Signage Legibility Distances as a Function of Observation Angle

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ABSTRACT: Signage systems are widely used in buildings to provide information for wayfinding, thereby assisting in navigation during normal circulation of pedestrians and, more importantly, exiting information during emergencies. An important consideration in determining the effectiveness of signs is establishing the region from which the sign is visible to occupants, the so-called visibility catchment area (VCA). This study attempts to factor into the determination of the VCA of signs, the observation angle of the observer. In building regulations, it is implicitly assumed that the VCA is independent of the observation angle. A theoretical model is developed to explain the relationship between the VCA and observation angle and experimental trials are performed in order to assess the validity of this model. The experimental findings demonstrate a consistency with the theoretical model. Given this result, the functionality of a comprehensive evacuation model is extended in accordance with the assumptions on which the theoretical model is based and is then demonstrated using several examples.

KEY WORDS: signage, visibility, evacuation, evacuation simulation, evacuation model.

INTRODUCTION

SIGNAGE WITHIN COMPLEX building spaces is intended to provide occupants with information relating to wayfinding. A successful signage system can reduce the apparent complexity of an enclosure, thereby improving wayfinding under both general circulation and emergency conditions. While inefficient signage may contribute to loss of commercial earnings in general circulation situations, there are more serious

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consequences in emergency situations. It has been known for many years [1,2] that in emergency situations occupant unfamiliarity with exit routes can contribute significantly to resulting casualties [3–7].

While a number of physical and psychological factors influence the effectiveness of the wayfinding signage systems, such as, level of lighting, the presence of smoke, visual noise created by other (commercial) signs, and the ability of occupants to correctly interpret the sign, first and foremost, the sign must be physically visible to the occupants. To ensure reliable recognition and comprehension of signage information, safety signs are required to conform to certain design criteria specified in various national and international standards and guideline documents.

These documents usually contain basic requirements relating to the size of the sign, the size of the premises, and the intended use of premises [8,9]. As an example, consider the NFPA Life Safety Code Handbook [8]. This suggests that reflective signs that have a lettering height of 152 mm are legible for up to a distance of 30 m [8]. To extend the visibility of a sign the letter height can be increased, with a linear relationship existing between lettering height and visibility distance. These design criteria are generally based on the data collected from standard eyesight tests, which involve participants viewing a sign of a given size at an observation angle of zero degrees (i.e., the sign is viewed straight on). This enables the determination of maximum viewing distances as a function of the letter height. However, in reality, occupants may approach a sign from a multitude of angles (i.e., non zero observation angles), which in turn will influence the ability of the individual to resolve the sign. This influence on sign legibility has been virtually ignored to date.

Evacuation and pedestrian circulation models [10] have also generally ignored the interaction of occupants with the wayfinding system; the implicit assumption in most of these techniques is that the occupants ‘know’ the route. While this may be appropriate in many situations, it is clearly a simplification of the reality. In order to produce realistic representation of evacuation and circulation in arbitrarily complex structures, it is necessary to represent the interaction between the occupants and signage systems.

Recently the representation of the interaction between modeled agents and signage systems has been introduced into the buildingEXODUS evacuation model through the concept of the visibility catchment area (VCA) [12,13]. The VCA of a sign is defined as the region where it is physically possible to visually receive and discern information from the sign. Within this model, the maximum viewing distance or the VCA termination distance, is currently arbitrarily set as the distance specified in regulations [8].

In this article, through theoretical analysis and experimentation, the relationship between sign size, observation angle, and maximum viewing distance is examined. Through such a study, new maximum viewing distances as a function of observation angle are established. These results are then incorporated within the VCA concept and several demonstration applications of the new model are presented.

The main concern here is determining the maximum viewing distance from which the text on a sign is legible. This distance is intended to represent the maximum distance from which the information conveyed by the sign could be interpreted by an observer. It is important to note that this work does not include recognition of signage pictograms. While not proven, it may be expected that recognition of pictograms can occur at greater distances than the legibility distance of text. If this is the case, then the legibility distance represents a conservative or lower limit of the maximum recognition distance.

THE EVACUATION MODEL

The core software used for demonstration purposes is an evacuation model, buildingEXODUS V4.0, which takes into consideration people–people, people–fire, and people–structure interactions. The basis of the model has frequently been discussed in other publications [14–18] and so it is described only briefly here. The model tracks the trajectory of each individual as they make their way out of the enclosure, or are overcome by fire hazards such as heat, smoke, and toxic gases. The behavior and movement of each individual are determined by a set of heuristics or rules. For additional flexibility these rules have been categorized into five modules, the OCCUPANT, MOVEMENT, BEHAVIOUR, TOXICITY, and HAZARD submodels that operate on a region of space defined by the GEOMETRY of the enclosure. These five submodels work interactively to simulate the evacuation and movement of a population specified within structures.

VCA Concept

buildingEXODUS V4.0 currently includes a method of representing the visibility of a particular object through the application of the VCA concept [13]. The VCA of an object is defined as the region of space from where it is possible to visually receive information from that object; i.e., from where the object can be seen. The VCA of a sign attempts to address only the physical aspects of visibility, leaving the psychological and physiological aspects of sign recognition to the behavior component of the model.

The algorithm uses a line of sight search method to determine the locations within the geometry that have visual access to the sign. Geometrically, the VCA of a sign is assumed to correspond to the visibility polygon [19] spanning outwards from a point. The calculation of the VCA considers the location of the sign, the size of the lettering on the sign, its height above the floor, the position and size of any obstructions, and the observer height.

In complex spaces the height of the observer will have an impact in determining the extent of the VCA. For simplicity the algorithm used to determine the VCA makes use of the central point of the lower edge of the sign and a point in space at a height equal to that of the average occupant, which is a user defined parameter. In this work the default average occupant height is arbitrarily taken as 1.75 m. The rationale for using the center point of the sign base is simply because, if this point can be seen it is likely that the entire sign will be seen, at least for 'small' signs. For very large signs, it is possible that while the center point of the base may be visible, part of the top of the sign may be obscured. In the current implementation, the actual physical size of the sign is not considered. However, the physical size of the sign is taken into consideration when determining the terminating distance of the VCA. The extent of the VCA is terminated at a distance suggested by local building codes and is dependent on the size of the sign and the nature of the sign illumination [11,12].

