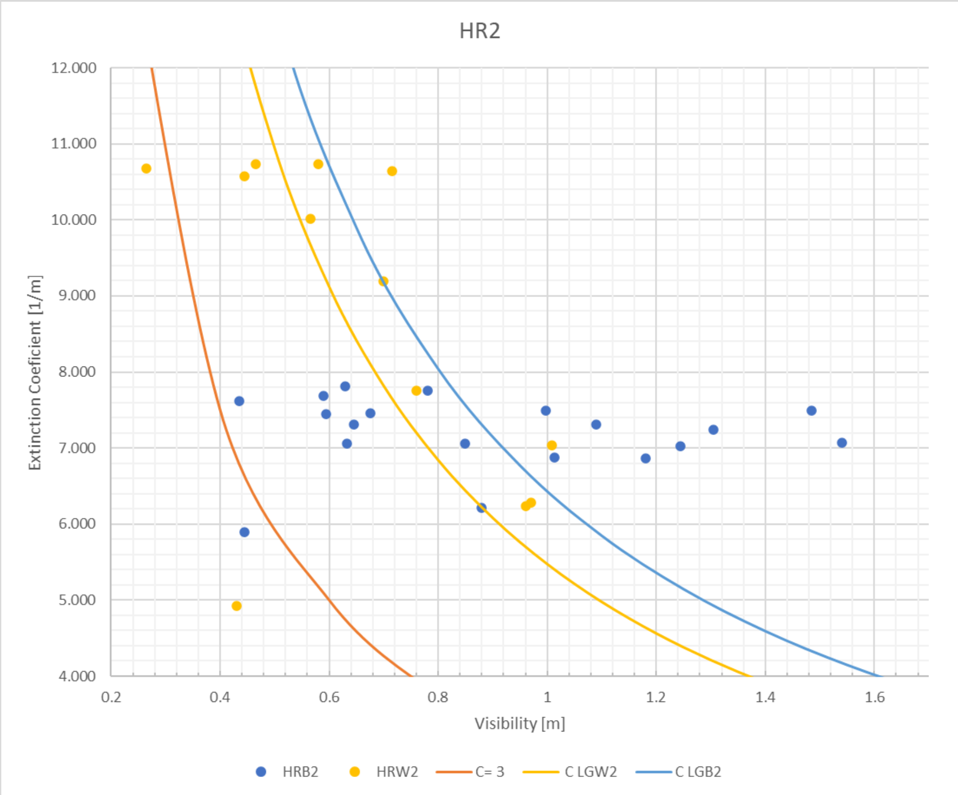


Figure 23 Comparison of results for Scenarios including: High Brightness, Red Light position 2, under white and black smoke conditions.

