SIMULATION OF PERCEIVED VISIBILITY IN SMOKE LADEN ENVIORNMENT

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ABSTRACT

An image based computer simulation tool for visibility in smoke (VST) is presented together with the experiment to validate it. The predicted visibility in smoke agrees well with the experimental data under different colour and ambient light conditions. Both the experiment and simulation have shown the significant effect of ambient light on the visibility of an illuminated sign in smoke. The effect of sign colour on its visibility decreases as the optical density of smoke increases. A new concept of floor map of visibility (FMV) is introduced. It offers a simple and concise safety assessment for designer.

INTRODUCTION

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 include those of Jin [1, 2], where the smoke concentration was related to the visibility distance of internally illuminated and reflecting signs. Jin et al. found that in non-irritant smoke, the walking speed of individuals decreased with increasing smoke density, such that with an optical density of $0.5m^{-1}$ the walking speed was decreased by over 75% and individuals behaved as if they were in total darkness. When exposed to irritant smoke this effect occurred at even lower smoke concentrations. Jin also postulated the main reasons for decrease in visibility through smoke as a reduction in light intensity of the sign and background due to the obscuring smoke, and scattered light off smoke particles from other light sources that reach the subject's eye.

Rea, Clark, and Ouellette [3] examined the effects of ambient illumination on visibility in smoke. The later work of Ouellette [4] supported their earlier conclusions confirming that ambient illumination as low as 0.55lx reduced sign visibility in smoke. Their results demonstrated that ambient illumination reduced sign visibility by creating a luminous veil of scattered light from smoke particles. The intensity of scattered light increased with either an increase in smoke concentration or the level of ambient illumination, effectively reducing the readability of a sign. Furthermore they found that on average, signs with white trans-illuminated backgrounds (panel designs) required greater luminance than those with darker backgrounds (stencil designs), consistent with the hypothesis that signs with trans-illuminated backgrounds generate more luminous veil in smoke, hence reducing their own readability.

As part of an extensive study, Collins, Dahir and Madrzykowski [5] studied exit sign visibility in clear and smoke obscured conditions. They assessed some of the characteristics that influence visibility for twelve different internally illuminated convention and electro-luminescent exit signs, including both stencil and panel faced designs. Their results were in general agreement with Ouellette and again demonstrated that sign luminance, and to some extent uniformity and contrast, were important for visibility in smoke.

The previous research works have accumulated considerable knowledge in understanding the visibility in smoke. In the current paper, a computer simulation tool has been built to take the advantage of such knowledge base and serve the fire safety engineers in their verification of design work. Starting from an existing field of smoke concentration, most likely the result of CFD simulation, the software is capable to simulate visibility at each point in space and time taking into account of all the influential factors such as smoke concentration, locations of the target object and the observer, environmental lighting, background illumination and texture.

Experimental work has also been carried out to validate the result of simulation. Visibility under different colours, smoke concentration, forms of target sign and ambient light have been tested. As the output of VST, a Floor Map of Visibility (FMV) is introduced. It extracts concise information from vast amount of numeral and imaginary data and presents it in a more familiar contour map showing the potentially unsafe areas in a structure.

VISIBILITY IN SMOKE

There is no precise definition of visibility in smoke. Past research has suggested that the factors influencing the visibility in smoke are the smoke concentration, the distance between the object and the target, the brightness of the target and the ambient lighting condition [6]. Optical density has been used in most of the works mentioned in the last section as a measure of visibility. It has addressed the first two influential factors but not the rest.

Contrast is another measure of visibility in the work of Jin [2] and others such as Sychta [7]. In smoke related visibility study, contrast is often defined as a ratio in the following form

$$contrast = \frac{Luminance\ difference}{Nominal\ luminance} \qquad [1]$$

Different definition of contrast defines different luminance difference and nominal luminance. For example, Webber contrast is expressed as [8]

$$C = \frac{L_T - L_B}{L_B} \qquad [2]$$

where L_T is the luminance of the target and L_B is the luminance of the background. In the Underwriters Laboratory UL924(1989) standard, the contrast of a sign has been defined as [5]

$$C = \frac{L_g - L_l}{L_g} \qquad [3]$$

where L_g and L_l represent the luminance of either the target or its back ground. L_g is the greater of the two and L_l is the lesser of them.

Existing definitions of contrast are based on the luminance of the sources. When the space between the source and the observer is filled with smoke, the contrast received by the observer might be very different and change with time and location (not simply distance). In the current paper, a definition of contrast based on the image of the sign at the position of an observer and at the time of observation is proposed as

$$C = \frac{\Delta L(t,\vec{x})}{L_{mean}(t,\vec{x})} \qquad [4]$$

In equation $C = \frac{\Delta L(t,\vec{x})}{L_{mean}(t,\vec{x})}$[4], ΔL is the standard deviation and L_{mean} is the mean valu

COMPUTER MODEL

In computer simulation of fire safety, there are two categories of model: the physical model and the model of human behaviour. The physical model includes structure/lighting model (CAD model) and fire/smoke model (CFD model). It provides the virtual fire scenario. The human behaviour model simulates the response of people to the scenario. In linking the two models, there should be a third model – the model of human perception. Generally, it can be classified into the human behaviour model. . Generally, researchers intend to treat it as a model of the second class. In this paper, it is singled out from the modelling chain as depicted in

Figure 1. Among other environment properties that a person may sense in a fire/smoke situation, only

the visual perception – visibility is dealt here.