Another feature which will influence the size and shape of the VCA is the observation angle. The observation angle is defined as the angle subtended by the observers line of sight to a normal line bisecting the surface of the sign. An observation angle of 0° means that the observer is viewing the sign striaght on. There will be a maximum observation angle beyond which it will no longer be possible to resolve the sign and hence it will not be possible to detect the sign. Due to the lack of data, in the current implementation [13], the extent to which the observation angle of the viewer impacts the shape of the VCA is arbitrarily set to 85°. (For full details relating to the VCA calculation, refer to reference [13].)

A Theoretical Representation for the Angular Extent of the VCA

In the previous section, the method of representing the VCA of a sign implemented within the software was described. However, this method only approximates the VCA due to the assumption that the level of visibility afforded to the individual viewing a sign (i.e., the maximum distance from which a sign can be seen) was independent of the observation angle. This was primarily imposed on the approach due to the lack of reliable data linking the observation angle with the maximum viewing distance.

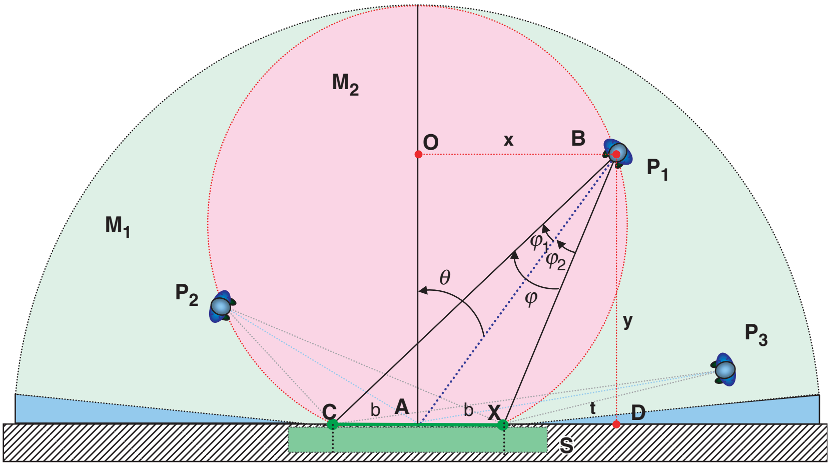


Figure 1. The geometric relationship between the observer and the sign. (The color version of this figure is available online.)

Using this approach, the VCA for a sign would include a region of space defined by a near semicircle, with a center point located at the center of the sign and a radius determined by the maximum viewing distance as defined by regulation. This region is represented in Figure 1 by the dashed semicircular line.

It was suggested in [13] that the size and shape of the VCA is further influenced by the ability of a viewer to resolve the angular separation of the sign. This is defined as the apparent angular separation of the ends of the sign as measured by a distant observer (i.e., angle φ in Figure 1). The angular separation of the sign is dependent on the size of the sign (or more correctly the size of the letters on the sign), the distance of the observer from the center of the sign, and the observation angle. The observation angle is defined as the angle subtended by the observers line of sight to a normal line bisecting the surface of the sign (i.e., θ in Figure 1). An observation angle of 90° (i.e., viewing the sign side on) results in an angular separation (φ) of 0°, effectively making the sign invisible to the observer, while an observation angle of 0° (i.e., viewing the sign straight on) provides the maximum angular separation.

Clearly, there will be a minimum angular separation (φ_{min}) beyond which it will no longer be possible to resolve the sign and hence there will be a maximum observation angle beyond which it will be impossible to detect the sign. In this work, the minimum angular separation (φ_{min}) which can be resolved by the human eye is taken as a constant. For a sign of fixed size with an observer at a fixed distance from the center of the sign, as the observation angle (θ) increases, the angular separation (φ) of the sign decreases until a maximum observation angle is reached beyond which it is no longer possible to resolve the angular separation of the sign (i.e., $\varphi < \varphi_{\min}$). Thus, for a sign of given sign size, in order to resolve the angular separation of the sign, as the observation angle increases, the maximum viewing distance must decrease. Similarly, for a given viewing distance there will be a maximum observation angle beyond which the sign cannot be resolved. As the size of the sign increases, both the maximum viewing distance and the maximum observation angle increases.

For an observer to be able to resolve a sign (i.e. make out the individual elements in the sign) at the maximum observation distance, the observation angle should be such that the angular separation of the individual elements making up the sign are greater than or equal to $\varphi_{\min}$.

To estimate $\varphi_{\min}$, assume a maximum viewing distance for viewing signs with an observation angle of 0° (i.e., straight on) to be as specified in the NFPA Life Safety Code Handbook. For signs with lettering of 152 mm height, the maximum viewing distance is 30 m. This produces a $\varphi_{\min}$ of 0.29°.

Thus, in order to resolve the information on a sign at the maximum viewing distance, the observation angle should be such that the angular separation of the elements in the sign is greater than or equal to $\varphi_{\min}$ or 0.29°. This problem can be described geometrically by considering the relative positions of the observer, the sign, and the observation angle. Depicted in Figure 1 are the positions of a sign S and observer P_1. Angle φ represents the angular separation of an element of the sign S from the observer P_1. In order for the observer to be able to read the lettering on the sign the distance from the sign must be such that the angle φ is greater than or equal to $\varphi_{\min}$ or 0.29°. Thus, as the observation angle increases, the maximum distance AB must decrease in order to maintain the angular separation of the sign to $\varphi_{\min}$. By determining the length of the line AB within the constraints of the angular resolution of the eye the visibility catchment area of the sign can be defined.

The most efficient method of determining whether the sign is visible from a particular location within the geometry, given the considerations described above, would be to determine the geometrical shape that is formed by the maximum viewable distance from the sign. In the proceeding section, the geometrical considerations previously discussed are examined in order to determine the nature of the VCA. Considering the configuration of Figure 1, the known variables are listed in Table 1.

