

QUANTITATIVE VALIDATION OF SIMULATED VISIBILITY IN SMOKE LADEN ENVIRONMENTS

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ABSTRACT

The visibility of exit signs in smoke has been extensively studied through human field trials resulting in established guidance criteria for visibility in terms of the optical density of the smoke layer. The most widely cited works are those by Jin, where optical depth was related to the visibility of internally illuminated and reflecting signs. Jin postulated that the main reason for a decrease in visibility through smoke was the reduction in light intensity of the sign and background due to the obscuring smoke and reduction in contrast by scattered light from smoke particles and secondary light sources.

The potential for the quantitative simulation of visibility through a smoke laden environment has been previously demonstrated, whereby the output from a time-dependent computation of smoke production and movement was employed as the basis for the numerical solution of the radiative transport equation in the visible wavelengths, taking into account both direct illumination and scattered illumination from surfaces and smoke particulates. The resultant renderings appeared to be realistic but were not validated.

In the present paper we describe the validation of the numerical predictions with reference to experimental data on light extinction collected in a laboratory scale smoke test tunnel.

NOMENCLATURE

c_y	Luminosity function	β	Normal aperture of camera
ΔD	Camera dynamic range	λ	Wavelength (m)
i	Irradiance of a pixel	σ	Extinction coefficient (1/m)
L	Radiance (W/sr.m ²)	σ_{abs}	Absorption coefficient (1/m)
p	Phase function	σ_{sca}	Scattering coefficient (1/m)
s	Distance (m)	τ	Optical depth
\vec{s}	Line of sight (m)	ω	Solid angle (sr)
t_{exp}	Camera exposure(s)	$\tilde{\phi}_\eta$	Normalised mean pixel brightness
		Ψ	Camera calibration cons

INTRODUCTION

The loss or reduction of visibility in building fires may lead to increased inhalation of toxic combustion products and additionally incite panic reaction among evacuees. This is arguably the most important indirect cause of fatalities in building fires. Typically, prescriptive building design codes incorporate the effects of visibility in terms of concepts based upon a threshold visual distance, originally inherited from meteorology, defence and aviation. Such concepts of visibility largely ignored the context of the target object (colour, formation, light emission etc.), the relative angle between the target and the observer and the heterogeneity of media. These complexities do not exist in meteorology and aviation since they are concerned with targets far from the observer (in kilometres) and nearly homogeneous media under very stable conditions where the changes are measured in terms of minutes or even hours instead of seconds as in fire scenarios.

In fire safety, visibility is primarily concerned with safe evacuation and therefore the reliable identification of exit signs. Provided the sign is visible, the distance between the sign and the evacuee is unlikely to be an issue. A sign may not be far away from the evacuee in terms of physical distance but it may be obscured, for example by other objects, scattered ambient light or intermittent smoke clouds. The sign may be not facing the evacuee directly or become less obvious among other brighter objects, for example illuminated advertising or commercial product displays as occur in retail stores. All such unfavourable visibility conditions may cause delay in evacuation particularly when people are in panic.

Improving visibility of an emergency sign even when it is still visible requires a measurement basis that is additional to the current approach of employing a visual threshold solely based upon distance. One such measurement has been proposed in the current study based on perceived image.

PREVIOUS RESEARCH

In meteorology and aviation, visibility is interpreted as the maximum distance over which a target object can be seen. There, the target would be, for example, a distant feature of landscape that is visible in a clear atmosphere and under normal daylight illumination. Whether the target is visible or not is judged by the recognition of its outline that can be distinguished sufficiently clearly against its background. If the target is a tree then the observer must be able to say that it is a tree and not a house. An early attempt at a scientific definition and measurement was reported by Koschmieder in 1924¹. He measured visibility with the contrast between the brightness of the target surface and that of the background. A minimum value of 0.02 was set as the visual threshold, below which the target was assumed to be invisible.

Jin² followed the same route in measuring visibility in a smoke laden environment. He presented a simplified visibility calculation based on conventional wayfinding systems with a normal lighting environment. The formulation revealed the very basic relationship between smoke concentration and the visibility of an illuminated sign according to Lambert-Beer's law. The relative simplicity and limited alternatives have made this a popular choice within the fire protection community. Critics have commented up limitations with respect to addressing the variety of illuminating conditions and viewing directions³. As the interior of buildings become architecturally more elaborate, such issues will be of increasing concern.