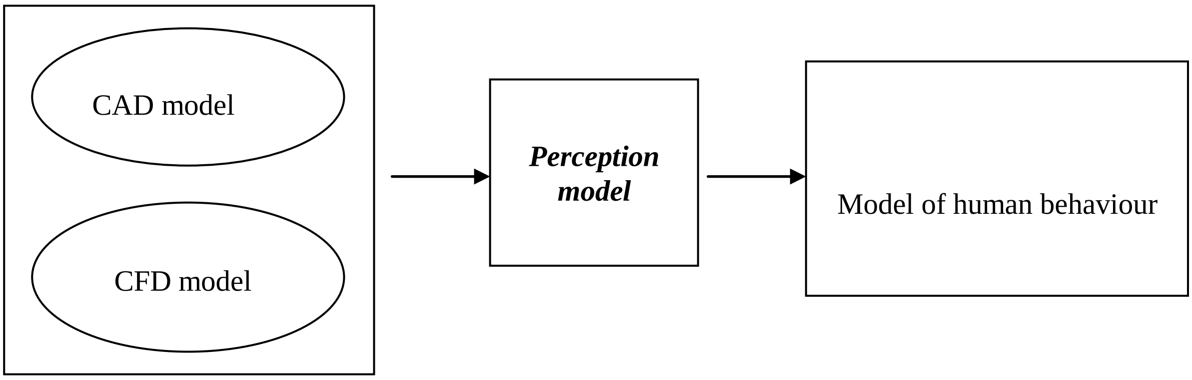


Figure 1

At this stage of work, the human visual perception is modelled as the image of the scenario at the point of observation. In experiment, the image is taken with a commercial SLR digital camera. In numerical simulation, the synthetic image is created by solving the transport equation of radiation [9]

$$\frac{dL_\omega}{ds} = \vec{\omega} \cdot \nabla L_\omega = \alpha_{abs}\left(L_{emit,\omega} - L_\omega\right) + \frac{\alpha_{sca}}{4\pi}\int_{4\pi} p_{\theta\to\omega} L_\theta d\theta \qquad [5]$$

Radiance L_ω in the above equation is defined as the radiant energy transferred per unit time, solid angle, spectral variable and area normal to the direction $\vec{\omega}$ of path s. α_{abs} and α_{sca} are the absorption and scattering coefficient of the smoke respectively. The phase function p_θ describes the local contribution of the scattered light from irradiance L_θ in the $\vec{\omega}$ direction. $L_{emit,\omega}$ represents light emission in case that the light passes through a region of fire. Otherwise, its value would be zero.

The last term in equation [5] accounts for the effect of ambient light. Previous research in fire safety was mainly concerned with the light attenuation along the line of sight. The effect of ambient light has been either ignored or included empirically as correction to the visibility curve in experiment [10]. It has been seen in the current study that this term is computationally expensive but ignoring it may leads to significant error. As the first approach, light scattering by the smoke has been considered to be isotropic. Under this assumption, $p_{\theta\to\omega} = 1.0$.

Smoke distribution has been simulated using FDS from NIST [11]. Although the result of simulation can be visualised with its post processor SmokeView (SMV), it only simulates the opaqueness of smoke through the line of sight. There is no estimation of the visibility through smoke layer [12]. By solving equation [5], particularly its last term, the current model has taken the effect of global illumination into account.

On the boundaries, surface radiance is calculated by

$$L_\omega = L_{emt,\omega} + \int_\Omega f_{\theta\to\omega} L_{irr,\theta} d\theta \qquad [6]$$

where the subscript ω refers to the direction of observation, $L_{emt,\omega}$ is the radiance of emission from the surface in the direction of ω. $L_{irr,\theta}$ is the irradiance in the direction of θ and $f_{\theta\to\omega}$ is the bidirectional reflectance distribution function (BRDF) between the incident and reflective direction. **Ω** is the hemisphere in front of the surface. For Lambertian surface, $f_{\theta\to\omega}$ is expressed as

$$f_{\theta\to\omega} = \frac{\rho}{\pi} \qquad [7]$$

where ρ is the reflectivity of the surface.

Equation [5] and [6] are solved iteratively using a hybrid algorithm of radiosity and Monte Carlo ray tracing. Details of the algorithm will be given in later publication [13].

The model has been compiled into the VST and will be freely available in 2010.

