Visibility Criteria and Application Techniques for Roadway Lighting

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Two related issues must be considered in assessing roadway visibility. Suitable criteria defining roadway visibility must be established, and practical measurement techniques must be developed to measure compliance against the criteria. This paper addresses both issues. It makes recommendations for setting roadway visibility criteria based upon a model of visual speed and accuracy, and for utilizing photometric image analysis systems to evaluate roadway applications.

Good visibility is essential for safe driving. At highway speeds exceeding 100 kph (28 m/s) a driver must make decisions quickly and correctly about the condition of the roadway and objects in the path of the vehicle. Therefore, it is necessary to design roadways, and their illumination, so that a driver can see potential hazards and have enough time to avoid them.

Proper roadway design must address two fundamental issues. First, criteria must be established for evaluating roadways in terms of visibility, and second, equipment must be available for making these assessments. This paper discusses these issues and makes recommendations for

(1) Design evaluation criteria based upon a model of visual speed and accuracy, and
(2) Utilization of computer-based imaging photometry for assessing the performance of actual roadways according to the model.

SPECIFICATION OF THE STIMULUS

Visibility, however defined, is affected by a relatively small set of stimulus parameters. The spatial and luminous characteristics of static objects are the primary aspects of the visual scene that must be specified if one is to predict a driver's visual response. Color and motion are also important to visibility, but these will typically play a minor role in driving safely. Of course, the spatial-luminance characteristics can be quite complex and produce a wide range of levels for visual response (*1*,*2*). Nevertheless, measurements of object luminances and sizes are the first major steps towards predicting roadway visibility.

Direct and Subjective Techniques

Techniques for specifying luminance and size fall into two distinct classes. The first technique employs instruments for assessing object size (e.g., a tape measure) and luminance (e.g., a luminance spot photometer). Importantly, the values recorded should come from reliable, calibrated instruments whose readings can be verified independently.

The second technique utilizes a human being as the instrument. Typically these "human instruments" provide magnitude estimations of object parameters. For example, a person might evaluate the contrast or size of an object on a roadway. This technique is quite effective if the human instrument has been calibrated. Most industries avoid "human instruments" if at all possible. Although they can be used reliably, the calibration exercise requires a great deal of effort and not all individuals are well suited to such tasks. In the brewing industry, though, calibrated tasters ensure quality control because the human instrument can more reliably diagnose differences in certain key flavors than can mechanical, optical, or chemical techniques. It is important to stress that these tasters have been carefully selected and educated, and their responses have been validated in so-called "blind" comparisons to avoid costly repercussions.

Although subjective techniques have been employed in the lighting industry (*3*,*4*), the roadway community is fortunate in being able to specify the relevant visual stimulus aspects directly. In practice, tape measures and luminance spot photometers have been used to measure the size and luminance of objects placed on the roadway. Unfortunately, such procedures are extremely tedious, expensive, and prone to recording errors. As an example, in August 1987 the Roadway Lighting Committee of the IESNA completed field measurements at an outdoor roadway facility. The exercise took many months to complete, and upon reflection the committee resolved that erroneous data had been included.

Computer-based Imaging Photometry

A luminance-measuring and image analysis system known as CapCalc (for *cap*ture and *calc*ulate) that quickly and accurately records spatial and luminance information from a visual scene has been recently developed at the National Research Council Canada (NRCC). The system replaces the tape measure and luminance spot photometer. CapCalc consists of a V-lambda corrected solid-state video camera, an image processing board, and a personal computer (see Figure 1). It captures, stores, retrieves, and analyzes video pictures comprising a quarter million luminance values (pixels). Image capture is complete in approximately 30 ms. Figure 2 shows a digitized image generated by CapCalc. The system overcomes many of the problems currently facing application spe-

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FIGURE 1 Components of the National Research Council Canada luminance and image analysis system known as CapCalc.

FIGURE 2 Digitized image of a roadway scene generated by CapCalc.

cialists concerned with specifying roadway size and luminance information.

Several months have been spent in developing and calibrating the system (*5*). Its photopic spectral response is equal to or better than that of conventional spot luminance photometers and can provide luminance data under all conventional light sources. It responds linearly to light from mesopic levels (about 1 cd/m^2) to high photopic (daylight) levels; the dynamic range can be adjusted by manipulating the lens aperture and neutral density filters. The system's response remains constant over the entire field-of-view so that a given luminous point anywhere in the visual scene will produce the same luminance value from any of its pixels. Further, the calibrated zoom lens yields accurate information about the apparent size of objects. Thus, CapCalc is a true imaging photometer that can provide accurate object luminance and size information throughout the entire visual scene in a matter of seconds. Additionally, data can be stored for subsequent retrieval and assessment, making CapCalc a practical system for specifying visual stimuli on roadways.

