FINAL REPORT

EVALUATION OF NEW REFLECTIVE MATERIALS FOR OVERHEAD HIGHWAY SIGNAGE

by

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ABSTRACT

Unlighted highway signs using newly developed retroreflective materials were installed along the Gowanus Expressway. Photometric measurements of the signs were used to assess the visibility of the signs using the relative visual performance model. The calculated visibility of the unlighted signs was similar to that of a lighted sign conforming to present recommendations for exterior sign lighting. The results of a series of subjective observations of sign contrast suggest that individuals can see differences in sign appearance that could have little or no impact on visual performance.

1. INTRODUCTION

Overhead highway signs are an important part of the roadway visibility system (Van Derlofske et al., 2001). These signs provide drivers with information regarding destinations and driving maneuvers that will be required in order to reach those destinations. As such, overhead highway signs must be highly visible and legible so that drivers can detect, read and interpret the information contained on the signs in time to respond appropriately.

The Manual on Uniform Traffic Control Devices (MUTCD; FHWA, 2003) requires that guide signs (the typical green signs along highways that contain destination and exit information) be either *illuminated* or *retroreflective*. Illuminated signs could include those illuminated from behind (back-illuminated), using external luminaires that illuminate the face of the sign from the front, or using luminous elements such as light-emitting diodes (LEDs) to make up the characters of the signs. Retroreflective signs could include individual "button" elements that, in a similar manner to LEDs, would make up the characters on a sign, or materials that provide retroreflection over their entire surfaces. These latter materials are commonly used on modern highways. An advantage of retroreflective materials is that they do not require electrification because they rely on passive (and relatively efficient) reflection of light from vehicle headlamps back toward drivers. Since the angle between a driver's sight line to a sign and the light rays from the driver's headlamps is typically small, especially for far viewing distances, retroreflective materials are relatively good at directing the light from headlamps back toward a driver's eyes. As this angle increases, the luminance of a retroreflective material will generally decrease.

The specific properties of retroreflective materials have evolved as new approaches to efficiently redirecting light develop. Retroreflective sheeting materials are categorized into different types (ASTM, 2007) denoted by Roman numerals (e.g., type I, type II, type III, etc.). Generally speaking, the retroreflective properties of these materials tend to increase as the numerical type increases, but this is not the purpose of the numeric designations (they simply represent different types of performance), and some materials with higher numeric types could have narrower angular distributions than others such that their luminance might be brighter in a "head on" situation but lower in an "off-axis" situation. Some materials can meet the performance requirements for more than one ASTM type. A commonly used material for present-day sign applications is type III, an encapsulated lens material. Newer materials (with higher ASTM type numbers) use microprismatic reflectors to provide reflection of light toward the source.

A number of studies have been performed to investigate the effectiveness of different materials on sign visibility, either through photometric measurement of sign luminance, or through studies of visual performance or subjective evaluation. Generally, these studies have corroborated the promise of several newer reflective materials (e.g., types VII, VIII and IX) to provide superior performance to more commonly used materials (e.g., types I and III) in terms of higher luminances or longer legibility distances, for example (Bible and Johnson, 2002; Carlson and Hawkins, 2003; Carlson and Holick, 2005; Zwahlen et al., 2003). However, the relationship between a material type and its luminance is very dependent upon the light source used to illuminate the material, the geometry, location and angular displacement of the sign, age and cleanliness of the sign, the presence of ambient illumination, complexity of the surrounding environment, weather, and many other factors that are almost always beyond the control of highway engineering practice (Goodspeed and Rea, 1999; Hildebrand, 2003; Nuber and Bullock, 2002; Carlson and Urbanik, 2004). Some studies have not found reliable differences between encapsulated lens and microprismatic material types (Garvey et al., 1997).

Ultimately, the reason for desiring high levels of retroreflectivity of highway signs is to try to ensure sufficient luminances for adequate legibility of the characters on the signs. The relationship between luminances required for adequate legibility are dependent upon factors such as distance (which affects the apparent size of the characters) (Graham et al., 1997; Carlson and Hawkins, 2002; Holick and Carlson, 2002); observer age (Graham et al., 1997), the luminance contrast between the sign background and the characters (Schnell et al., 2004) and the type of characters on the sign (i.e., letters versus symbols) (Zwahlen and Schnell, 1998).