The points A, C, and X in Figure 1 have the following coordinates: $A = P(0, 0)$, $C = P(-b, 0)$, and $X = P(b, 0)$, where $P(x, y)$ represents the point x, y. As the line segment AB has to be determined, the point $B = P(x, y)$ is an unknown. Considering the equation of a line $(y_0 - y_1) = m(x_0 - x_1)$,

Table 1. Variables used during formulation.

Known values	Description
Φ	Angular separation of the sign; $\varphi=\varphi_1+\varphi_2$
Θ	Observation angle
CX	Size of an element that an individual uses to resolve the sign (i.e., sign lettering)
B	*b* is set to half of the size of the recognizable element (*CX*)

the line XB is defined by $m_1=-y/(b-x)$ and the line CB is defined by $m_1=y/(b+x)$. Using the following trigonometric identity

$$\tan(\varphi)=\frac{m_1-m_2}{1+m_1m_2}, \tag{1}$$

and the equations for *XB* and *CB* defined above, one obtains

$$\tan(\varphi)=\frac{[-(y/(b-x))]-[y/(b+x)]}{1+[-(y/(b-x))][y/(b+x)]}=-\frac{2yb}{b^2-x^2-y^2}. \tag{2}$$

Then rearranging (2) and adding $b^2/\tan^2(\varphi)$ to both sides of the equation, one obtains

$$b^2+\frac{b^2}{\tan^2(\varphi)}=x^2+y^2-\frac{2by}{\tan(\varphi)}+\frac{b^2}{\tan^2(\varphi)}. \tag{3}$$

Finally, simplifying (3) produces,

$$\left(\frac{b}{\sin(\varphi)}\right)^2=x^2+\left(y-\frac{b}{\tan(\varphi)}\right)^2. \tag{4}$$

This has the equivalent form of a circle with center at point $(0,b/\tan(\varphi))$ and radius $b/\sin(\varphi)$.

This circle defines the VCA of a sign S that is formed of text elements of dimension *CX* (Figure 1) assuming a constant angular separation of $\varphi_{\min}$ degrees (i.e., 0.29° derived from the NFPA regulation). Assume in this calculation that the human ability to resolve vertical components of the sign (i.e., the height of the text) is equivalent to the ability to resolve horizontal components.

Figure 1 depicts the catchment area of sign S generated using the original algorithm (area M_1) – which effectively ignores the dependence of VCA on observation angle. This image is overlapped by the catchment area of the formulation derived in the preceding theoretical treatment, labeled as M_2 in Figure 1. The restrictions imposed upon the VCA produced by the formulation are clearly evident, as is its circular appearance.

Note that the original method implemented within the building EXODUS attempted to crudely approximate the influence of observation angle by imposing an arbitrary restriction to the observation angle resulting in the VCA being defined by area M_1 in Figure 1, effectively excluding region M_3.

It has to be noted that the theoretical formulation derived here does not produce a circle that is at a tangent to the center of the sign. Instead the element used (i.e., a letter on the sign) constitutes a chord that intersects the VCA circle as shown in Figure 2. However, because the width of this element is much smaller than the diameter of the VCA (by a factor of approximately 200), it is assumed that the VCA circle is at a tangent to the sign for the purpose of its calculation.

For the configuration discussed in this article the offset t (Figure 2) is equal to

$$t = 2r - h = 2\frac{b}{\sin(\varphi)} - h \approx 0.04\,\text{m},$$

while the diameter of the circle is about 30 m. It is then assumed that the distance t is negligible and can therefore be ignored. By using this method on a proposed signage system it becomes a relatively easy task to determine the VCA coverage of any particular sign. By knowing the size of the elements on the sign (i.e., lettering height) and the angular separation resolution, the VCA of a sign can be simply determined by calculating the circle defined by the Equation (4).

It has been shown theoretically that if the ability of a viewer to resolve a sign is based on the assumption that the eye can resolve angular separations down to a constant minimum value (irrespective of the observation angle), then the maximum viewing distance will decrease as the observation angle increases. This is an important result as the regulations implicitly assume that viewing distance is independent of the observation angle. Furthermore, instead of the VCA being defined by a semicircular region, as is implicitly assumed in regulation, the preceding analysis shows that the VCA has a circular appearance with diameter approximately equivalent to the radius of the previously assumed semicircular VCA.

In the next section, this theoretical finding is examined through a series of experimental trials designed specifically to examine this aspect of signage visibility.

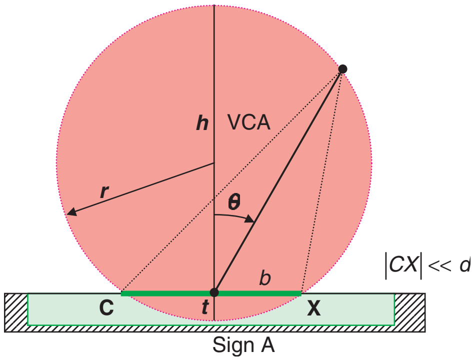


Figure 2. *The circular VCA of sign A is not precisely at a tangent to the element on the sign (i.e., a letter) but the segment CX is a chord on the VCA circle. In order to illustrate this clearly the ratio between element CX and h of the VCA is highly exaggerated. It should be noted that this is not to scale and that in reality the width of the element measured would be much smaller than the diameter of the VCA. (The color version of this figure is available online.)*

EXPERIMENTAL METHOD

The purpose of the trials was to test the theory presented in the previous section that the distance from which a sign can be perceived is dependent upon the angle at which it is approached. The experimental trials have been designed specifically to examine the distances from which the individual participants are able to recognize the text (or some portion of it) within the sign for given observation angle.

The trials were completed by 48 volunteers, consisting of 29 males and 19 females, each of whom experienced the same number (15) of experimental conditions. The order in which these conditions were experienced was varied in a systematic manner in order to minimize the influence of uncontrolled variables; e.g., learning. The vision of approximately 55% of the sample required constant correction in the form of spectacles or contact lenses, which were used during the trials. A detailed analysis of the results according to the number of variables (e.g., prior eye workload, text size, and use of visual correction) was produced; however, the presentation of this material is beyond the scope of this work.