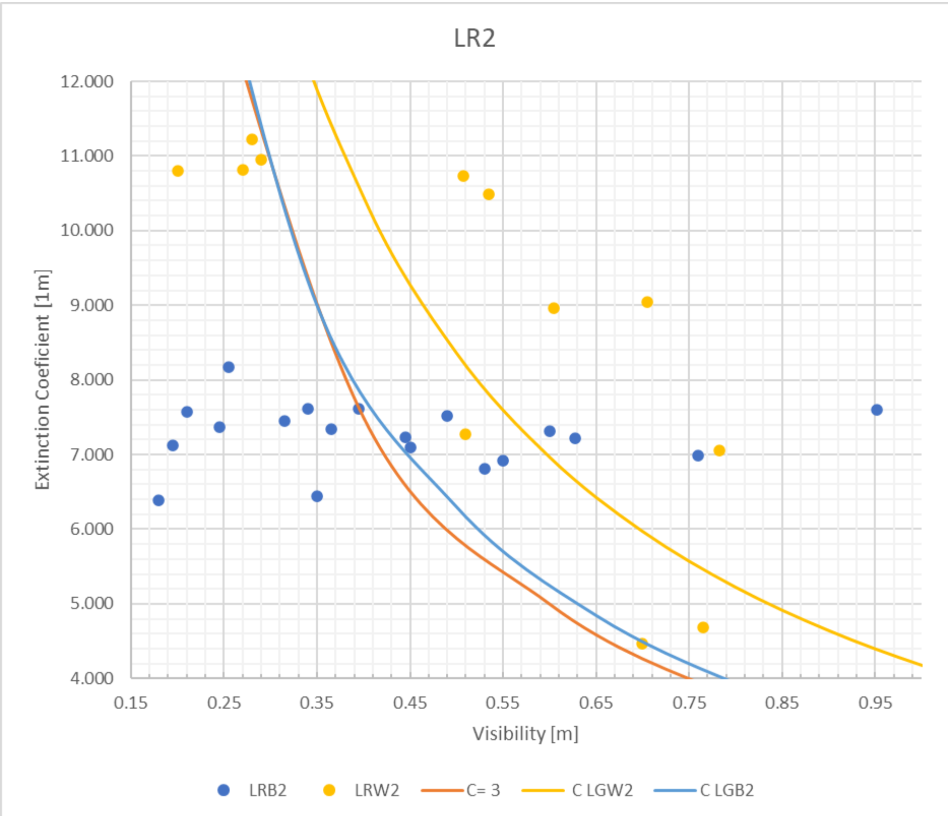


Figure 24 Comparison of results for Scenarios including: Low Brightness, Red Light position 2, under white and black smoke conditions.

Visibility did not seem to be affected by whether the participant was wearing corrective lenses or not. In addition, no participant was knowingly colorblind, hence this factor was not studied during this experiment. As all participants were within the same age group, difference in visibility cannot be linked to age difference.

However, an interesting observation was made while studying the results. There seemed to be a trend in the experiments, where female participants reported a higher visibility constant than male participants in most scenarios, a phenomena that seemed even more evident under black smoke conditions. This difference is less prominent in reflective lights setting, but still noticeable (Figure 25 & Figure 26).

While no research has been made with a focus on the difference in visibility in smoke between the two genders, some previous research was made on the perception of color. In their paper, (Jain et al., 2010) led a research which included 60 individuals equally divided between men and women, aged between 17 and 22 years. Results of the study concluded that female participants were quicker at distinguishing colors and more correct, than male participants especially for red and green. (Jain et al., 2010) concluded that "women see more shades of colors than males".

It could be that with increasing smoke, as the light is being absorbed/ refracted, and as its wavelength is changing and getting mixed, female participants were still able to distinguish it in a faster manner than male participants, leading to a higher visibility constant than males.

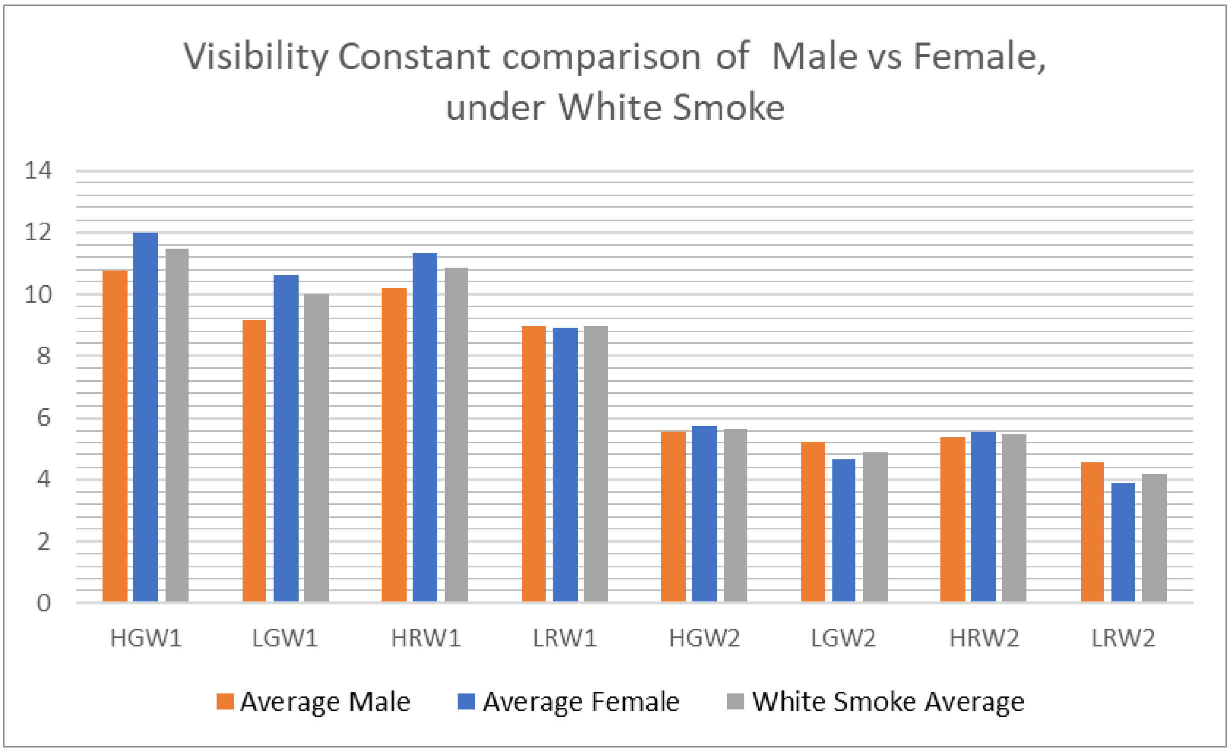


Figure 25 Comparison of averaged visibility constant between Male and Female Participants as well as the general average under white smoke conditions.