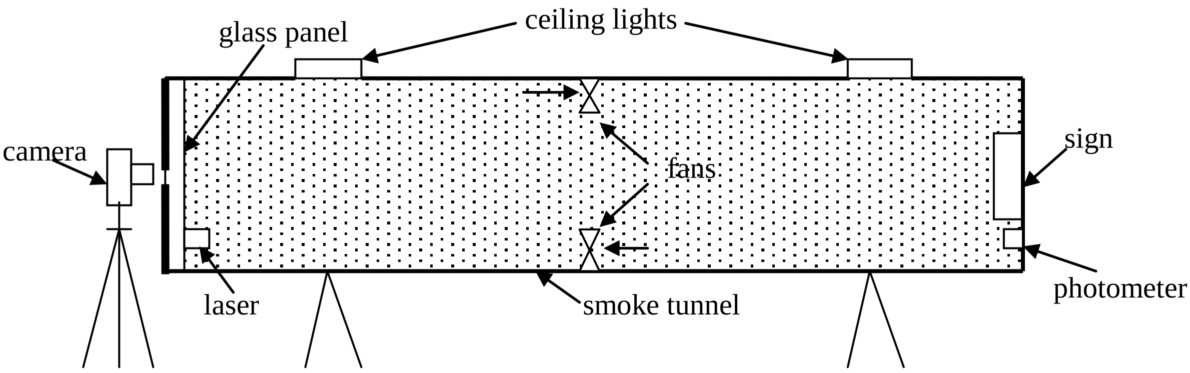


Figure 2

EXPERIMENT

The experiment of visibility in smoke tunnel has been carried out in parallel to the development of VST. The tunnel is 4.0m long with square cross section of 1.0 x 1.0m^2. The internally illuminated sign is put at one end and a digital SLR camera is put at the opposite end of the tunnel as depicted in Figure 2. The tunnel is filled with non-combustible smoke (glycol) from commercial smoke generator. The two fans fixed in the middle of the tunnel blow in the opposite directions to keep homogenous smoke distribution. The extinction coefficient of the smoke is measured by the laser and photometer pair. Images were taken with a Canon EOS 10D digital camera fitted with ϕ58mm zoom lens (100-300mm). The camera has been calibrated with a monochrometer. Figure 3 shows the calibration curve of the camera.

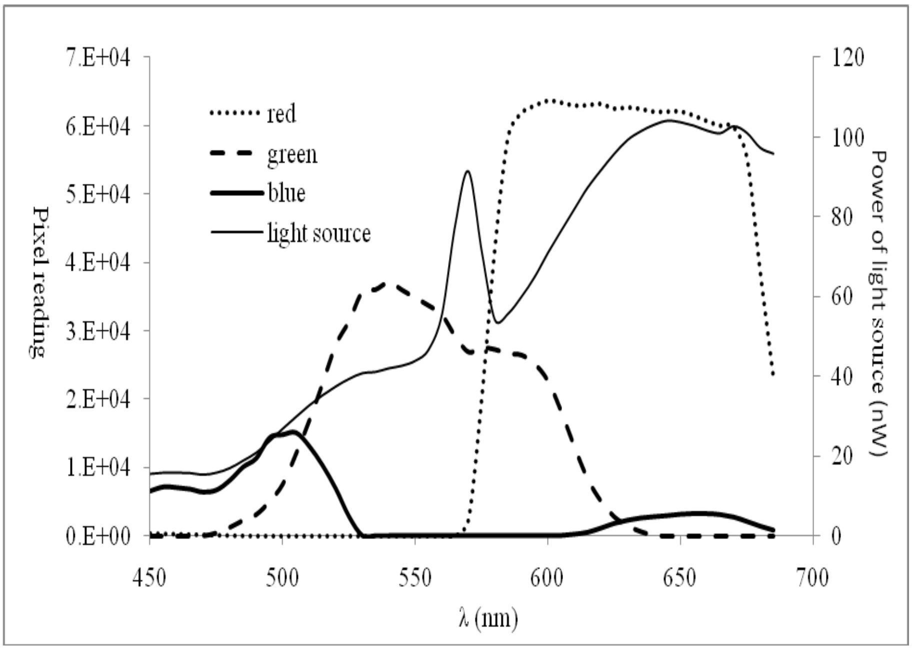


Figure 3

The sign is internally illuminated with 12W LED stage light. 2 lays of 4mm Perspex sheet are placed in front of the LED light to achieve uniformity of its output. A single Perspex sheet is placed in front of the ceiling LED light for the same purpose.

A number of stencil masks have been used to create different forms of sign. Three of them are shown in Figure 4. More details of the experiment procedure can be found in [13].

Figure 4

CAMERA MODEL

Modern digital camera is the best equipment in recording human visual perception of the environment. The recorded image can be stored, transferred, copied and presented without any modification to the original. Camera manufactures have made great effort to model the functionality of human eyes such as the photometric effect. In the current study, digital camera has been used in the experiment and modeled in the numerical simulation in place of human eyes. The result is subject to correction whenever differences appear.

In order to create the synthetic images comparable to the photo images from the camera. It is important to have a numerical model (virtual camera) that accurately reflects the characteristics of the physical camera.