VISIBILITY CRITERIA

Distinct from the concept of visual stimuli, but of equal importance, is the ability to evaluate those stimuli in terms of visibility. In other words, it is necessary to have a model of visibility that will predict a driver's response to the visual characteristics of a roadway.

Seeing is a complex process, and there is no single definition of visibility that is appropriate for every task. Rather, a suitable definition will depend upon the situation. If, for example, the presence or absence of a target has to be detected, without regard for the time required to perform the task, a detection threshold model of visibility will suffice. If, on the other hand, a suprathreshold target must be identified (a muffler or paper bag lying on the roadway) within a limited length of time, a detection threshold model is inherently inappropriate.

Detection Threshold Models

Visibility has often been defined in terms of detection threshold (*6,7*). Such a definition is appropriate if the concern is only with the break-point between seeing and not seeing. For most roadway applications, however, objects are above the detection threshold, so that this definition is of limited utility for establishing visibility recommendations, standards, or guidelines for roadways. This limitation has been recognized by those trying to establish visibility performance criteria (*8*). To evaluate the visibility of suprathreshold objects, it has been assumed that all objects with contrasts at three times their respective detection threshold values will be equally visible. In principle then, a visibility performance criterion of three times detection threshold might be recommended, but the assumption underlying such a recommendation would not be valid.

Detection threshold is only one of many constant criteria that can be adopted by a human observer over the full range of visual response. In fact, an observer could adopt both detection and readability criteria for the same object (*9,10*). For example, the amount of contrast (size or overall luminance) required to read a sign is greater than that required to detect the sign. Readability is a higher threshold criterion than detection because a higher level of visual response is required.

Contrast threshold data can be obtained for a wide range of adaptation (overall luminance) levels. Importantly, the threshold functions for detection and for readability relating contrast and adaptation luminance differ not only in height but in shape as well (see Figure 3). Because the two threshold functions are not separated by a single multiple over their entire range, it is incorrect to assume that two objects at three times their respective detection threshold will be equally visible (*9*).

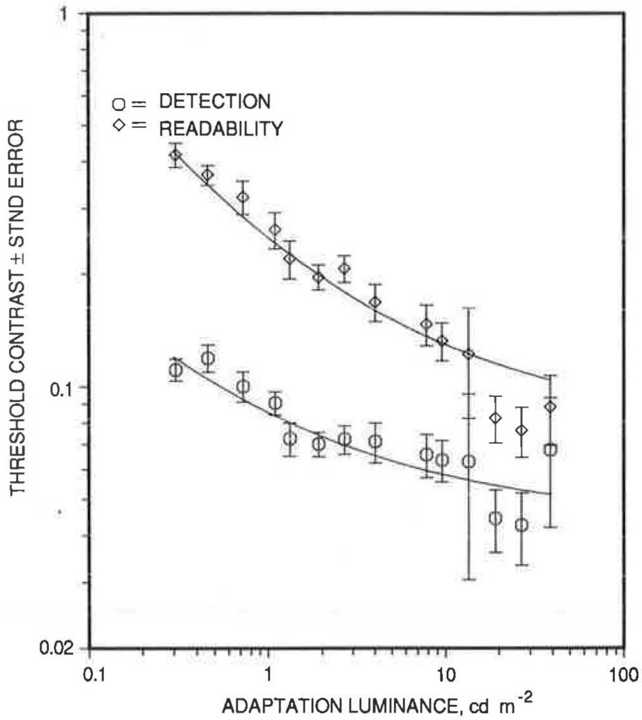

FIGURE 3 Detection and readability threshold data for steady viewing of five-digit numbers (*16*).