The experiment was performed in a corridor 39 m in length with strong consistent artificial illumination along its length. The relative luminance of the signs was not taken into consideration in this work, but was not considered by the authors to be a strong influential factor under these experimental conditions. Three signs were used during these trials: two plastic signs and one photo luminescent sign (Figure 4(a)). These varied in the letter size of the text, the case of the text and the background colors

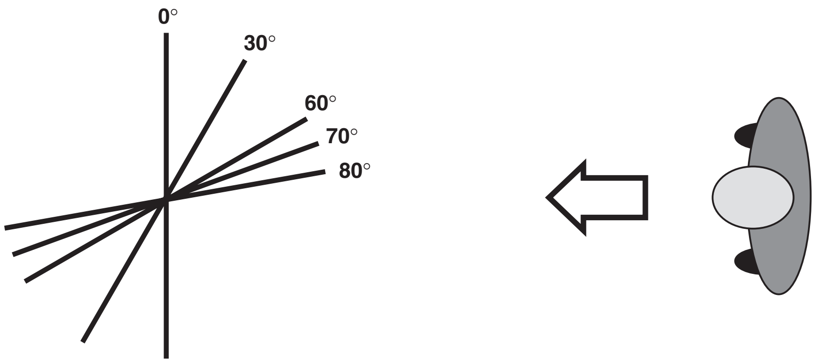


Figure 3. *Pivoting of the sign to modify the observation angle at which the participant observes the sign.*

of the signs (Figure 4). The text within these signs differed in the height and the width of text, and the thickness of script that formed the text. Although the three signs used were of standard designs, it was felt that a variety of text types and signage designs were required in order to strengthen the credibility of the results produced.

Given the restricted nature of the corridor, the sign used in each trial was placed on a pivoting platform. Thus the observation angle was changed by varying the orientation of the sign to the observer rather than the observer to the sign. In this way each participant commenced the trial in the same location and approached the sign along the same path, irrespective of the observation angle. Five different observation angles were experienced by each participant: 0°, 30°, 60°, 70°, and 80° (Figure 3). For each observation angle the viewer would approach the sign until the lettering on the sign was legible.

The signs were placed individually on a white board at a fixed height. During the trials the board was pivoted to a series of pre-determined angles relative to the center line of the corridor. A participant from a representative sample was then led to the far end of corridor (≈39 m from the sign) and then asked to approach the sign until they were able to resolve half of the letters in the sign (Figure 4(b)). The resolution of half of the letters was selected (rather than 100% of the letters) as it was felt that the text (i.e., the words) could be ascertained, given that 50% of the letters were recognizable. The distances between the participant and the sign were then measured and recorded and later analyzed. The average viewing distances

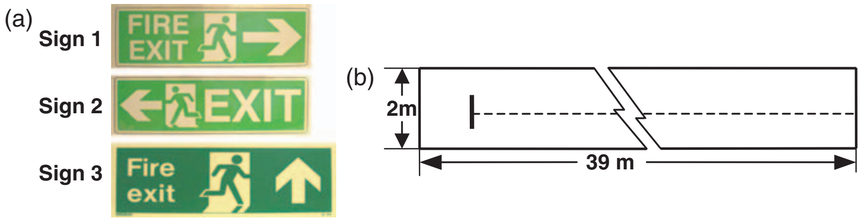


Figure 4. *(a) The fire safety signs used during the trials and (b) the corridor in which the trials were conducted. (The color version of this figure is available online.)*

measured from the participants reading the signs at different angles are expected to reflect the VCAs of the signs.

Prior to the commencement of the trials, each participant was asked to prepare for the trial by relaxing from their work for at least 10 min, in order for them to acclimatize to the experimental conditions. After this, the individual was taken to a lounge area to read a briefing and complete a questionnaire, in order to familiarize them with the trial procedure.

Once the trial commenced, the individual slowly approached the sign along the center line of the corridor, until they claimed to be able to resolve (i.e., clearly discern) half of the letters in the sign; their distance from the sign at this point was recorded. The individual then continued their approach until they could resolve the full text, in order to demonstrate that the distance recorded for this event was indeed closer than was the case when viewing a subset of the text. These steps were then repeated for the 15 trial conditions (3 signs × 5 angles) for each individual.

THE EXPERIMENTAL RESULTS

The average viewing distance for each of the three signs at the five observation angles are shown in Table 2 for each of the categories. The results presented in Table 2 clearly demonstrate a relationship between the observation angle and the distance from which the text in the sign could be resolved: for all of the signs as the angle of observation is increased, the maximum viewing distance at which the text in the sign could be resolved decreased. The manner in which the relationship between the distances at which the sign can be resolved and the observational angle is more clearly demonstrated in Figure 5. From this figure it is apparent that the relationship between maximum viewing distance and observation angle is nonlinear and consistent for each of the three types of sign.

To further examine the relationship between observation angle and viewing distance the data is plotted using polar coordinates, with θ

Table 2. Mean viewing distances of three signs at 5 different angles.

		Observation angle				
Sign	**Viewing distance (m)**	**0°**	**30°**	**60°**	**70°**	**80°**
1	Mean viewing distance	23.38	21.09	14.82	10.12	5.10
2	Mean viewing distance	33.11	30.79	21.23	13.64	6.34
3	Mean viewing distance	19.84	18.98	12.65	9.04	4.60

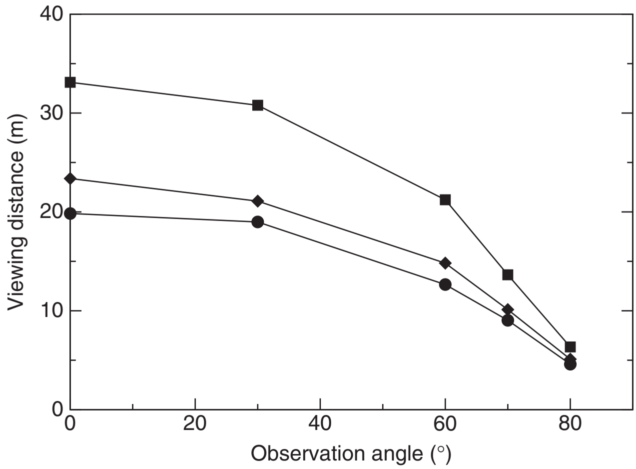


Figure 5. *Empirical data of the mean viewing distances of Sign 1(◆), Sign 2 (■) and Sign 3 (●) at five angles.*

(the rotational ordinate) representing the observational angle and r (the radial measurement) representing the distance at which the text in the sign could be resolved. In Figure 6 the results are presented in this form for each of the signs examined. In these graphs each of the data-points collected is presented. For each of the data-sets collected a solid curve passes through the average of all the data-sets collected, while a perfect circle of equal radius is plotted as a dashed line. It is apparent that although the size of the curve produced in each of these graphs is different, their general shape is similar: a semi-circle is approximated by the curve connecting the averages of the five experimental conditions examined for each of the signs.