A wide range of acceptable levels of visibility have been proposed in the fire protection literature. For occupants familiar with a building, being able to see a distance of 3-5 m may be sufficient. For those less familiar with the building, a distance of up to 25 m has been recommended⁴. In the experiment carried out by Rea, Clark, & Ouellette⁵, there were two visibility criteria being referred: detectability and readability (legibility). They found that greater smoke density is required for detectability threshold in comparison to the readability threshold. Other conclusions drawn by the same authors were that ambient illumination can reduce the visibility of an egress sign and that brighter signs are more visible in smoke. The recent NFPA 130 standard⁶ requires that the smoke level of egress be kept below that point at which a sign internally illuminated at 80 lux is discernable at 30 m and doors and walls are discernible at 10 m. The quantitative definition of ‘discernable’ is however complex.

Recent developments in the CFD simulation of building fires have made it possible to estimate visibility, taking into account a fully three dimensional heterogeneous smoke distribution. One such approach is to determine the spatial distribution of optical density according to the given smoke concentration. The result can be used to estimate local visual distance with the help of Lambert-Beer’s law⁷. For the visibility of signs, walls and doors, Husted etc⁸ carried out integration along the line of sight in their CFD fire simulation. By converting the unit of OD into 10m of visual distance, an estimation of visibility was provided in the predetermined directions at certain heights. More sophisticated methods include those employed by FDS-SmokeView⁹ and some computer graphics packages¹⁰ though these are often aimed at the visual effect of smoke rather than quantitative accuracy.

VISIBILITY BASED UPON PERCEIVED IMAGE

The study presented in the current paper has raised a question on the direct inheritance of the meteorological definition of visibility into fire protection engineering. Although the visual distance of a target is important for the pilot of an airplane but for some one trapped in a building filled with smoke, the important thing is to find the sign for egress. The distance between the person trapped and the sign has little significance. In any building compliant with existing fire regulations, the signs would be distributed at prescribed distances. In such cases, it might be more important to quantify how discernable is the egress sign than the distance from the observer. The current study follows this rationale and defines visibility in terms of the perceived image received by the observer. The measurement of visibility defined in this way is not concerned with environmental factors such as the distance or the media between the target and the receiver (eye, camera etc.) and therefore can be applied in any circumstance.

In order to have an objective measure of visibility as defined above, the current study has employed the concept of a perceived image that is assumed to represent the image perceived by a healthy person. The image is the result of both physical light transport and the physiological perception by the human visual system. A simple model was defined by Zhang¹¹ as:

$$F_{\eta} = h_{rms,\eta} \tilde{\phi}_{\eta} c_{y,\eta} \quad [1]$$

where the subscript η represents a colour channel which may represent colour at a particular wavelength or a spectral bandwidth. For example, in a RGB based system, η can be any one of the R, G or B channels. $h_{rms,\eta}$ is the RMS contrast of the image and $c_{y,\eta}$ is the colour correction constant derived from the luminosity function of human eye. For an image generated with digital camera, the normalised form of the mean brightness (pixel value) would be

$$\tilde{\phi}_\eta = \frac{\beta}{\psi_\eta t_{exp} \Delta D} i_{mean,\eta} \quad [2]$$