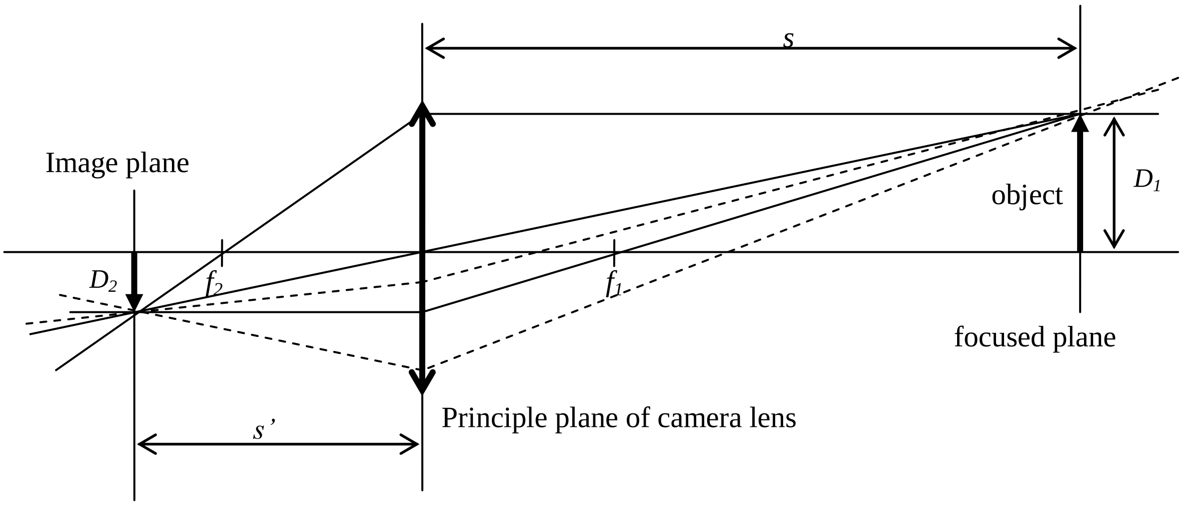


Figure 5

The camera model used in the current study is described by the following set of equations

$$\begin{cases} s + s' = S \\ \frac{s'}{s} = \frac{D_2}{D_1} \\ \frac{1}{s'} + \frac{1}{s} = \frac{1}{f} \end{cases} \qquad [8]$$

where f is the focal length of the camera and the rest symbols are explained in Figure 5.

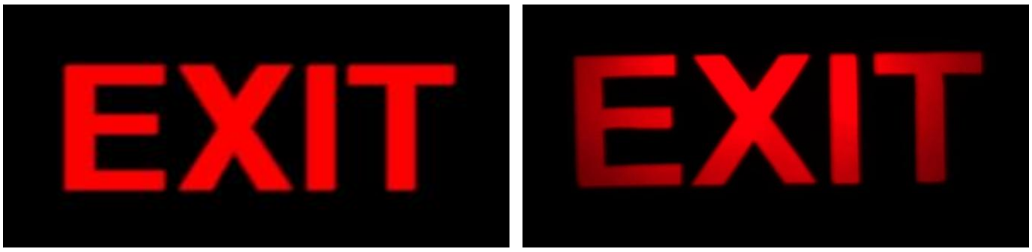
In the left column of Figure 6 are the synthetic images generated from the virtual camera. On the right hand side of each image is the photo taken with the physical camera. Each pair has exactly the same camera settings. Details of the camera model and its implementation are given in (13).

HUMAN VISIBILITY TEST

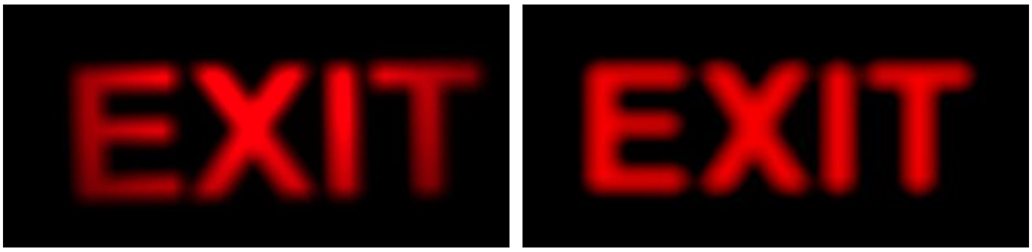
Human eyes and camera are definitely different. One significant difference encountered during the current study is the sensitivity to contrast. When the contrast of an image becomes unrecognizable to human eyes, it can still be detected in the photo of a camera. Simple human visibility test has been conducted with 6 people. All of them are the colleagues of the authors. Among them, two are directly involved with the experiment. The “point of disappearance” (POD) was the parameter being tested. The recorded POD is the optical density above it the sign would become invisible to the human eyes. Later the POD is converted to corresponding value of contrast. The POD value of contrast has been found to be around 0.2 (±0.04). In the following sections, the invisible region of contrast is masked in grey. Without ambient light, the grey area covers the region of optical density close to $1.0m^{-1}$ that is consistent with the study of Webber and Aizlewood [14].