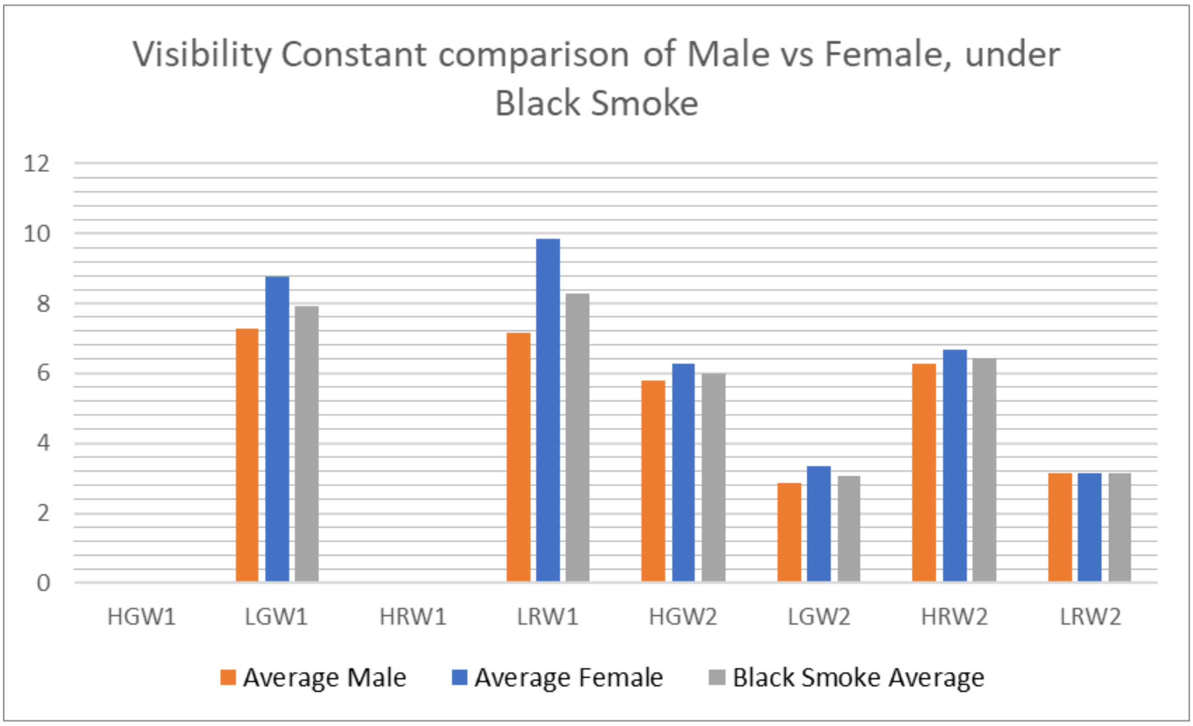


Figure 26 Comparison of averaged visibility constant between Male and Female Participants as well as the general average under black smoke conditions.

5 Discussion

This chapter will present the discussion of the obtained results presented in the previous chapter. The discussion will include a comparison to the above mentioned literature, re-iterate the scope of application of the obtained results, discuss how these results can be applied in the context of signage design, and finally discuss future prospects.

5.1 Comparison to previous literature

As seen in Table 13, the results obtained in the current experiments fall in a larger range than those obtained in (Jin, 1978). In addition, in continuation with what was seen in the previous chapter, the results obtained in the current experiments have shown higher visibility constants than those reported by Jin. In both light emitting and light reflecting cases, the obtained results from the experiments run for this thesis are seen to have a higher average and maximum value than Jin's and a lower minimum value for the visibility constant.