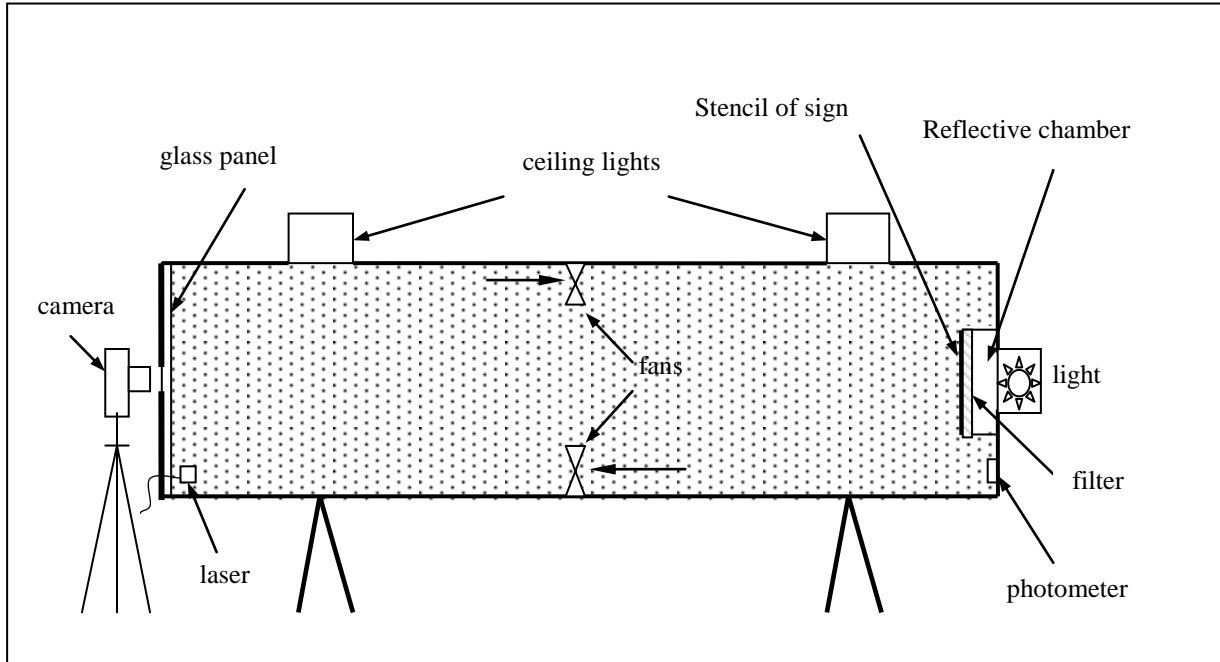


Figure 1 Smoke tunnel

Where $i_{mean,\eta}$ is the mean pixel irradiance for colour channel η of the image and ΔD is the dynamic range of the camera. Typical digital SLR cameras have a dynamic range, ΔD , of 65535 for each colour channel. t_{exp} is the camera exposure and ψ_η is the intensity response function of channel η determined during camera calibration. β is the aperture area ratio of the camera defined by the ratio of the camera aperture stop to a nominal aperture. In the present study, the nominal aperture has been selected as the largest aperture f/5.6 (representing an aperture area of $2.254 \times 10^{-03} \text{m}^2$). Therefore

$$\beta = \left(\frac{a}{5.6} \right)^2 \quad [3]$$

Equation 2 implies that the visibility of an object is proportional to the RMS contrast, the mean brightness of an image as well as the colour sensitivity of the human eye to the image.

SMOKE TUNNEL EXPERIMENT

A series of experiments were carried out to collect data for validation of the concept of image based visibility. The experimental procedure was designed to quantitatively define and measure visibility with digital images under various smoke, luminance and colour conditions. The results were also analysed to see if they assist with our understanding of visibility in smoke. The experimental data will also be compared with results from computer simulation, as described in the following section.

Figure 1 illustrates the smoke tunnel. The tunnel has a length of 4m and cross section of 1m x 1m. Smoke obscuration is simulated with misty smoke produced from an ACME HPLine smoke generator. Two fans are located at opposite diagonals across the middle section of the tunnel to ensure a homogenous smoke distribution. A stencil barcode sign or text is located at the far end of the tunnel and internally illuminated by a LED light source. The light source can be in single or mixed colour of red, green or blue. A laser source and photometer are employed to determine the optical density of the smoke in the tunnel. Environmental lighting is provided by the two ceiling lights centrally mounted in the roof of the tunnel.

A Canon EOS10D SLR camera with Canon EF 100-300mm zoom lens protected by a UV filter was utilised.

Figure 2 presents the spectral response of the camera sensor as measured by a monochromator across the visible spectrum and the response of the camera sensor due to the change of light intensity. The details of the camera calibration procedure are reported in Zhang¹¹. Figure 3 illustrates the spectral distribution of the LED light source, demonstrating the presence of peak intensities at 638, 523 and 463nm for each colour channel.