This becomes more evident when the results produced are depicted on the same graph and are reflected on the vertical axis. From Figure 7(a) it is immediately apparent that the curve generated is approximately a circle. The validity of this action is based on the assumption that the observational

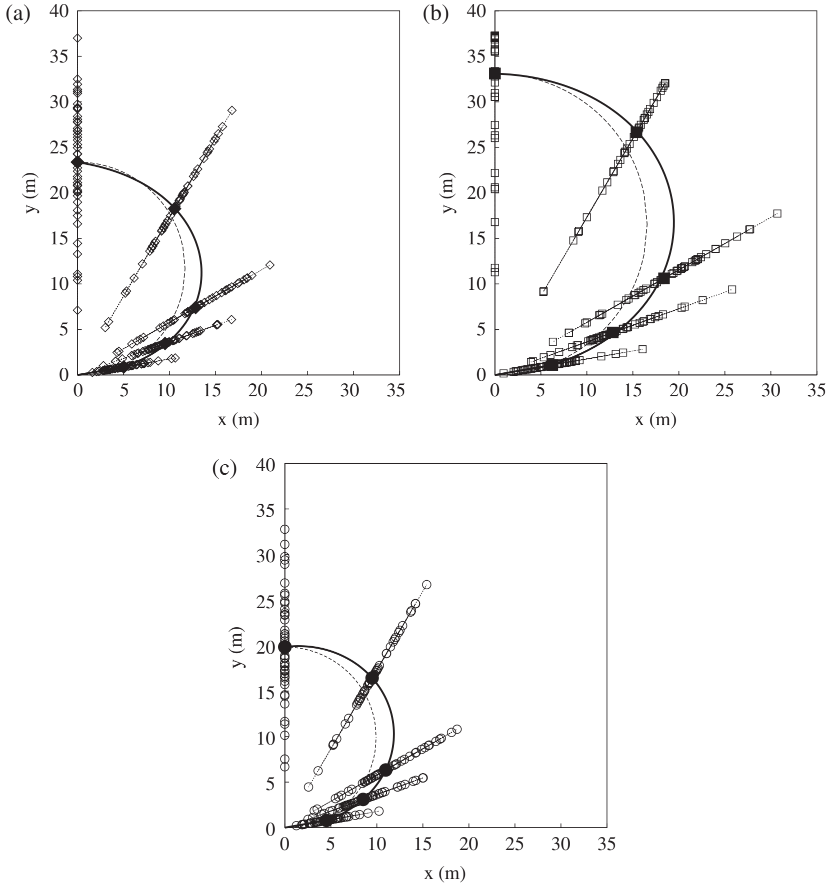


Figure 6. *For each sign examined: (a) Sign 1 (◇); (b) Sign 2 (□); and (c) Sign 3 (○), the maximum viewing distance is plotted as a function of observation angle. For each sign and each of the five observation angles, all the collected data points are plotted and a curve linking the average maximum viewing distance is plotted (solid line) together with a perfect circle of similar radius (broken line).*

angle is independent of the direction of the approach to the sign (i.e. whether they approach from the left or the right side).

The curves generated from the experimental data represent a slightly flattened circle; moreover, from Figure 7(b) this closely approximates the theoretical findings discussed in the earlier section describing the theoretical representation for the angular extend of the VCA and clearly contradicts the implicit assumption used within building regulations that the maximum distance from which a sign can be resolved is independent of the observation angle (see also (Figures 8 and 9)).

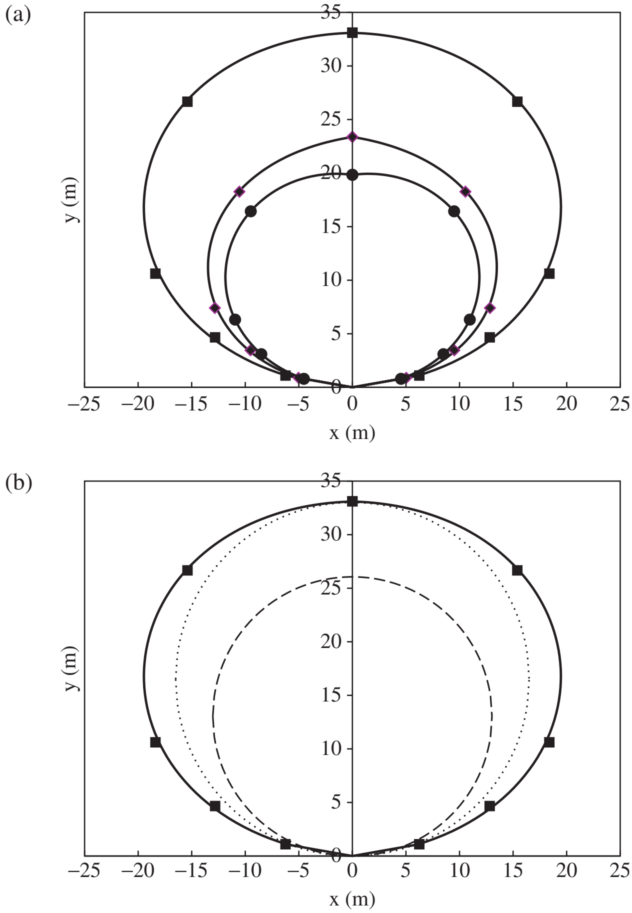


Figure 7. *(a) The reflection of the original experimental data of Sign 1 (◆), Sign 2 (■) and Sign 3 (●), across the vertical axis, and (b) the comparison of the experimental VCA of Sign 1 (solid curve) and two VCAs of the same sign based on the theoretical model of the VCA discussed earlier using the maximum viewing distances defined in BS 5499 [9] (dotted curve) and the NFPA Life Safety Code Handbook [8] (dashed curve) respectively. In both cases, the safety factor of 2 is excluded.*