The American Association of State Highway and Transportation Officials (AASHTO, 2005) provides design light levels for illuminated signs when it is believed that retroreflectivity alone will not provide sufficient legibility of the sign. Recommended light levels are given in illuminance (lux or footcandles) and in luminance (cd/m²); there are also different levels for different degrees of ambient lighting in the environment ranging from low (rural areas without roadway lighting) to high (urban areas with high levels of roadway lighting, commercial signage and illuminated building façades). Because the luminaires used for exterior highway sign lighting are typically not located along the same axis as a driver's line of sight to the sign, the sign acts as a diffuse (Lambertian) reflector, with the relationship between the illuminance on a sign and the luminance of that sign defined by the following equation:

$$L = E\rho/\pi \qquad \text{(Equation 1)}$$

where L is the luminance (in cd/m²), E is the illuminance (in lux [10.76 lux = 1 footcandle]), and ρ is the reflectance of the sign (0=perfect black, 1=perfect white).

For practical reasons, much of the research on retroreflective sign legibility has taken place in locations that have relatively low levels of ambient illumination, such as unused roadways or decommissioned airport runways. Recently, the New York State Department of Transportation (NYSDOT) has installed several signs containing materials of ASTM (2007) types VIII, IX and a material meeting the specifications of a proposed type (XI, which is not presently defined by the ASTM) as well as those of an existing type (IX) in NYSDOT Region 11, along the Gowanus Expressway in Brooklyn, as part of an experimental investigation to evaluate visibility-related characteristics of *unlighted* signs constructed from these materials. The materials come from different manufacturers, and for the purpose of this report, are designated as follows:

- VIII_a: meets ASTM (2007) type VIII specifications
- VIII_b: meets ASTM (2007) type VIII specifications
- IX: meets ASTM (2007) type IX specifications
- proposed XI: meets proposed type XI and existing ASTM (2007) type IX specifications

For all of these signs, both the background and characters were constructed from the same type of material, in green and white, respectively.

These materials might potentially result in higher retroreflectivity, and therefore higher luminances, than signs constructed from type III materials usually used by NYSDOT for highway sign lighting. In addition, since the ambient illumination levels around the Gowanus Expressway are expected to be higher than those found in rural areas, such illumination might also contribute to sign luminance. Exterior illumination would normally be used for highway signage in such locations, but if the newer, unlighted materials could result in similar visibility as lighted signs, possible savings in terms of energy and maintenance might be achieved as a result, as well as reductions in light pollution.

The present report summarizes research activities undertaken by Rensselaer Polytechnic Institute's Lighting Research Center (LRC) to:

- Measure the luminances and luminance contrast values of the signs as installed along the Gowanus Expressway
- Measure the subjective appearance of signs of various luminance contrast values
- Estimate the visual performance of drivers approaching these signs compared to lighted signs meeting AASHTO (2005) recommendations for exterior sign lighting

These activities were conducted in a series of three phases, each outlined in a separate section of the present report.

2. PHOTOMETRIC MEASUREMENTS

On-Highway Measurements

The project team visited the locations along the Gowanus Expressway (Figure 1) in order to perform photometric measurements of the sign luminances. The site was visited on April 20 and on June 13, 2006. Nighttime measurements were made during both visits; daytime measurements were made during the latter visit only. Measurements were made with a spectroradiometer (PhotoResearch, SpectraScan 705) equipped with a telephoto lens. The spectroradiometer was mounted onto a tripod in a NYSDOT vehicle (Dodge Caravan) and driven, with a shadow vehicle behind it for safety, along the highway and stopped approximately 100 m (minimum 97 m, maximum 108 m, measured using a Bushnell lidar range finder). Care was taken to position the lens of the spectroradiometer as closely as possible to the vehicle driver's eye level.

Nine signs were installed along the Gowanus Expressway using the four materials described above: two type VIII_a signs, two type VIII_b signs, four type IX signs and one proposed type XI sign. For the daytime measurement session and the second nighttime measurement session, two additional type III signs were measured. While these latter signs were outfitted with exterior luminaires, the luminaires were not functioning at the time of measurement, so the type III signs were effectively unlighted.

Luminance measurements were made by positioning the measurement spot of the spectroradiometer onto three background and three character locations of the signs. Tables 1 through 3 list the measured luminances for each sign during each measurement session (nighttime session 1, daytime session 1, and nighttime session 2, respectively) as well as the luminance contrast calculated using the following equation:

$$C = |L_c - L_b|/\max(L_c, L_b) \qquad \text{(Equation 2)}$$

where C is the luminance contrast, L_c is the luminance of the characters (in cd/m^2) and L_b is the luminance of the background (in cd/m^2)

In equation 2, since the luminance of the white characters is higher than that of the green background, the maximum of the two will always be the luminance of the characters (L_c). This would not be true for a yellow sign containing black characters, for example.