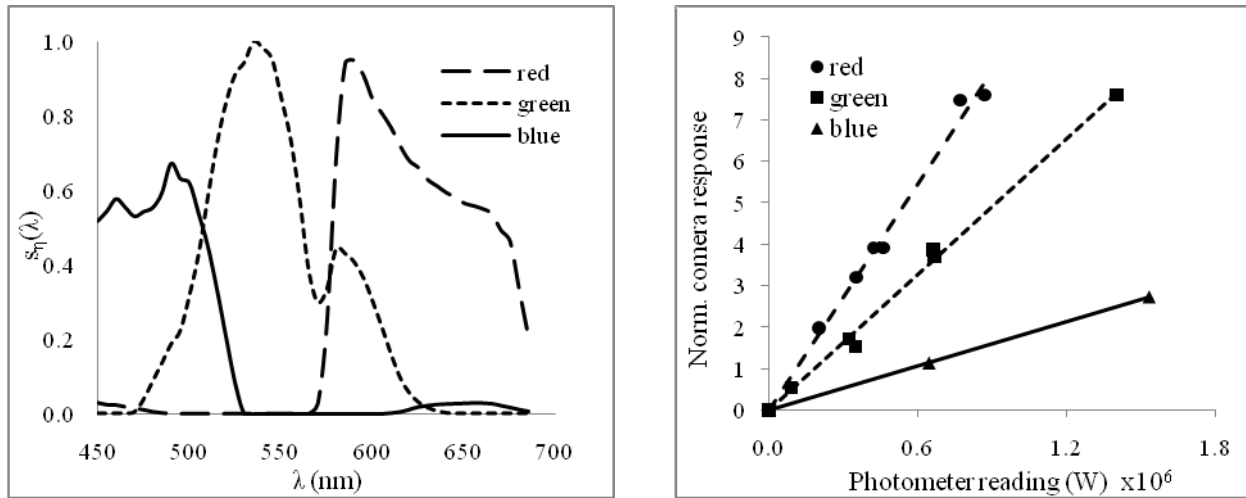


Figure 2 Spectral and intensity response of camera

NUMERICAL MODELLING OF LIGHT TRANSPORT IN FIRE SMOKE

In the most general case, the calculation of visibility in smoke laden environment requires solving the radiative transport equation (RTE) in three dimensional space, given by¹²,

$$\frac{dL_\lambda}{ds} = \vec{s} \cdot \nabla L_\lambda = \sigma_{abs,\lambda} L_{b,\lambda} - \sigma_\lambda L_\lambda + \frac{\sigma_{sca,\lambda}}{4\pi} \int_{\Omega} p_{\omega \rightarrow s,\lambda} L_{\omega,\lambda} d\omega \quad [4]$$

On the RHS of equation 4, the first term represents light emission followed by the light extinction along the line of sight \vec{s} . The last term represents light in-scattering toward \vec{s} . Ω is the full spherical space. It is this term that has differentiated the current approach from previous approaches in visibility simulation.

In the current study, equation 4 has been solved with a hybrid of a Monte Carlo ray tracing (MC) method and zonal method. The MC method resolves the in-scattering term of equation 4 and saves the result in a mesh commonly found in the zonal method. Scattering from smoke particles is assumed to occur isotropically. The mesh can be dynamically adapted to both boundary conditions and the cached scattering. As implemented, the two pass algorithm delivers a high quality of image and is relatively economical in terms of required computational effort.