In the first edition of BS 5499 [9] the following formulation is provided relating the viewing distance (D) to the height of text (h)

$$D = 250h. \tag{5}$$

As mentioned previously, this formulation is based on the result of the eye sight tests that people with normal (or corrected to normal) vision can

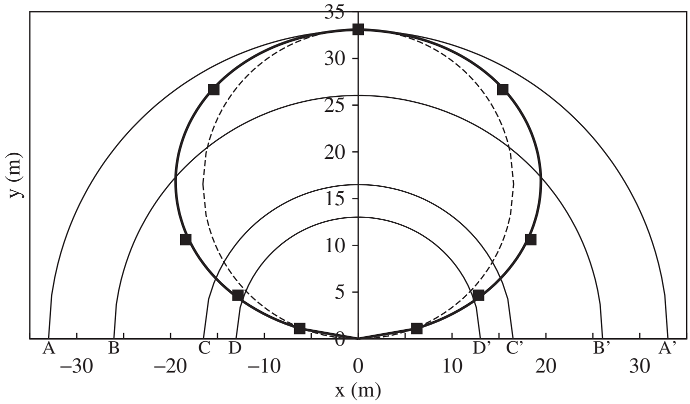


Figure 8. *Average maximum measured viewing distances for Sign 2 (■) compared with viewing distances according to various national guidelines. Arcs AA′ and BB′ are viewing distances of a sign with text height equivalent to Sign 2 (66 mm) based on BS 5499 [9] and the NFPA Life Safety Code Handbook [8] respectively excluding the safety factor; arcs CC′ and DD′ are the viewing distances including the safety factor. Dashed line is a circle with diameter equal to the maximum average viewing distance for Sign 2 with observation angle of 0°.*

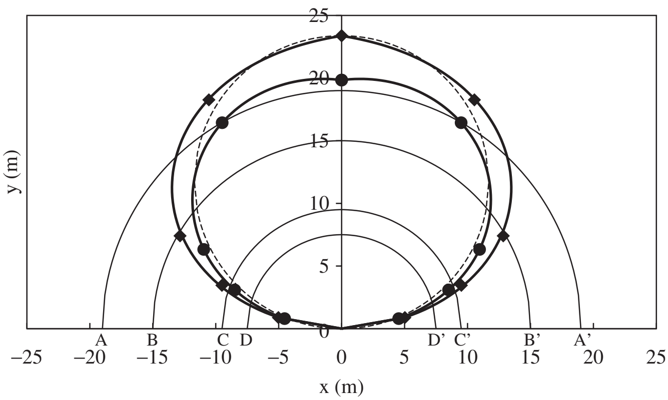


Figure 9. *Average maximum measured viewing distances for Sign 1 (◆) and Sign 3 (●) compared with viewing distances according to various national guidelines. Arcs AA′ and BB′ are viewing distances of a sign with text height equivalent to Sign 3 (38 mm) based on BS 5499 [9] and the NFPA Life Safety Code Handbook [8] respectively excluding the safety factor; arcs CC′ and DD′ are the viewing distances including the safety factor. Dashed line is a circle with diameter equal to the maximum average viewing distance for Sign 1 with observation angle of 0°.*

reliably resolve a detail that subtends an angle of 1 min. This formulation also includes a small additional margin of extra difficulty in resolving some complex letters and a safety factor of 2.0 in order to guarantee a conservative estimate of the distance from which the sign can be resolved.

Finally the coefficient is rounded off to two significant figures [20]. For instance, given the height of the text on Sign 2, the results produced by the formulation is

$$D = 250 \times 0.066 = 16.5\,\mathrm{m},$$

which is approximately half of the measured average viewing distance (33.11 m) for Sign 2 with observation angle of 0°. Given the incorporated safety factor of 2.0 and the other correctional factors mentioned, this approximates the findings of the experimental trials. The value describing the angular resolution of the eye demonstrated in this experiment is therefore consistent with the advice provided in the regulatory documentation. Alternatively, it should be noted that the NFPA Life Safety Code Handbook [8] suggests a viewing distance of 30 m for the exit lettering with a height of 152 mm. Again if the safety factor is taken into consideration, this approximates the relationship between sign size and average maximum viewing distance produced during the experimental trials.

Figures 8 and 9 map the empirical viewing distances of the VCAs associated with the corresponding signs; also shown are the VCAs outlined by the NFPA Life Safety Code Handbook [8] and BS 5499 [9] with and without the associated safety factors. Figure 9 includes reference to both Sign 1 and Sign 3 due to the approximately identical height of the text that appeared on both signs. It is apparent that the maximum viewing distances recorded during the trials approximate the values assumed in the NFPA and BS 5499 formulation, adding some credibility to the experimental conditions. It is also clear that the empirical VCA of a sign is a flattened circle. Therefore, applying a slight simplification, it can be assumed that the VCA of a sign can be approximated by a circle with its diameter equal to the viewing distance of the sign approached perpendicularly.

The results of the experiment indicate that the VCA of a sign approximates a circle. This confirms the initial hypothesis that a sign can be seen by an observer from a circular area located at a tangent to the surface of the sign. This is due to the constant nature of the angular resolution of the human eye and the nonlinear relationship between the observational angle and maximum distance from which the sign can be resolved. Within the buildingEXODUS the theoretical model describing the nonlinear relationship between observation angle and maximum viewing distance has been implemented. This produces conservative results as it generates a circular VCA with the same maximum radius as the flattened circle generated from the experiment (VCA circle from theory lies within the flattened VCA circle produced by the experiment).