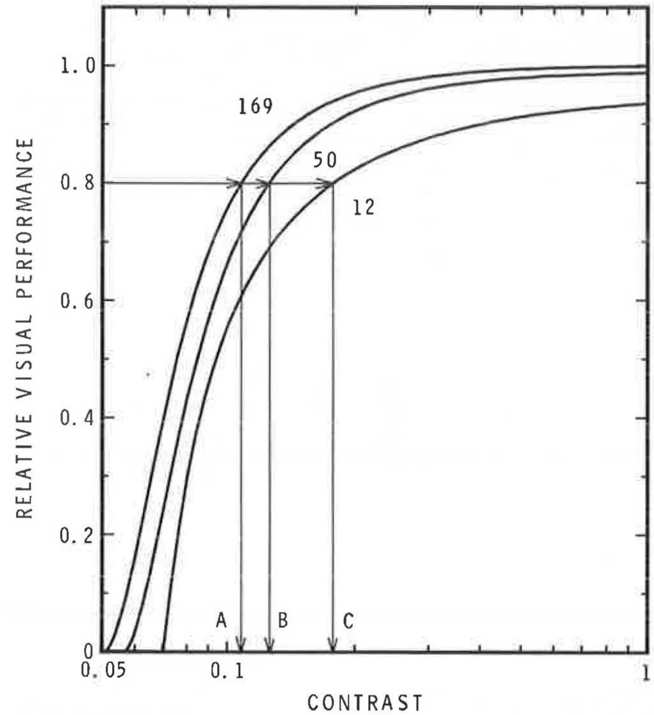

FIGURE 4 Constant luminance lines from the Relative Visual Performance (RVP) model developed by Rea (*11*). The curves are labelled in units of background luminance, cd/m². Points labelled A, B, and C are derived from a constant criterion of 0.80 from the RVP model for 169, 50, and 12 cd/m², respectively.

Constant Criteria from a Suprathreshold Model

Relative Visual Performance

It is possible to establish constant criteria and determine lines of "equal visibility" if a complete set of suprathreshold functions is available. Figure 4 is from the suprathreshold visual performance model developed by Rea (*11*) and shows Relative Visual Performance (RVP) changing as a function of contrast for three adaptation levels. Zero on the ordinate corresponds to the "readability" threshold criterion. Other higher constant criteria can be adopted by selecting a given ordinate value. For example, three contrast values, A, B and C, have been derived for 169, 50 and 12 cd/m², respectively, from the constant criterion of RVP = 0.8.

Figure 5 shows several constant criterion (or threshold) lines from the RVP model in a log contrast versus log luminance coordinate system along with the three derived contrast values at 169, 50 and 12 cd/m² from Figure 4. It is important to recognize that in Figure 5 these constant criterion functions are not parallel in the log contrast versus log luminance coordinate system (i.e., they are not separated by fixed multiples). Again, equal visibility lines cannot be obtained by simple fixed multiples of detection threshold. It is possible to set equal visibility levels, however, but only after a complete set of suprathreshold functions has been obtained. In any event, a visibility performance criterion can be established by adopting a constant criterion in a suprathreshold visibility space (see Figure 6).

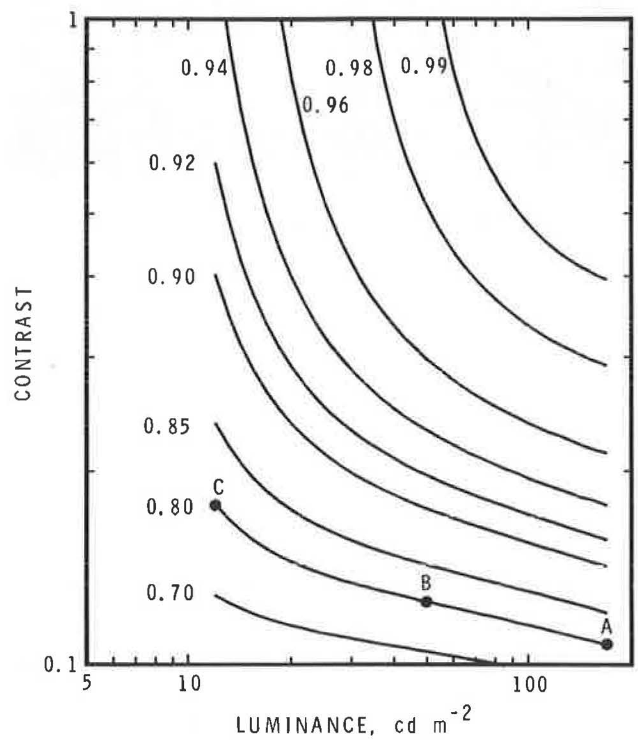

FIGURE 5 Constant performance lines through the Relative Visual Performance (RVP) model developed by Rea (*11*). The curves, labelled in units of RVP, are comparable to threshold functions. Points labelled A, B, and C correspond to those derived in Figure 4.