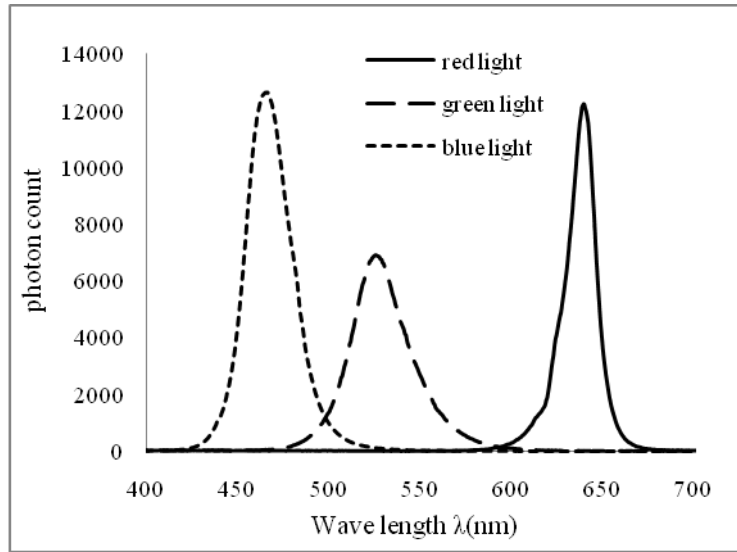


Figure 3 Spectral distribution of the LED light source

In the second pass of the simulation, the final image is generated by launching rays from each pixel of the synthetic image into the domain through a virtual zoom camera, emulating the physical camera as used in the experiment. In a similar manner to the experiment, the image generated from the simulation of radiation transfer must be converted into a perceived image by taking into account the spectral sensitivity of the human eye. The mean brightness of the image takes the following form

$$\tilde{\phi}_\eta = c_\phi \frac{\beta}{\varepsilon_\eta \Delta D} i_{mean,\eta} \quad [5]$$

where ε_η is the energy of a photon at the given wavelength¹². The conversion of $i_{mean,\eta}$ into photon count is necessary to match the physical experimental data defined by equation 2, since the pixel value in a digital photographic image is proportional to the photon count falling on the pixel during exposure¹³. c_ϕ is a proportional constant, taken to be 1.5 in the current study. More details of the simulation model can be found in Zhang¹¹.

COMPARISON OF MODEL PREDICTION WITH EXPERIMENTAL DATA

The results from the simulation have been compared with the experimental data obtained in the smoke tunnel for a variety of target symbols and letters. Figure 4 illustrates the barcode signs employed in the current experiment and simulation. Each barcode has the same height but a different aspect ratio defined as the ratio between the widths of the illuminated section to the opaque section.

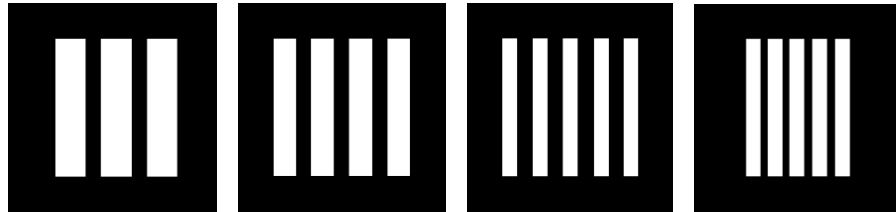


Figure 4 Barcode signs (Aspect ratios 2:1, 1.5:1, 1:1, 0.5:1)

Figure 5 presents a comparison of predicted visibility with measurement for barcodes of aspect ratio 2:1 illuminated with red light. The optical depth τ is defined as

$$\tau = \sigma s \quad [6]$$

where s is the distance between the target sign and the camera. For consistency, the extinction coefficient, σ , was measured with a red laser (635 nm). Figure 6 presents a comparison for barcodes of aspect ratio 1.5:1, illuminated by green light. The extinction coefficient, σ , was determined using a green laser (532 nm) to take into account spectral variation. In both cases the agreement between simulation and experimental data is excellent.

Figure 7 presents a comparison between the predicted and measured visibility for barcodes of aspect ratio 1.5:1, illuminated by green light, in the presence of a ceiling light. In this case the visibility of the target sign has been reduced by scattering from ambient illumination, as demonstrated in both prediction and measurement. Overall agreement is reasonable.