RESULTS AND COMPARISON

Figure 7 shows the relation between contrast and optical density for the red square sign in Figure 4. It can be seen that the contrast of the sign almost linearly diminishes with the increase of optical density. Such relation is not generally true for other form of sign as demonstrated in Figure 8 that shows the same relation for the red barcode sign. The contrast value of the barcode is generally higher than that of the square sign and varies as a quadratic function of optical density.



Focused plane is 4.2m from the lens (in focus)



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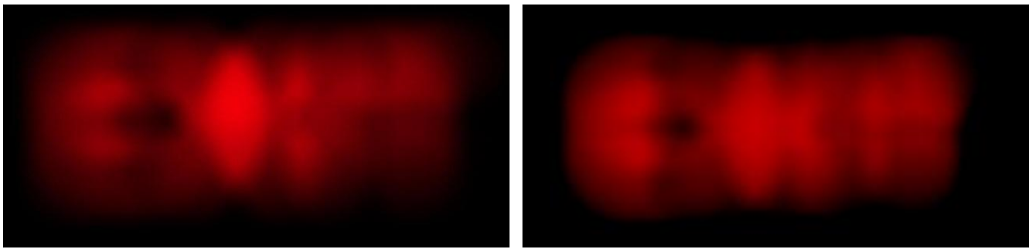

Focused plane is 10.0m from the lens (out of focus)

Figure 6

In terms of the colour of emergency sign, safety engineers in Europe have different opinion from their

American colleagues. The argument is both physical and psychological. In the current study, the difference in terms of perceived contrast of images is presented as part of the physical evidence. Figure 9 shows the comparison of the measured contrast between red and green barcode signs. With low optical density of smoke, the contrast of red sign is superior comparing to the green sign but difference decreases significantly as the optical density of the smoke increases.

EFFECT OF AMBIENT LIGHT

The existence of ambient lights may reduce the visibility of an emergency sign. The traditional estimation of visibility based on the line of sight can't accurately quantify the effect of ambient lights. The current model solves equation [5] in the way that both local and global energy are balanced. At least in principle, all ambient lights would be fully accounted for.

In Figure 2, there are two LED lights on the ceiling of the smoke tunnel. One light is near the sign and the other is near the camera. In the current experiment, it has been found that the light near the camera is more effective in reducing the visibility of the sign than the one close to the sign.