Table 13 Experimental Results Comparison to Jin T results

	Visibility Constant					
	Light Emitting			Light Reflective		
	Experiment	Jin T.	%Difference	Experiment	Jin T.	%Difference
Average	9.21	8	15.07	4.86	3	62.00
Max	16.04	10	60.39	11.12	4	178.07
Min	3.83	5	-23.39	1.15	2	-42.53

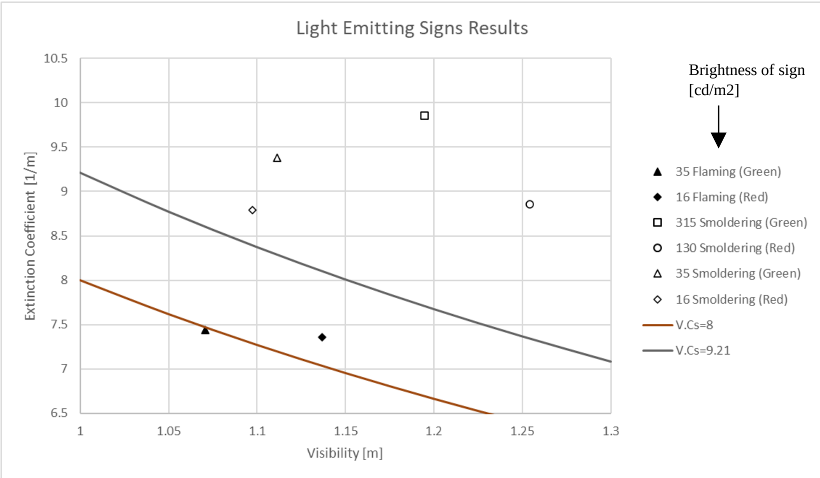
However, directly comparing the results of both experiments is not this straight forward. There are many factors related to the set-up of both experiments that differentiates them (Table 14), most importantly the extinction coefficient ranges, sign brightness, scale of experiment, the visible distance, and number of participants (both having low numbers of participants).

Table 14 Differences between Jin's experimental set-up and the current experimental set-up

Difference	*Jin's Experiment*	*This Experiment*
Light intensity	500-2000 cd/m^2	16-35 cd/m^2
Extinction Coefficient	0-2 m^{-1}	5-12 m^{-1}
Scale	Full scale, people looking through glass window onto a big room.	Small scale, people looking through a small duct.
Distance	Up to 15m	Up to 2m
Number of participants	12	12-20

In addition, Jin had a more controlled environment, where he was adjusting the ambient light to be the same for all participants, a factor not controlled in this work's experiment. Moreover, Jin had control over the amount of produced white smoke, which was not the case here. Finally, in the experiment presented, the participants field of vision was not as wide as the one in Jin's experiment. Looking through a narrow duct and knowing exactly where the target is, might have had a positive impact on the visibility. It is also worth noting that some participants pointed out that while conducting the experiments, the safety glasses might have had a negative impact on their visibility.

Considering these differences, taking a quick look at Jin's graphs, a noticeable characteristic is the scatter or whether the lack of in the results he presented, especially in comparison to the results obtained in this experiment. Figure 27 shows a side by side comparison of the graph provided by Jin which represents the extinction coefficient in function of the visibility for the different experiments that he ran under light emitting conditions, and the results from the experiments ran as part of this thesis. Looking at Jin's graph, it seems as though the obtained results lie perfectly along that C=8 line, while the averaged points from this thesis' experiment are a lot more scattered in comparison to the average visibility constant line.