IMPLEMENTATION OF ALGORITHM INTO EVACUATION SOFTWARE

The algorithm presented in the earlier section describing the theoretical representation for the angular extend of the VCA has been implemented in prototype form within buildingEXODUS. In the following two sub sections we demonstrate the performance of the algorithm using two examples: the first, assumes a simple compartment without internal obstacles, while the second assumes a complex compartment with many internal obstacles.

Comparison of New VCA Determination with Previous Implementation

To demonstrate the differences between the new algorithm and the previous representation of the VCA within the software, a simple geometry without internal obstacles is initially examined. The geometry comprises a single exit with an associated exit sign placed above it connected to a large square compartment. The dimensions of the compartment are sufficient to extend well beyond the confines of the VCA generated using either technique. In both cases the lettering on the sign is such that the maximum viewing distance is assumed to be 30 m, as specified in the NFPA documentation [8] and the observer is assumed to have the default height of 1.75 m.

Using the original VCA algorithm within the software the VCA for the sign is generated. It should be noted here that the VCA generated using this approach does not take into account the observation angle of the viewer, save to exclude extreme observation angles in excess of 85° (areas labeled M_3 in Figure 10). The VCA in this case approximates a semicircle, with center point at the center of the sign, with a radius of 30 m. This area is

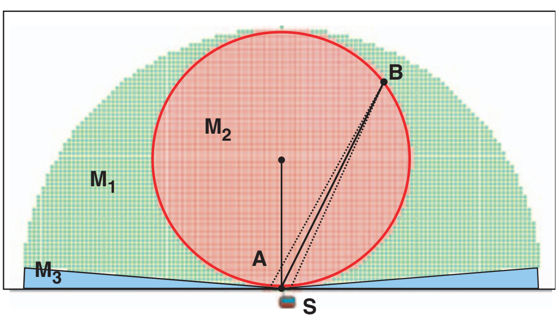


Figure 10. *VCA generated using the previous and prototype methods. (The color version of this figure is available online.)*

labeled M_1 in Figure 12. It is apparent that the sections within 5° of the tangent to the surface of the sign do not fall within the VCA. The VCA determined using this approach should therefore equate to

$$170/180 \times \pi \times 30^2 \times 0.5 = 1335\,\text{m}^2.$$

Using the implementation within buildingEXODUS V4.0, the VCA is estimated to be 1345.0 m^2, representing an error of under 1%. This error can be attributed to the representation within the software of the circular shape by square nodes.

The VCA determined using the prototype algorithm is also shown in Figure 10 and is labelled M_2. The shape of the VCA is now circular, closely reflecting the theoretical assumptions highlighted in the section describing the theoretical representation for the angular extend of the VCA; in this instance the observation angle clearly influences the distance and hence the area from which the sign can be seen and subsequently the VCA produced. The anticipated area within this VCA was

$$\pi \times 15^2 = 707\,\text{m}^2.$$

Using the prototype implementation within the software, the VCA is 708.0 m^2, representing an error of 0.1%. From this simple example it can be seen that the previous implementation of the VCA, which is consistent with guidance sets down in various standards [8,9], potentially over estimates the area from which a sign is visible by some 90%. This has important implications not simply for modeling applications, but for the positioning of signage in general.

In the example presented in this section, the compartment was free from obstacles that could potentially further restrict the size of the VCA. In the next example, the impact of the new algorithm is considered when applied to a more complex geometry.

Comparison of New VCA Determination within a Complex Geometry

The geometry used in this example is the supermarket layout used in previous analysis of the VCA [13]. The geometry is only briefly described in this section as a fuller account can be found in previous publications [13]. The supermarket contains an array of internal shelving components, tills, and a café in the southern part of the geometry (Figure 11). Four main exit (exits 3–6) points are located at the south side of the building. Four emergency exits (exits 1, 2, 7, 8) are available: two on the east side and two on the west side. The total free area of the supermarket has been calculated within the model to be approximately 2927 m^2 after the shelving and

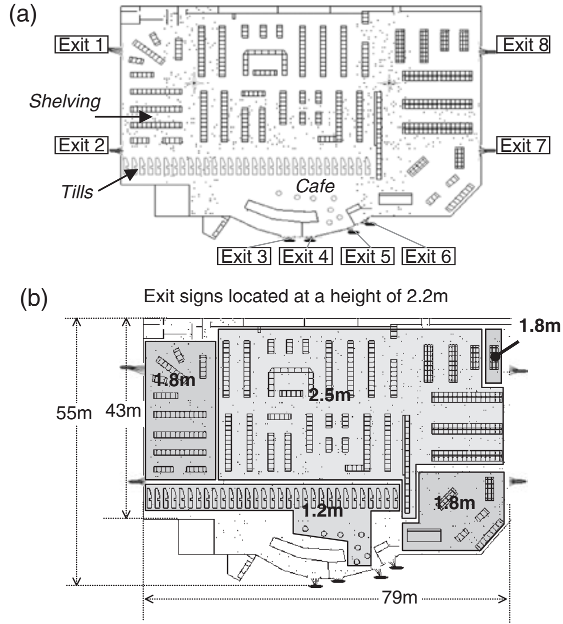


Figure 11. The supermarket layout as represented within the buildingEXODUS model: (a) showing location of exits and shelving and (b) indicating the height of the various internal features of the supermarket.

other furnishings have been taken into account. Signage is provided by exit signs located above each of the exits (main and emergency) and by two sets of four signs at the cross aisles as shown in Figure 12.

The majority of the shelving extends to a height of 2.5 m. However, there are some shelves with a height of 1.8 m and the tills and tables in the café area have a height of 1.2 m (Figure 11(b)). The emergency exit signage is positioned at a height of 2.2 m above the floor (Figure 11(a)). All the remaining features are at ceiling height thus preventing any visibility access past them. The height of the shelving and furnishings is taken into account when calculating the VCA of each exit. The width of each door is assumed to be 2.5 m. The signs are assumed to have lettering of 152 mm corresponding to a visibility cutoff distance of 30 m as suggested by the NFPA Code [8] and the observer is assumed to have the default height of 1.75 m.