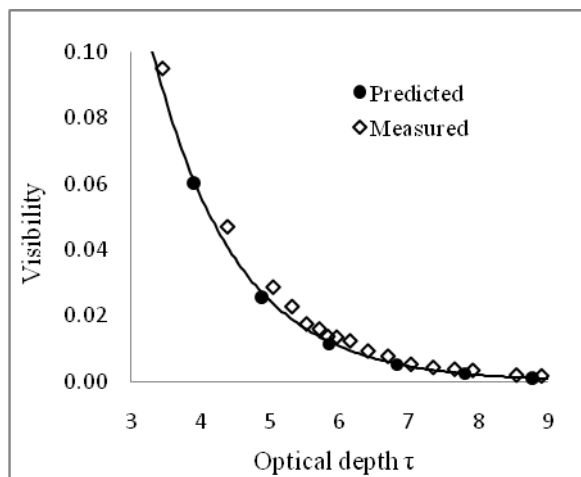


Figure 5 Red barcodes with aspect ratio 2:1

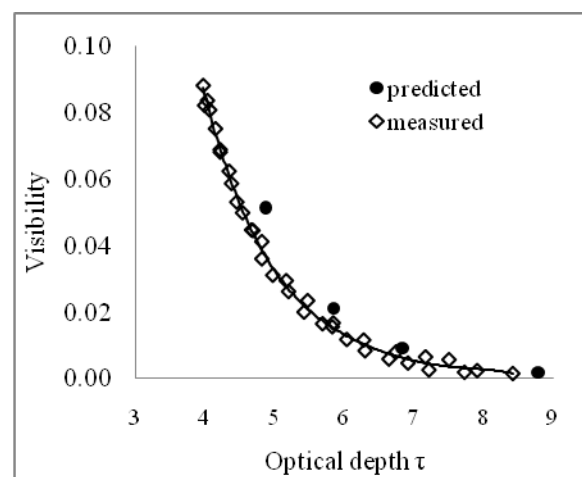


Figure 6 Green barcodes with aspect ratio 1.5:1

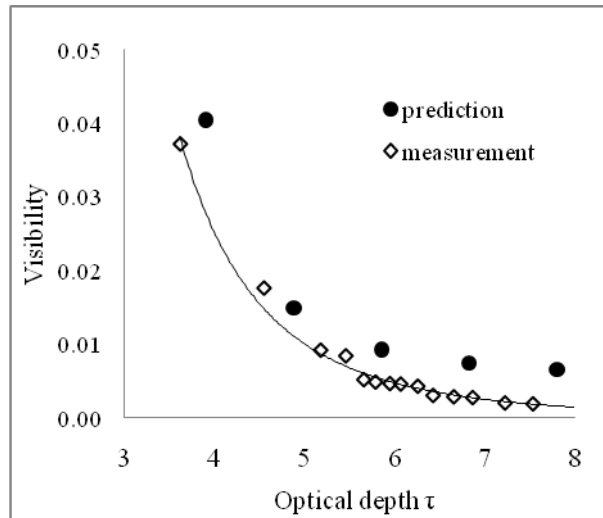


Figure 7 Green barcodes (1.5:1) with ceiling light

SPATIAL REPRESENTATION OF VISIBILITY

Although the image based estimation of visibility in smoke has enhanced our understanding of the phenomena, the simulated images are only for individual points in space and for a specific target. In order to provide a design tool for fire protection engineers, a novel floor map visibility (FMV) is proposed, offering a spatial representation of the overall visibility assessment for a given design. The FMV is represented as common contours at a certain height above floor level (eye level for example) that clearly maps out the regions where visibility is poor. An example of an FMV is shown below in Figure 8.

Figure 8 presents the simulated visibility in a hall with 8 entrances and an open bar area. The plotted plane is at a height of 1.7m above the floor. The fire source is located in the middle of the hall with a heat release rate of 1.0MW. The smoke concentration distribution was obtained from a prior FDS simulation. The figure represents a snapshot in time. The FMV may be considered to represent the probability of a person standing at a point in the room, being able to see any of the exit signs, where in this case one is located above each exit.

In the construction of the FMV, the floor was discretised by a user defined 2D mesh (independent from both CFD mesh and that in the visibility simulation). At each node of the mesh, images from all exit signs were generated at a prescribed height (eye level, 1.7m from the floor) and the most visible sign is selected as the visibility of the node point. The figure demonstrates that close to the fire source the exits are least visible as represented by the dark grey region of the filled contours.

Figure 9 presents contours of smoke concentration for the same case and same height as Figure 8. What is most apparent when comparing Figure 8 to Figure 9 is that the contours of visibility do not resemble the distribution of smoke concentration. For example, in the region close to the middle section of the top or bottom wall, the smoke concentration is relatively low but the visibility is almost as poor as in the vicinity of the fire source. The explanation is that in this region the optical depth for the exit signs on the side

walls or on the opposite wall is large and the viewing angle for the signs on the wall of the same side is also significant. Both conditions lead to poor visibility.