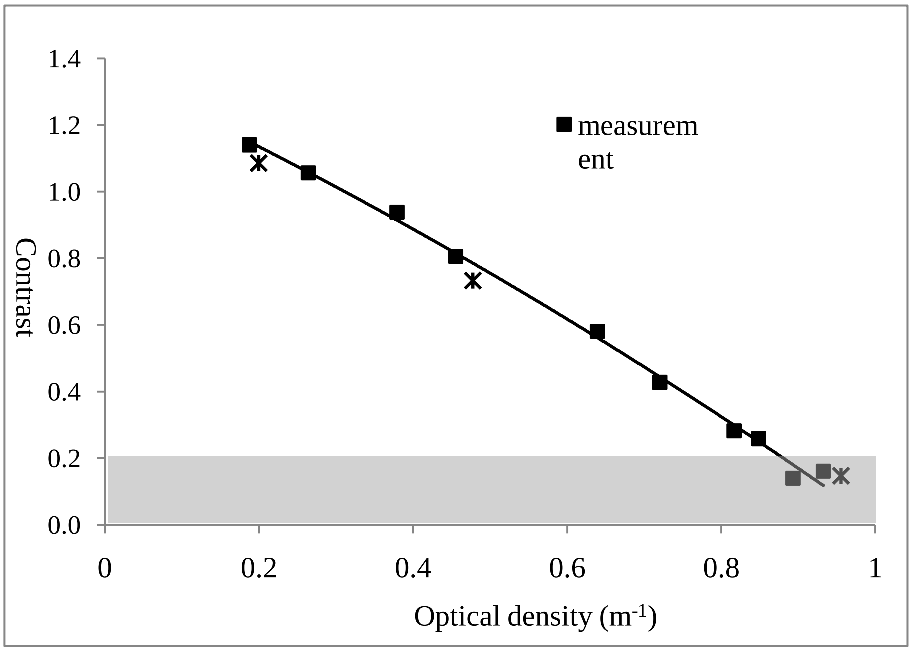

Figure 7

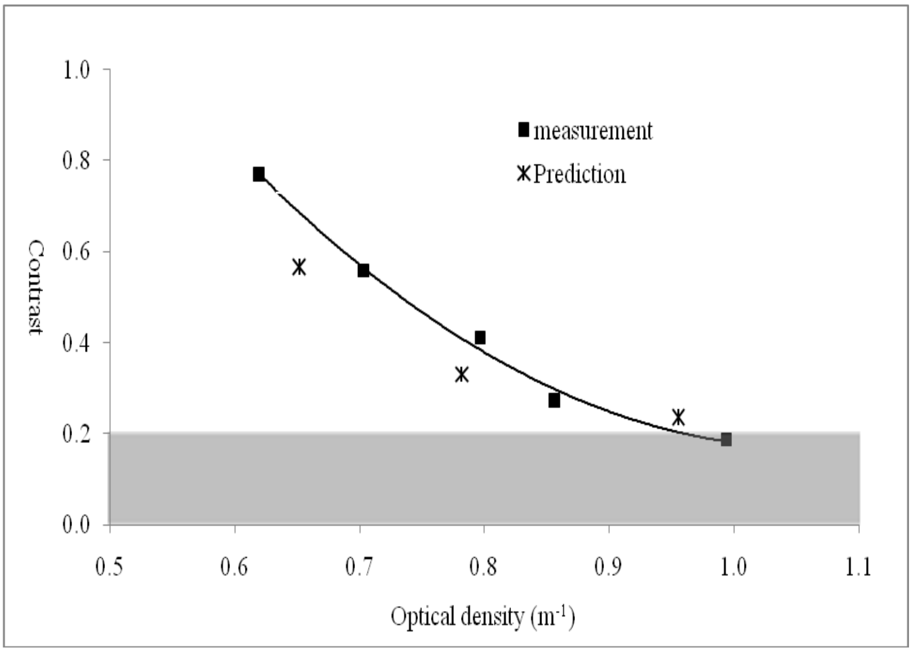

Figure 8

Figure 10 shows the image contrast of the barcode sign with and without red ceiling light close to the camera. Figure 11 shows the same effect for different colour. The dashed lines represent the same functions as the solid lines but under the influence of ambient light. In each case the sign and the ambient lights are in the same colour (red-red, green-green). It can be seen that the effect of ceiling light is much more significant than the colour of the sign.