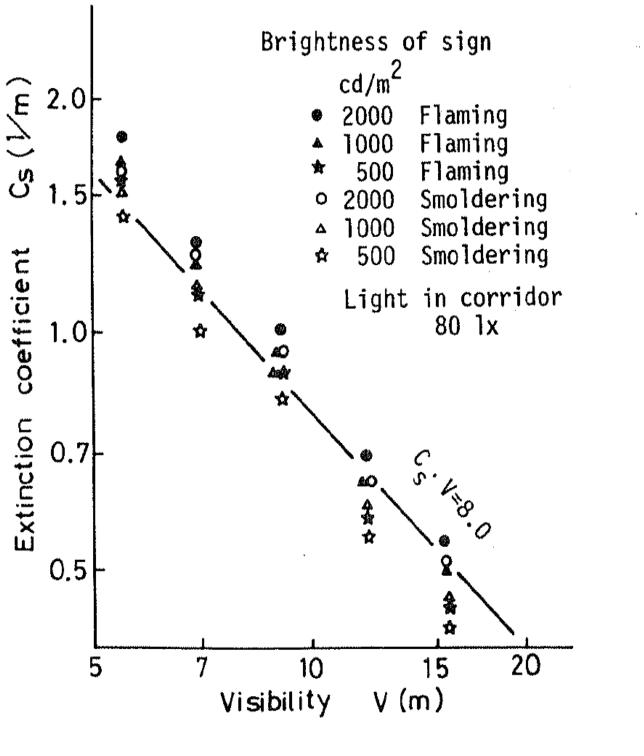
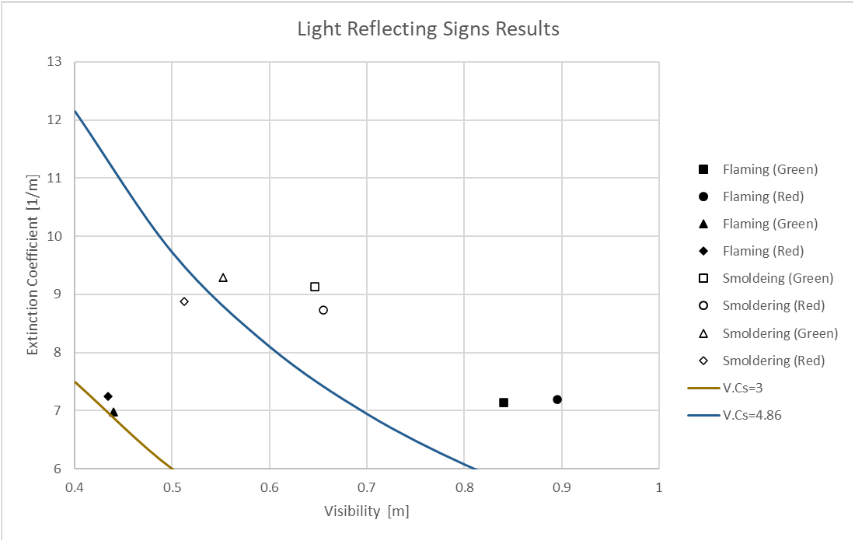


Figure 27 Light Emitting Sign Results in comparison to Jin T. Results

Similar to the light emitting signs, the results for light reflecting signs were also higher in comparison to the results obtained by Jin in his experiments (Figure 28). The same factors to the above mentioned ones could have drastically affected the results, such as sign brightness, extinction coefficient and visibility order of magnitude, and scale of experiments, along with others. Additionally, the reflectance of the signs used in this experiment could not be calculated which is an additional factor. Similar things could be said in regard to the scatter difference between Jin's and this thesis' results.



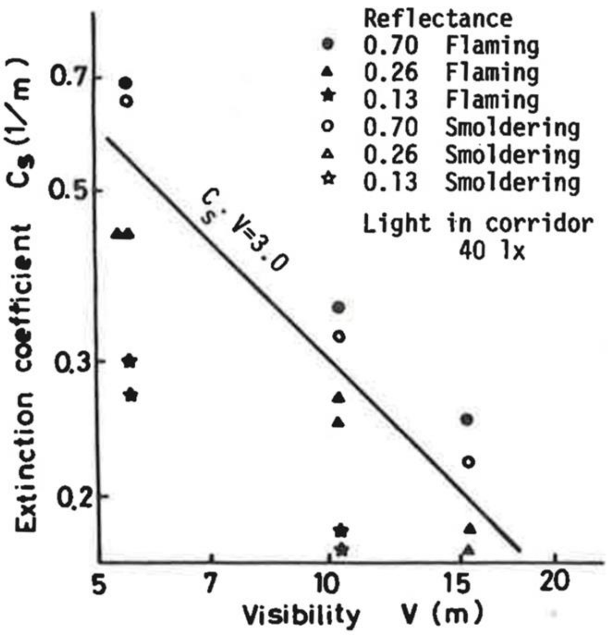


Figure 28 Light Reflecting Sign Results in comparison to Jin T. Results

With the differences in experimental set-up highlighted, it is still undeniable that the difference in the results is large. Especially when it comes to the results under black smoke, where in the results obtained in this research, no exact reason could be given but a speculation is that for higher values of the extinction coefficient, Jin's equation could not be valid. Relating the visibility and the extinction coefficient with a constant, or any relationship, cannot be done as the results are scattered and do not follow any obvious pattern. It is especially concerning, seeing that Jin's results fall so gracefully along the visibility constant line for all of his scenarios. One would expect that in the conducted experiments we would also get similar results, that would somewhat follow a constant visibility line as well but that was not the case. This comparison leads to questioning the confidence behind the results reported by Jin and with that, the reliability of any calculations made based on his results.