Appearance

A visual performance model based upon speed and accuracy, similar to that illustrated in Figure 6, is not the only possible

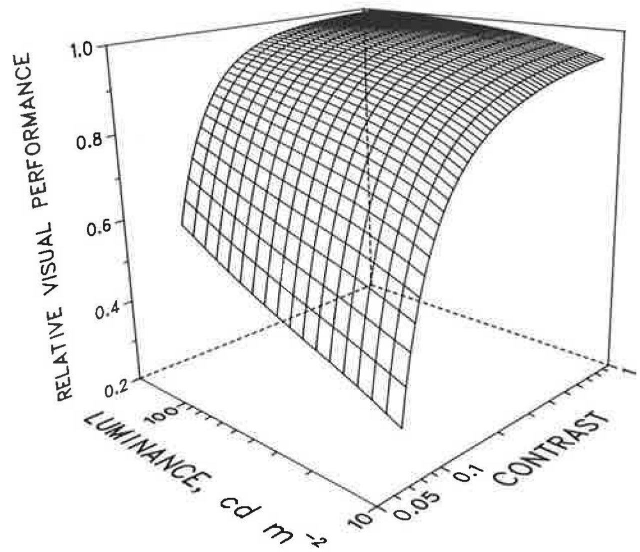

FIGURE 6 A three-dimensional representation of the Relative Visual Performance (RVP) model developed by Rea (*11*).

suprathreshold visibility model. A suprathreshold model of "apparent visibility" could also be determined by magnitude estimations of the type described in the previous section using "human instruments." Several investigators have shown that magnitude estimations are related to stimulus contrast by a power function with an exponent near unity (*12*). In other words, the contrast response function is nearly linear when using magnitude estimations. An "apparent visibility" model, which has yet to be developed, could, in principle, be used to establish a visibility performance criterion. It would be less appropriate for roadway applications, however, because it would not model the speed and accuracy of visual response that are critical for safe driving. Rea and Ouellette (*13*) have recently extended Rea's (*11*) model using reaction times. They show that reaction times to low-contrast (e.g., 0.2) small (e.g., 2×10^{-6} steradians) targets will require more time to process at 1 cd/m^2 than at 10 cd/m^2. At 100 kph, or 28 m/s, their model predicts an incremental distance for avoidance of 11 m for a typical 20 year old and 22 m for a typical 65 year old (assuming there have only been changes in retinal illuminance with age). These calculations assume that at 1 cd/m^2 the 20 year old has a retinal illuminance of about 18 trolands and at 10 cd/m^2 retinal illuminance will be about 130 trolands. The 65 year old, on the other hand, will have retinal illuminances of about 10 and 76 trolands, respectively. Nevertheless, it is interesting to compare responses based upon "apparent visibility" (from magnitude estimations) and RVP (based on speed and accuracy) to the same stimuli.

RVP Versus Appearance

Subjects in two independent experiments were presented with lists of printed numbers having different contrast created by variations in the ink pigment density and the lighting geometry. In one experiment (*11*) subjects were obliged to read the numbers as quickly and accurately as possible. In the other experiment subjects were asked to rate, from 0 (threshold) to 10 (very black on white), the apparent contrast of the numbers; background luminance was held constant at 20 cd/m^2 in this experiment. Figure 7 compares the functions derived from the two experiments at 20 cd/m^2 and shows that for the same stimulus the suprathreshold visual responses are markedly different and depend upon the task required of the subjects. Under these stimulus conditions the RVP function, based upon speed and accuracy, follows a well documented, step-like function (*11,13*). On the other hand, the "apparent visibility" of the same numbers is an almost linear function of contrast. These different responses may have neurologically different bases in the visual system (*14,15*).

To establish a correct visibility performance criterion then, one must consider the driver's task. This will determine the appropriate visual model. Since speed and accuracy are critical to driver performance and appearance is not, the RVP model is more appropriate for roadway visibility criteria.

CONCLUSION

Two problems must be resolved before suitable recommendations and standards for roadway visibility can be established. First, an appropriate visibility performance criterion must be set, and second, practical techniques must be found for evaluating compliance with that criterion. Performance criteria based upon detection threshold are not appropriate because suprathreshold visibility must be considered. Although an "appearance" criterion would be based upon suprathreshold visual response, it does not consider the speed and accuracy of visual processing. Thus, a model of suprathreshold visual performance like RVP that is based upon speed and accuracy should be used in setting criteria for roadway performance.