Observation of the values in Tables 1 and 3 show that the luminances of the signs were generally much lower during nighttime session 2 than during nighttime session 1, although the luminance contrast values were similar between the two nighttime sessions (Figure 2). It was noted during nighttime session 2 that the vehicle used for measurements had headlamps with very cloudy lenses; the lower luminance values from this session are consistent with the lower expected light output of these headlamps. These lower luminances would not be expected to reduce the luminance contrast, since both the sign background and characters would have lower luminances.

Another observation from Tables 1 through 3 is that the luminance contrast values for the daytime session (mean 0.66) are consistently lower that for either of the nighttime sessions (mean 0.78). Such differences would not necessarily be expected since the luminance contrast is a function of the ratio of the reflectances of the green and white sign materials, which should not change significantly from nighttime to daytime. Part of the explanation for this difference is the possibility of scattered light in the telephoto lens of the spectroradiometer. Indeed, if a luminance of 300 cd/m² is subtracted from both the background luminances and the character luminances in Table 2, the resulting luminance contrasts would average 0.78 as they did during the nighttime sessions. Assuming a daytime sky luminance of 8000 cd/m² (IESNA, 2000), this corresponds to an average scatter of less than 4% of the overall luminance. Using a value of 2 cd/m² as representative of the luminous conditions in urban nighttime environments (Li et al., 2006), the nighttime luminance values in Tables 1 and 3 are probably higher by no more than 0.08 cd/m² owing to scattered light. This amount is quite small compared to the luminances in these two tables, and therefore, the values from these tables are used in subsequent analyses of visual performance for nighttime viewing conditions, assuming this amount of scatter can be considered to be negligible.

Finally, it should be noted that the nighttime luminance values in Tables 1 and 3 show significant variations even among the signs constructed form the same materials. As an example, signs #1 and #4, both constructed from type IX materials, had background luminances ranging from 0.9 to 3.4 cd/m² during nighttime session 1, and from 0.5 to 2.5 cd/m² during nighttime session 2. It should be recalled from the previous section of this report that the precise luminances of retroreflective materials can vary considerably based on a number of factors including the specific roadway geometry, the location of the signs, the precise amount of ambient light on the signs at each location, and the density of traffic along the highway during the measurement period. Therefore, it is not possible to quantify the relative impact of these factors and of the likely decreased headlamp illumination during nighttime session 2, when interpreting the values in Tables 1 through 3. It can only be stated that the range of values for each type of sign material demonstrates the range of luminances that can be found along the Gowanus Expressway. Certainly, the degree of variation limits the extent to which generalizations about the legibility of signs constructed from specific materials can be made.

Controlled Field Measurements

For comparison, the project team performed luminance measurements of the same green and white sign materials used in the signs installed along the Gowanus Expressway. NYSDOT provided 12-inch square material samples, which were mounted 100 m ahead of a properly-aimed projector headlamp set with projector optics (General Motors), and mounted 16 feet above the ground. The same spectroradiometer used during the field measurements along the Gowanus Expressway was used for these measurements, which occurred on July 11, 2006. The luminance of each sample was measured and luminance contrast values were calculated using Equation 2. The results of these measurements are listed in Table 4. In general they confirm the range of luminance contrasts measured during the nighttime sessions along the Gowanus Expressway. The luminance values of the background and characters of the sign materials are closer to those in Table 1 than in Table 3, consistent with the poor headlamp lens condition associated with the data in Table 3.

3. VISUAL PERFORMANCE ANALYSES

The photometric data in Tables 1 through 3 were used, along with photometric values calculated from the AASHTO (2005) guidelines for highway sign lighting, to estimate the visibility of these signs relative to lighted signs meeting AASHTO recommendations.

Relative Visual Performance Model

The basis for the visual performance analyses outlined in this section is the relative visual performance (RVP) model developed by Rea and Ouellette (1991). This model provides a basis for calculating the speed and accuracy with which visual information can be processed given a number of input parameters:

- Size of the visual target
- Luminance of the background around the visual target
- Luminance contrast between the visual target and its background
- Age of the observer

The RVP model (Rea and Ouellette, 1991) was based on the results of a series of experiments, some of which measured the response time to flashed targets of varying size and luminance contrast against backgrounds varying in luminance. Some of the experiments measured the speed and accuracy with which people could perform a numerical verification task consisting of pages printed with two matching columns each containing twenty five-digit numbers. On each page, anywhere from zero to six of the five-digit numbers contained a single mismatched digit, and subjects were instructed to identify these mismatches. This latter task was performed under a range of lighting and luminance contrast conditions. Of interest, the results of both types of experiments, despite obvious methodological differences, provided nearly identical results when converted to speed and accuracy of visual processing. Relative visual performance is compared to speed and accuracy of a reference condition corresponding to high light levels, high luminance contrast and large size (e.g., reading black 10-point type on white paper under typical office light levels), which is defined to have an RVP value of 1.0. RVP values close to 1.0 are expected to result in similar speed and accuracy as the reference visual task. RVP values of zero correspond to the threshold for legibility or recognition, and negative RVP values correspond to visual targets that can be detected but not recognized.