When it comes to the effectiveness of red colored lights in comparison to green ones, previous literature ((Jin, 1977),(Clark et al., 1985), & (Collins et al., 1992)) has showed that red lights performed better under black smoke which was also seen here, whereas under white smoke red was seen to be less favorable. Going back to Table 12, we can see that under white smoke, red light never performed better than green in any of the eight scenarios. As for their performance under black smoke, the average always showed the red lit signs to be better performing.

The higher values that were obtained here for the visibility constant under white smoke conditions, go hand in hand with the SFPE's decision to remove the recommendation in their older versions of the handbook, and opt for informing their readers that the values are actually higher than previously thought (Hurley et al., 2016). But again, with such a big scatter across the results for black smoke, no conclusion can be made with confidence.

This on the other hand shows that modeling software companies which were previously mentioned, might still be a bit behind on this as they still use the recommended values of 3 and 8 for light reflecting signs and light emitting signs respectively. However, using a lower constant in the simulations will lead to more conservative results and hence a safer design. In addition, an engineer should always be skeptical about simulation results and know the extent of their applicability as well as the software's scope of application.

5.2 Scope of Application and Signage Design

As mentioned earlier in the paper, the obtained results do not represent a real case scenario of looking for an exit sign during evacuation on multiple aspects:

- Smoke irritation: as shown by (Jin & Yamada, 1985), smoke irritation can exponentially decrease visibility due to tears disabling the individual from opening their eyes, hence not even having the chance to actually look for an exit sign.
- Exposure to toxic fumes: participants were also not inhaling toxic fumes which would affect their ability to concentrate and stay focused.
- Scale of experiment: the experiments run for the sake of this study were far from what individuals would actually experience when it comes to the environment. Participants knew their safety would not be compromised, and thus the psychological aspect that comes with the perception of danger was not present here.

This study focused on the pure physical aspects of signs and comparing the different sign design factors to each other under the same visibility conditions.

On a final note, before moving on to the conclusion, it is important to highlight the following:

- The results obtained from the current experiment under black smoke conditions exhibit a great deal of scatter, leading to any conclusion being made regarding black smoke conditions to be taken with a pinch of salt.
- The results under white smoke conditions have an acceptable level of scatter and thus a few conclusions can be made with somehow of a certainty.
- Directly comparing the results obtained by Jin to the current experiment's is not as straightforward, taking into consideration the previously mentioned differences.

6 Conclusion

In this paper a literature review was made which goes over the relevant research that have recently been made in relation to visibility in smoke. In the literature review it was shown that a common way to calculate visibility in smoke is to use the equation presented by Jin with a visibility constant of C=8 for light emitting signs, and C=3 for light reflecting sings. Then, while most experiments done on visibility did not include the effects of smoke irritation, the latter has been shown to have a big impact on individuals' ability to look for an exit sign. In addition, other experiments on visibility have constantly shown that red colored signs perform better than green signs, but green signs have been adopted by most international standards. The decision to opt for green signs was made based on the psychological behavior seen in individuals where the color green was perceived as safe and red as danger. In addition, a section on modeling of visibility presented the different ways of going about modeling visibility, as well as the danger and level of certainty that comes with it.

Furthermore, an experimental study was also run as part of this thesis to further investigate the effect of different signage designs on visibility under white and black smoke. After running comparing the results to the previously presented literature, while focusing on the results obtained by Jin, some conclusions were made:

- Light emitting signs have shown to be more effective than light reflecting ones on all aspects, for both black and white smoke, as well as both red and green colored lights, agreeing with previous literature.
- Matching with what has recently been highlighted by the SFPE, the values for the visibility constant under white smoke conditions have shown to be higher than what was previously thought i.e., the visibility is in fact better than previously thought. This conclusion leads to reconsidering the values used in simulation software for visibility calculations and egress models.
- A striking lack of scatter in Jin's results in comparison to the scatter observed in the currently obtained results raises concern, especially under black smoke conditions.
- No conclusive conclusion was feasible for results under black smoke conditions as to why a big scatter was observed, but a hypothesis is that for higher values of the extinction coefficient, the suggested equation by Jin is no longer valid.
- When it comes to the performance of green light in comparison to red light, we have seen that under white smoke conditions, on average, green light has performed better than red. While under black smoke conditions, red light was the better of the two, in line with the previous research. Nonetheless, the reason why green is the most commonly used color still remains independent of its performance against red light. As previous literature has proven, people perceive green as safe and tend to choose it over red in these situations.
- An interesting observation regarding the results of female versus male participants has been made where female participants reported higher visibility constants. No scientific reason could have been given as to why that was the case.
- Unfortunately, today the Visibility Simulation Tool (VST) which they were working on is not in use. While no information can be found on why this tool has been discontinued or when, it might be due to several factors such as the validity of the results obtained through VST, thus no conclusion can be made with that regard.