In principle, then, it is possible to establish appropriate performance criteria for roadways using the RVP model. For example, on rural highways having little traffic, an RVP model of 0.50 might be recommended. Congested urban freeways

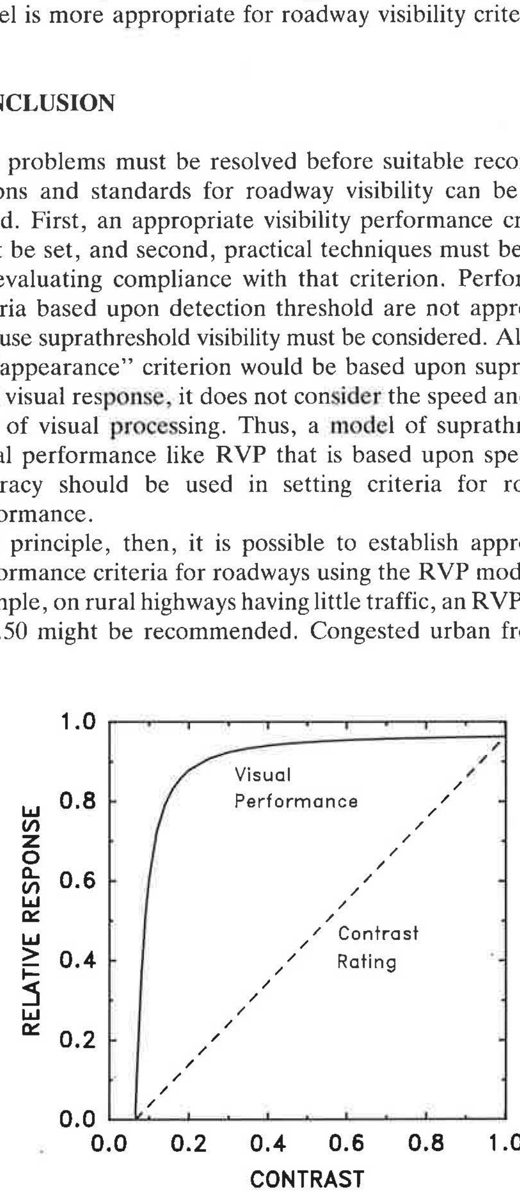

FIGURE 7 Two types of suprathreshold response to the same stimulus: printed five-digit numbers of different contrast. The solid line is based upon responses of speed and accuracy from the RVP model developed by Rea (*11*); the dashed line is from unpublished data using magnitude estimations of apparent contrast. Adaptation luminance was 20 cd/m^2 for both sets of data.

might require a higher recommended performance criterion of 0.80. Such standards would naturally translate into better roadway markings and illumination on urban freeways than on rural roadways. In essence, a priori performance criteria from the RVP model can be established by sanctioning bodies in accordance with "good practice." The roadway engineer would be left to achieve those performance levels with the most cost effective or innovative solutions.

To determine compliance with the recommended performance criterion, it is necessary to take measurements of the important stimulus aspects on the roadway. Subjective techniques using human beings as "instruments" are of dubious value for roadway applications. More conventional techniques employing tape measures and luminance spot photometers could be used, but they are impractical and prone to error. A computer-based imaging photometer like the NRCC CapCalc system can, however, acquire and store all of the relevant stimulus parameters (size, contrast and adaptation luminance) in a matter of seconds.

Such a device can also analyze the impact of these parameters on driver performance according to the recommended performance criteria. Software, implementing a recommended model of visual performance (based upon speed and accuracy), can be written to analyze the stimulus conditions on the highway. It can also incorporate transformations of the visual stimulus according to age-dependent changes in the optical characteristics of the eye. This one device can, therefore, acquire the relevant aspects of the stimulus and analyze their impact on visual performance in a matter of seconds.

SUMMARY

Current studies of the responses of the human visual system have produced a computational model of visual performance that is based upon speed and accuracy. Such a model is most appropriate for roadway visibility because speed and accuracy are important for safe driving. Specifications of minimum acceptable performance levels for different roadway applications can effectively guide roadway engineers in their designs.

Recent developments in imaging photometry enable engineers and enforcing bodies to determine whether specific roadway designs comply with requirements. Such systems make sophisticated evaluation of roadway visibility practical for the first time.

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