Figure 3 shows a three-dimensional surface plot of RVP for 10-point type varying in luminance contrast and against a background varying in luminance. When both luminance and luminance contrast are low, visual performance drops precipitously. Once both luminance and luminance contrast have reached nearly asymptotic values (close to 1.0), further increases in either luminance or luminance contrast will not result in substantial increases in visual performance. This *plateau and escarpment* nature of visual performance has been illustrated in many other experiments as well. Rea (1989) suggests an RVP value of 0.80 be used as a criterion for adequate visual performance along urban highways.

As described above, the size, background luminance, and luminance contrast of the visual target determine its visibility, but so does the age of the observer. Up to the age of about 70 years, the human visual system undergoes gradual changes, primarily with respect to the transmittance of light through the lens of the eye, and with respect to the size of the pupil (the aperture through which light enters the eye). The lens continues to increase in thickness and yellow, and the pupil size tends to become smaller as one ages, so that there is an approximately linear decrease in the amount of light reaching the retina as age increases. Figure 4 (Rea and Ouellette, 1991) illustrates this reduction in light as a function of age for 20 through 60 year old individuals. Until the age of about 70 years, these optical changes almost exclusively explain the reductions in visibility exhibited by older adults compared to younger adults. (After this age, neural and other physiological effects begin to contribute to visual deficits as well.)

The RVP model is referenced by the IESNA (2000) *Lighting Handbook* as one of the bases for assessing the impact of light levels for various lighting applications. An important consideration in the use of any predictive model of visibility is the degree to which the model has been independently validated. Eklund et al. (2001) performed an experiment in which subjects had to correctly identify alphanumeric codes of varying sizes (6 through 16 point text viewed from about 15 inches) printed in varying luminance contrasts (from 0.10 to 0.93) and background luminances (from 8 cd/m^2 to 2400 cd/m^2). The performance obtained from this experiment (Figure 5) was very highly correlated with the calculated RVP values.

In a context directly related to highway signs, Goodspeed and Rea (1999) studied the effects of luminance contrast and background luminance on people's ability to correctly identify the orientation of Landolt ring symbols similar in appearance to the letter "**C**". For simulated highway sign displays, subjects had to identify the direction of the gap in the symbol (e.g., for a properly oriented "**C**" the gap is to the right; for a rotated "℧" the gap is up). Subjects were presented conditions under varying levels of surround complexity as well as background luminance and luminance contrast. Goodspeed and Rea (1999) compared their data to predictions of response time generated by the RVP model, and except at the lowest luminance contrast, the RVP model very closely predicted the response times (Figure 6) measured by Goodspeed and Rea (1999), again reinforcing the ability to make and use predictions from the model.

In addition to the RVP values, the model also provides estimates of the visual processing time required for the visual target under consideration. As expected, lower values of RVP are associated with longer visual response times. Appendix 1 contains an algorithm for calculating RVP according to the model by Rea and Ouellette (1991).

Reference Conditions

In order to assess the visual performance of the signs measured along the Gowanus Expressway, they were compared to visual performance estimates for lighted signs meeting AASHTO (2005) recommendations for highway sign illumination. According to AASHTO (2005), the minimum recommended illuminances for highway signs are:

- 100 lux in areas of low ambient luminance (e.g., rural areas with little or no roadway or commercial lighting)

- 200 lux in areas of medium ambient luminance (e.g., urban areas with roadway and commercial lighting)
- 400 lux in areas of high ambient luminance (e.g., urban areas with high roadway light levels, commercial signage and illuminated building façades)

Information provided by NYSDOT engineering staff revealed that the location along the Gowanus Expressway would be classified as having a medium ambient luminance, so a value of 200 lux was assumed as the illuminance on the sign for the RVP calculations involving lighted signs. The diffuse reflectance of green ASTM type III sign material was assumed to be 0.09 based on ASTM (2007) specifications, resulting in a background luminance of 5.73 cd/m², according to Equation 1. Since the luminance contrast values of all sign materials measured along the Gowanus Expressway were similar, and averaged 0.78, this value was used for the luminance contrast of the sign in the RVP calculations for this sign.

Finally, the analyses assumed a driver age of 60 years old, and a letter height of 16 inches based on information provided by NYSDOT engineering staff.