7 Future Prospects

Obviously, there is still a lot of work to be done when it comes to the topic of visibility in smoke. We have seen that a lot of factors could come in to play when assessing visibility. Future research should:

- Include a more holistic view and a more controllable environment, especially when it comes to full scale tests involving the irritant effects of smoke on visibility.
- Come up with an ethical way to test the effects or irritation, which is not an easy task, but a task that is of high importance if we need to understand not only how visibility is affected but also the human behavior part of it, when people are subject to a more realistic scenario rather than sitting comfortably in the safety of a laboratory set-up.
- Be conducted on the perception of green and red lights, more specifically in the United States, as the above mentioned literature only included a small sample of people from one state. Additionally, the perception of pictograms instead of spelling of the word EXIT must be studied.
- Look into whether females do indeed have higher visibility in smoke than males, or whether this phenomena was exceptionally observed in this experimental work.
- Compare results from egress models which use the visibility constant, to full scale experiments and see to what extent these results are compatible with real life situations.

Researchers are also called upon to develop the experiment that has been introduced in this thesis by:

- Testing within a longer distance as my duct was only 2m long,
- Testing with different fuels, having a lower and higher extinction coefficient,
- Control the ambient light, as we have seen in previous literature that it does have an effect on visibility,
- Recruit more participants including older ages,
- Further investigate whether females do have higher visibility than males.

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Appendices

Appendix A Participation Form

Visibility in Smoke Experiments Participation

For a description of the experimental procedure please click on the link:
https://drive.google.com/file/d/1fb34SzjQoSPsOC61F7hNDXXaFKbbUzUl/view?usp=sharing
The experiments will be run in the Fire Engineering Laboratory in LTH's V-Husset.
The safety of the participants will be ensured and participants can stop the experiment at any point.
An email will follow with a link to fill in the timeslot you prefer (Please add a preferred time in the form below and I will try to accommodate everyone before releasing the sheet).
Thank you for your participation!