DISCUSSION

The measurement of visibility as utilised in this study is not defined in terms of environmental factors such as the distance or the media between the target and the receiver (eye, camera etc.) and therefore should have more general application.

The traditional measure of visibility, as determined by a threshold of visual distance remains implicit within the current definition. This is demonstrated in Figure 10, which presents the experimentally determined visibility of a barcode of aspect ratio 1.5:1, illuminated by red light with varying intensity. The figure demonstrates how the data converges when the optical depth becomes greater than 7.0. This is in agreement with Jin² who demonstrated in his experiments, that regardless the luminance of the sign and type of smoke, the threshold of optical depth is always about 8.0. The current approach can be considered to have extended the concept of visibility from a single threshold into the entire optical depth range.

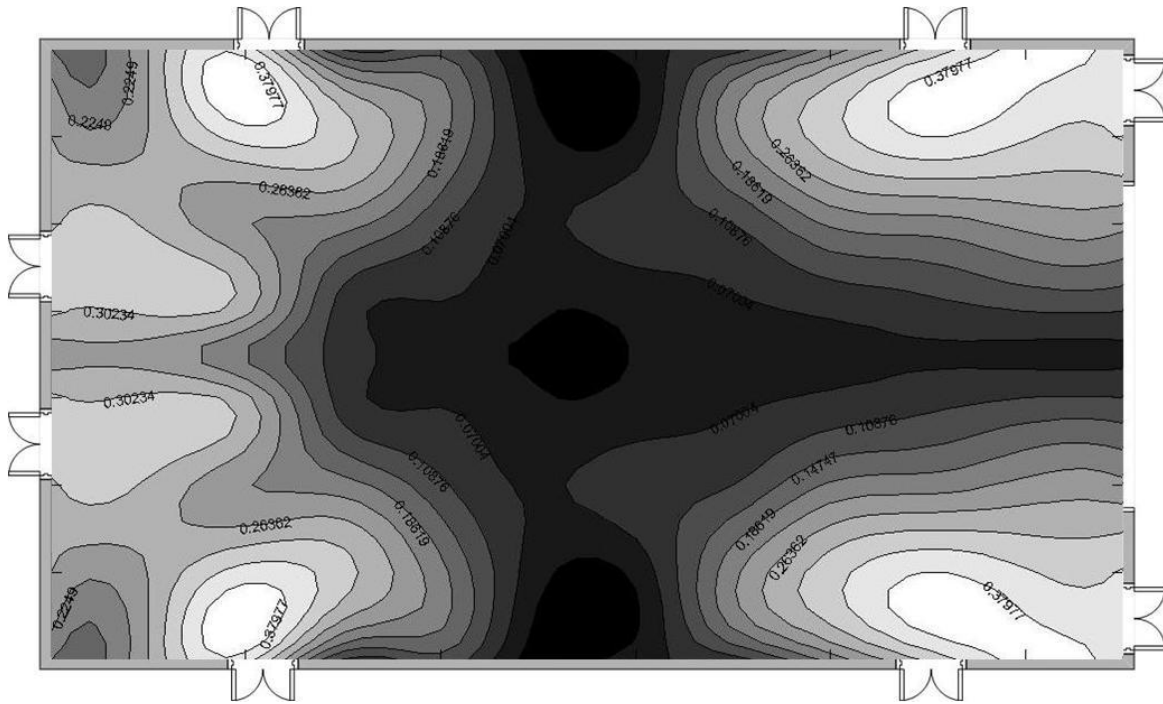


Figure 8 Floor map of visibility (dark grey indicates least visibility)