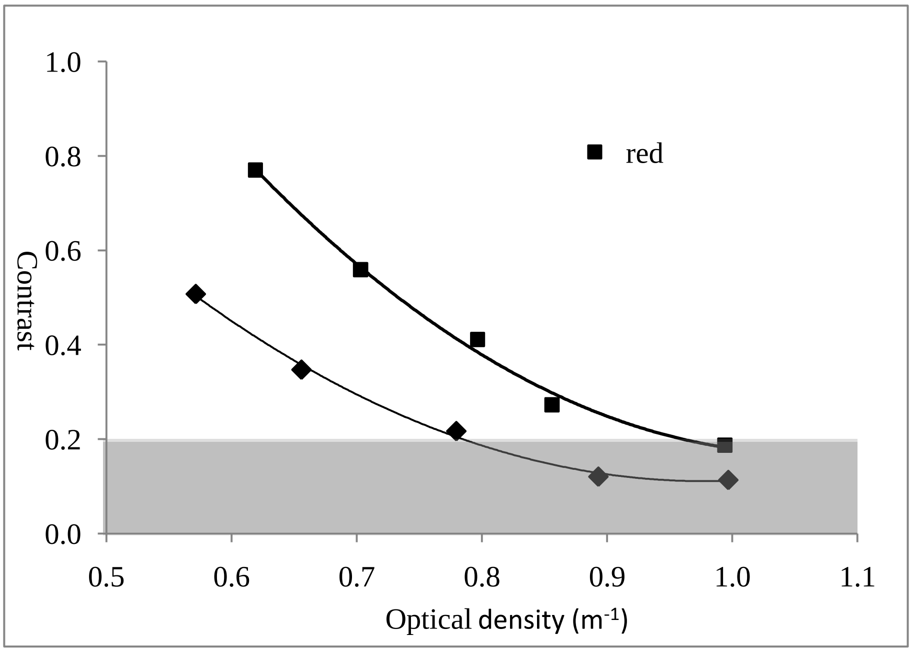

Figure 9

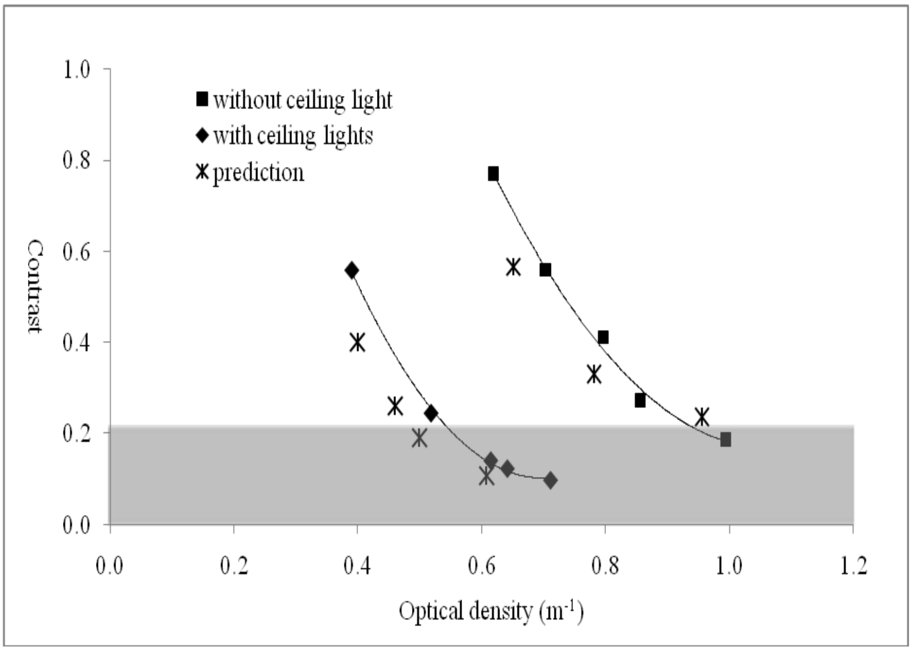

Figure 10

FLOOR MAP OF VISIBILITY

In the previous section, VST has been used to estimate the local visibility at a particular location and in a fixed direction. In fire safety engineering, it would be more useful to have a global and concise picture of visibility for a structure design under smoke condition. In this paper, a floor map of visibility (FMV) is proposed for such purpose.

FMV is defined as a snapshot of two dimensional contour at certain vertical level (eye level) that maps out the probability of wayfinding at each location in a structure. The probability is the maximum visibility of all emergency signs that are visible at the given location. The visibility is measured by the synthetic images generated from the VST. To demonstrate the concept, a hypothetical fire scenario is presented here.

The fire started in the center of a dancing hall. The dimension of the hall is 55x35x5 m^3. There are two doors on each side of the hall. Above each door there is an internally illuminated emergency exit sign. The fire size is 1MW. Figure 12 shows the floor plan of the hall and fire site.