The VCA of the signage system is determined using both methods. Using the existing method, the combined VCA of all the signs is 2006.25 m^2, while using the prototype algorithm produces a combined VCA of 1896.0 m^2. Thus, the existing method overestimates the VCA by some 6% (or 110 m^2). Presented in Table 3 are the examples of

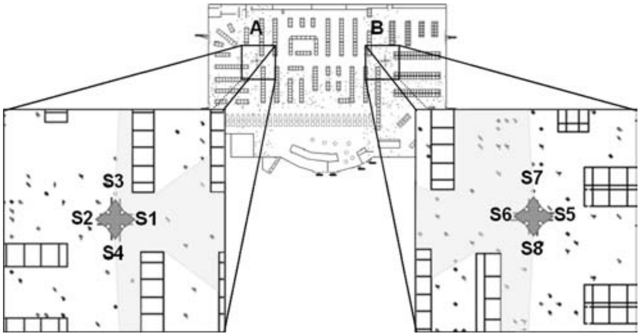
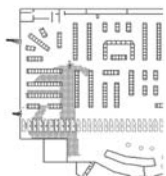
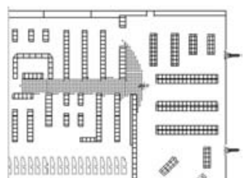


Figure 12. *The signage at the cross isles*

Table 3. VCA comparison between the existing and prototype methods.

	Exit sign 1	**Sign 4**	**Sign 6**
Existing VCA method			
Area covered	259.75 m^2	266.75 m^2	196.75 m^2
Percent coverage	8.87%	9.11%	6.72%
Prototype VCA method			
Area covered	224.75 m^2	212.25 m^2	142.75 m^2
Percent coverage	7.68%	7.25%	4.88%

the differences between the VCA produced by both methods for some of the signs.

In the previous simple example, the differences between the VCA produced by the two techniques was shown to be significant. However, these differences are somewhat diminished as the complexity of the compartment is increased through the introduction of internal obstacles. This is due to the presence of the obstacles intercepting and preventing the propagation of the VCA. In this way, the presence of the obstacles masks some of the over estimation produced by the earlier method.

Table 4. Summary of occupant evacuation time ranges using the old and new approach for the calculation of the VCA.

	Total evacuation time (s)	
	Old	New
Average	83 [68–88]	81 [74–88]

Table 5. Summary evacuation results for using the old and new approach for the calculation of the VCA.

	Congestion experienced (s)		Distance traveled (m)		Individual evacuation time (s)	
	Old	New	Old	New	Old	New
Average	10.9 [10.4–11.6]	9.9 [9.1–10.7]	28.7 [28.4–28.9]	29.5 [29.1–29.9]	34.2 [33.6–35.0]	33.8 [32.7–34.7]

Table 6. Average exit utilization using the old and new approach for the calculation of the VCA.

	Average exit usage (occ) avg		
Exit	Old	New	Difference
1	160	147	−13
2	102	103	+1
3	119	127	+8
4	167	173	+6
5	52	53	+1
6	162	164	+2
7	66	70	+4
8	172	163	−9

The main results for these simulations are presented in Tables 4–6. Note that the average total evacuation time was 83 s using the existing technique and 81 s using the new algorithm. The average individual evacuation time was 34.2 s and 33.8 s for the old and new approach, respectively. The average congestion experienced by an individual was 10.9 and 9.9 s, while the average distance traveled was 28.7 m and 29.5 m for the old and new approach, respectively.

As is to be expected, the reduction in VCA generated by the new algorithm has resulted in a greater number of occupants utilizing the normally used (or main) exits – i.e., exits 3–6. On an average there are some 17 additional people utilizing the main exits when the new algorithm is used to determine the VCA. As a result there is a slight increase in the average distance traveled, generated by a larger section of the population not utilizing the nearer emergency exits. In this case, the slight decrease in the number of occupants using the emergency exits has resulted in a slight decrease in the levels of congestion experienced (at the emergency exits) which in turn has resulted in a slight decrease in both the average overall evacuation time and the average personal evacuation time. Thus, the differences in the key results produced by the incorporation of the new technique of calculating the VCA in this example are small and self consistent.

CONCLUSION

During circulation and evacuation, wayfinding abilities can be influenced by the ability of occupants to interact with the signage system. While a number of physical, psychological, and physiological factors will influence the ability of the occupants to detect and correctly interpret the information conveyed by the signs, first and foremost, the occupants must be able to physically see the sign. In placing signs within a structure it is therefore essential to determine the visibility catchment area or VCA of the sign. In building standards the implicit assumption has been that the maximum viewing distance is independent of the viewing angle and so the VCA of the sign describes a semicircular area centered on the sign. The radius of the semicircle is given by the maximum viewing distance measured by viewing the sign straight on (i.e., with an observation angle of 0°).

In this article, it has been demonstrated both theoretically and through experimental trials that the maximum viewing distance is dependent on the viewing angle and that as the viewing angle increases, the maximum viewing distance decreases in a nonlinear manner. This is the result of the angular separation of the sign (or more precisely the angular separation of the lettering on the sign) decreasing as the angle of observation increases at fixed observation distance and the human eye possessing a lower limit to its angular resolving abilities. Furthermore, when the viewing angle is taken into consideration, the VCA associated with the sign describes an area defined by a flattened circle which is tangent to the surface of the sign with minor radius equal to the previously defined semicircle or half of that if the safety factor is considered.

These results are valuable in their own right as they more accurately define the visibility limits of the signs. In addition, the method of determining the VCA of signs has been implemented within a comprehensive evacuation model, providing a more accurate way of determining the visibility of the signs in complex geometries. The impact that the new developments may exert when combined with the other factors evident during a simulated evacuation have been shown to be sensitive to the complexity of the geometry and the scenario modeled. While the overall differences in the key evacuation indicators (e.g., average total evacuation time and average personal evacuation time) resulting from the introduction of the new developments may on occasion be small, it is essential to correctly represent these subtleties, if the model is to correctly represent reality.

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