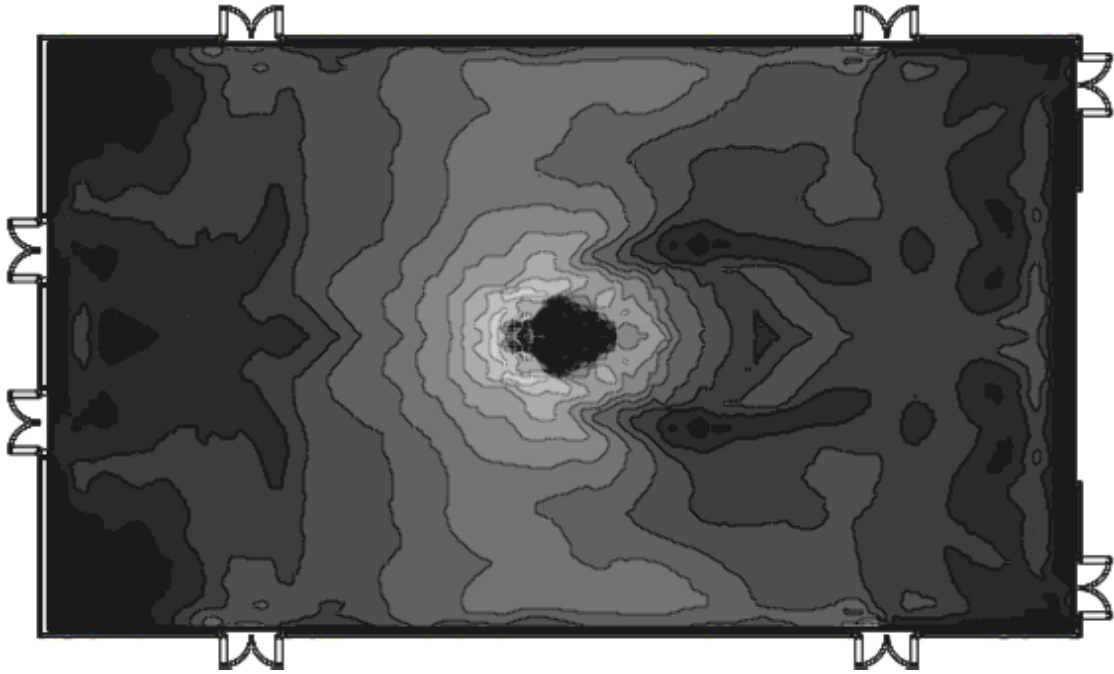


Figure 9 Smoke concentration (dark grey indicates high concentration)

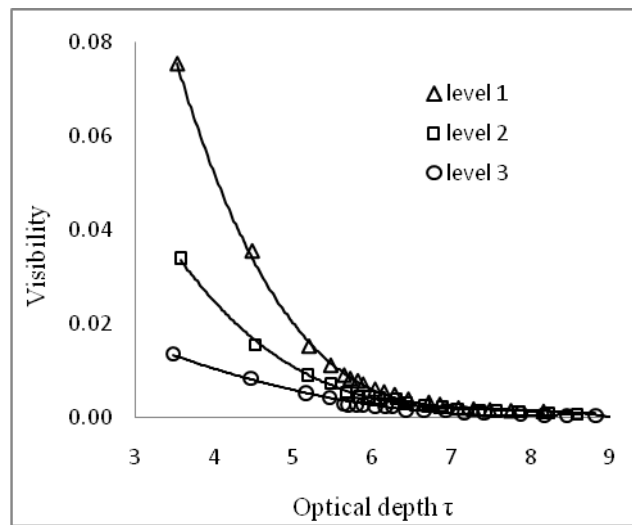


Figure 10 Red barcodes (1.5:1) with different level of luminance

CONCLUSION

The current study has successfully demonstrated the quantitative validation of a numerical model, against experimental data, for the simulation of visibility of illuminated target signs. Some discrepancies between the measurement and prediction remain, most likely due to the assumption of isotropic scattering. Some uncertainties in determining the boundary conditions also contribute to the departure of prediction from experimental data.

The concept of a Floor Map of Visibility is proposed as a useful design tool to assist fire protection engineers with the estimation of overall visibility performance of a design. The Floor Map of Visibility is comprehensive in terms of the information that can be revealed (smoke density, view distance, view angle, optical properties of the sign etc.) and avoids possible misinterpretation of raw smoke concentration or locally determined optical density as a measure of visibility.

During fire evacuation, most people will experience the visibility of egress signage under the sub-critical condition. As a design criteria, the threshold draws the line that should not be exceeded. However, to improve the speed of evacuation, the visibility of egress signage under such condition should be studied and compared.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support of the Engineering and Physical Sciences Research Council in the UK for this project.

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