Sign in to Google to save your progress. Learn more

* Required

Full Name *

Your answer

Email *

Your answer

Age *

Your answer

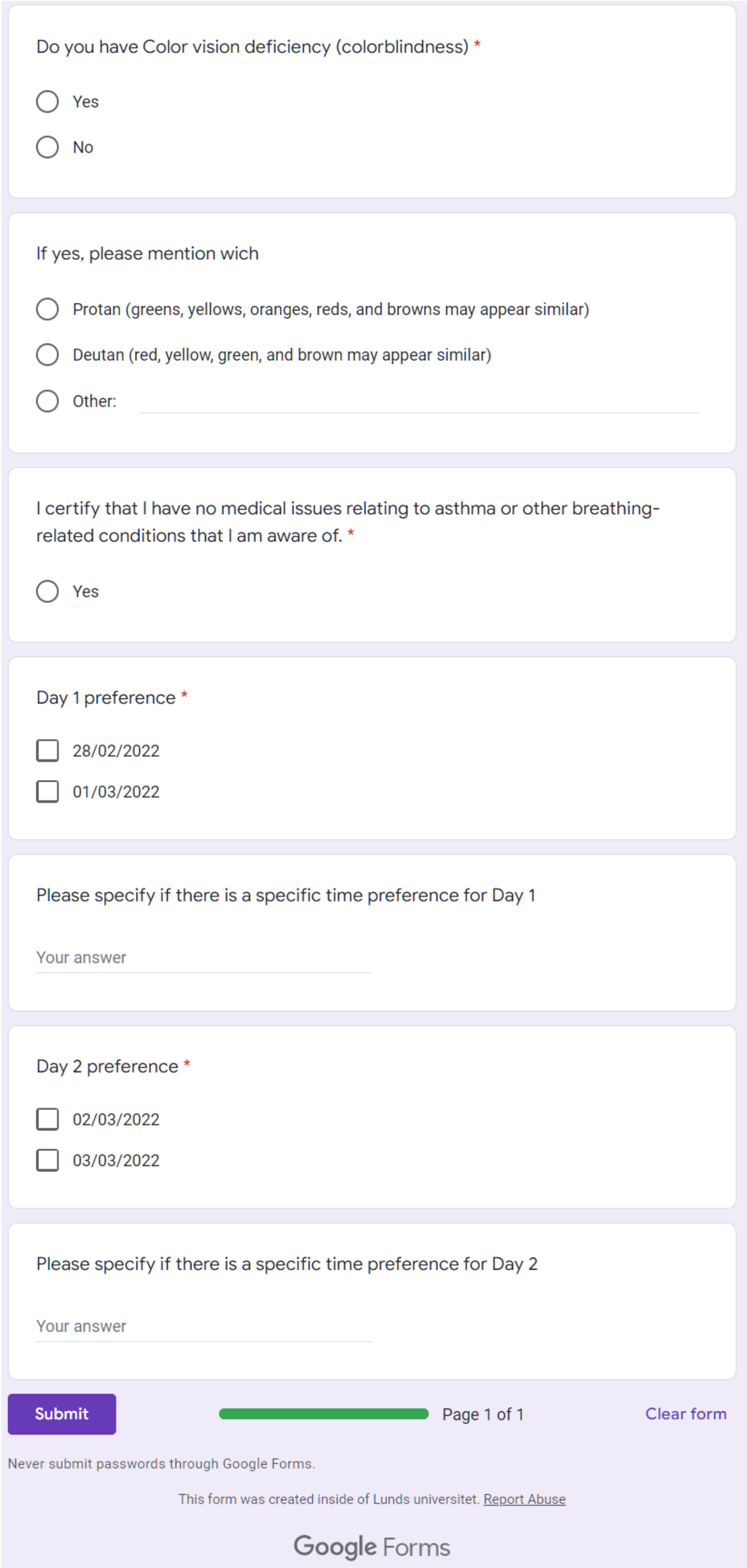
Gender *

- ◯ Female
- ◯ Male
- ◯ Other:

Do you wear corrective lenses *

- ◯ Yes
- ◯ No

Figure 29 Participants form part 1



Do you have Color vision deficiency (colorblindness) *

- Yes
- No

If yes, please mention wich

- Protan (greens, yellows, oranges, reds, and browns may appear similar)
- Deutan (red, yellow, green, and brown may appear similar)
- Other:

I certify that I have no medical issues relating to asthma or other breathing-related conditions that I am aware of. *

- Yes

Day 1 preference *

- 28/02/2022
- 01/03/2022

Please specify if there is a specific time preference for Day 1

Your answer

Day 2 preference *

- 02/03/2022
- 03/03/2022

Please specify if there is a specific time preference for Day 2

Your answer

Submit

Page 1 of 1

Clear form

Never submit passwords through Google Forms.

This form was created inside of Lunds universitet. Report Abuse

Google Forms

Figure 30 Participants form part 2

Appendix B Pictures of Experimental Set-up

Figure 31 Fuel used for black smoke (Acrylonitrile butadiene styrene (ABS) block)

Figure 32 White Smoke Machine

Figure 33 Experimental Set-up under the extraction hood

Figure 34 Movable target set-up

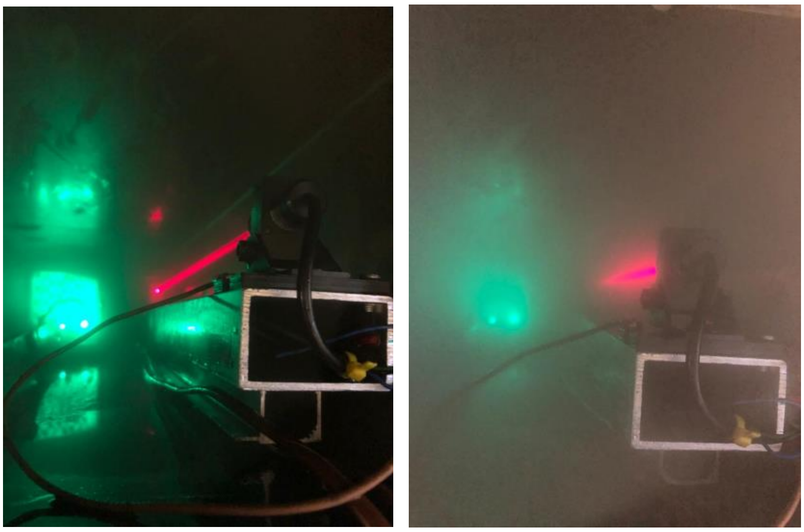


Figure 35 Light source and smoke density meter in duct (non-smoky environment (left) vs smoky environment (right))

Appendix C Results

To access the raw results as well as the calculation sheets and other files, you can click on or scan the below QR code.

Figure 36 Scan to access the drive file containing the excel sheets for this thesis work and other files