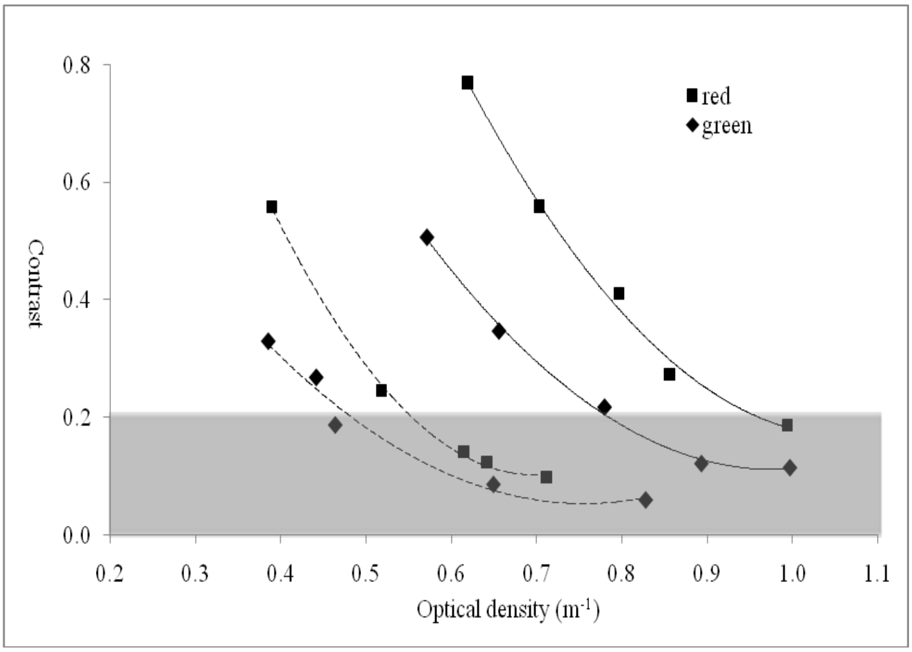

Figure 11

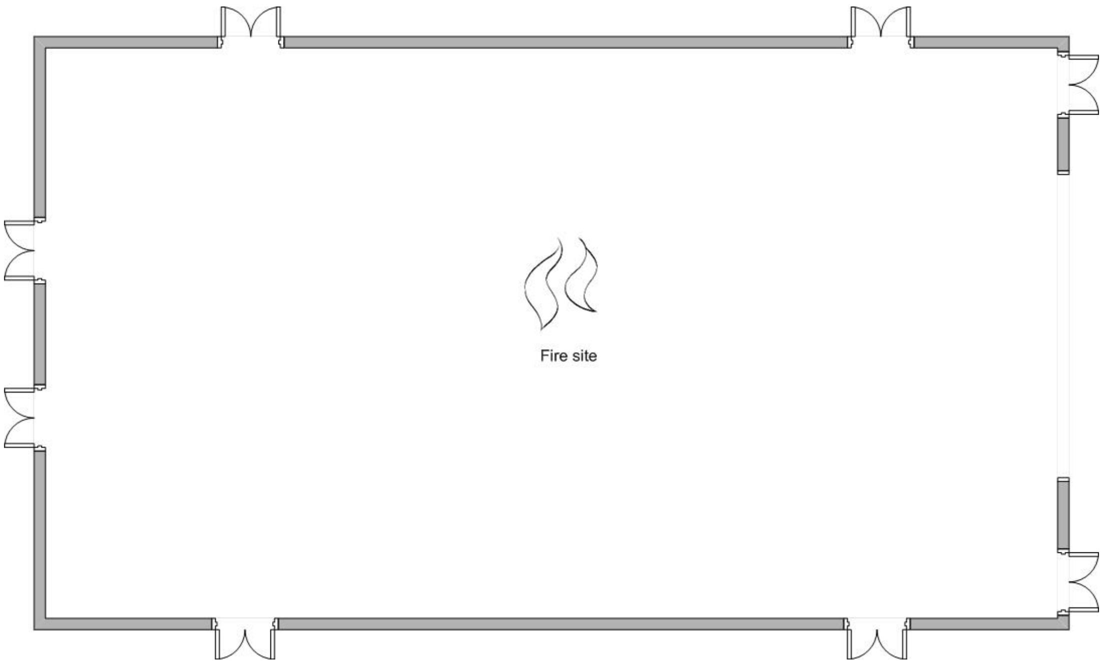

Figure 12

The smoke distribution in the hall had been simulated with FDS. The floor is divided by a 12x8 mesh. 10minutes after the start of fire, images are created at each nodal point of the mesh at average eye level (1.7m from the floor). Figure 13 show the created FMV. The visibility ranges from very good in the white regions to very poor in the dark gray regions. The black area in the center of the map is the fire site. Close to the fire site, the visibility is less than 0.1. It is almost certain that no sign of exit would be visible in this area. There are other two dark gray areas near the top and the bottom of the map. In such area, people are too far (in terms of optical density) from the doors on the left, right and opposite side and the view angle is too large for the nearest doors on the same side.

CONCLUSION

The current paper presents the Visibility Simulation Tool (VST) and the experimental work in validating it. The general agreement between the simulation and the experimental data is quite plausible. Apart from validating the simulation results, the experiment itself has offered interesting output. The difference in visibility of green and red sign decreases as the smoke becomes thicker; the visibility of barcode with large distance between the bars is generally better than that of bulky square; among all the conditions tested, ambient light is the most influential factor to be considered when it is close to the observer. The capability of producing the floor map of visibility (FMV) would be proven useful for the design engineers. It offers a concise picture of the overall safety level of the design in terms of the probability of wayfinding.

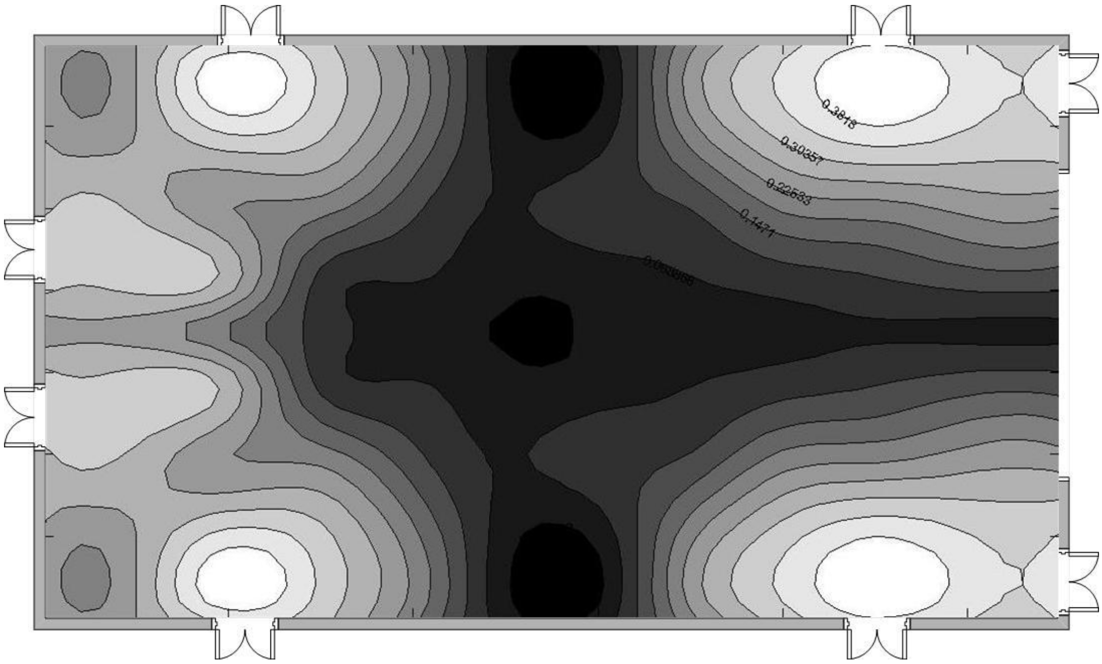

Figure 13

ACKNOWLEDGEMENT

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