Visual Performance Calculations

In addition to the nighttime reference sign condition, which assumed a lighted sign with a background reflectance of 0.09 and an illuminance of 200 lux on the sign surface, the data in Tables 1 through 3 were used to calculate response times and RVP values for these conditions, which are listed in Tables 5 through 7. The RVP values are also illustrated in Figures 8 through 10 for the two nighttime sessions and for the daytime measurements (for the daytime measurements, the nighttime reference condition is not illustrated because exterior illumination would not be used during the daytime).

Inspection of the data in Tables 5 and 6 and Figures 8 and 9 reveals that the calculated RVP values and visual response times for the unlighted signs are quite close to those for the reference conditions assuming illumination to AASHTO-recommended light levels. Some of the conditions during nighttime session 1 would result in improved visibility relative to the reference lighted sign condition, but none of the conditions in nighttime session 2 were as visible as the reference lighted sign condition. Nonetheless, all of the RVP values exceed 0.80, the value recommended by Rea (1989) as a visibility criterion for urban highways.

The visual response times listed in Tables 5 through 7 provide some utility in understanding the relative differences among the RVP values in these tables. From Table 7, for daytime viewing conditions, the average visual response time is 322 milliseconds. The visual response time for the illuminated sign is 366 milliseconds, a difference of 44 milliseconds. In other words, one might expect a 60-year-old observer to take 44 milliseconds longer to visually process the uppercase "E" character on a lighted sign at night than during the daytime. At a driving speed of 50 mph (22.4 m/sec), 44 milliseconds corresponds to a driving distance of 1.0 m.

For the data from nighttime session 1, the unlighted signs constructed from the newer materials would be expected to result in visual response times between 40 milliseconds and 87 milliseconds longer than for the average daytime sign (for the most and least visible signs in this set of data, respectively). These times correspond to driving distances from 0.9 to 1.9 m at 50 mph (22.4 m/sec). The difference in visual response times between daytime and nighttime are greater for nighttime session 2 (when the headlamp illumination was relatively poor): between 53 and 108 milliseconds longer for nighttime than for daytime conditions, corresponding to driving distances from 1.2 to 2.4 m at 50 mph (22.4 m/sec).

The visual target assumed for the analyses was a single uppercase letter "E." The visual task of reading a highway sign involves reading strings of characters to form meaningful words. However, it is unlikely that one simply detects and recognizes single characters in sequence. Shapes of words are also meaningful visual elements for reading (e.g., the word "Street," containing letters with ascenders, has a different shape profile than the word "Alley," which contains letters with both ascenders and descenders) and arguably, these shapes, having larger sizes than individual letters, could be relevant visual targets (Gibson and Levin, 1975). Individual parts of characters (e.g., the lower horizontal element of the letter "E" that is not present in the letter "F") are also meaningful visual targets in some cases. Reading speed data from Bailey et al. (1993) indicate that the size of the character is a reasonable visual target for reading. For the visual response times in Tables 5 through 7, an equation published by Bailey et al. (1993) relating RVP to reading speed (in words per second, for words averaging seven letters in length) estimates that the speed would be 3.1 words/second for daytime conditions, 2.9 words/second for the exterior-lighted sign illuminated to AASHTO (2005) recommendations, 2.6 to 2.9 words/second for signs #1 through #9 based on nighttime session 1, and 2.5 to 2.8 words/second for signs #1 through #9 based on nighttime session 2.

In general then, the calculated visibility of the unlighted signs constructed from new retroreflective materials as measured in the nighttime sessions along the Gowanus Expressway was close to, and sometimes exceeded, the visibility that could be expected from exterior illuminated signs. Differences in visual processing time were small, corresponding to 1 or 2 m of driving distance at a speed of 50 mph (22.4 m/sec), and probably have no practical significance in terms of one's ability to read and process the information on a sign. Estimated reading speeds for the nighttime sign measurements range from slightly longer to slightly shorter than those for the exterior-lighted signs.

Caveats

Of course, there are several caveats associated with the present visual performance analyses. The measured luminances and resulting RVP and visual response times are associated with a specific viewing distance of 100 m, corresponding to the distance at which photometric measurements were made. Because the retroreflective characteristics of different sign material types differ, the luminances of the signs would likely differ at different viewing distances. Additionally, as noted earlier, there were variations among signs constructed of the same materials, at least in part because of variations in roadway slope, sign location, overall traffic patterns and ambient light levels in specific locations.

4. SUBJECTIVE EVALUATIONS

The success of a highway sign installation is, of course, related to the ability of drivers to see the information on the sign. A separate but related issue pertains to the appearance of a sign. The RVP surface in Figure 3, for example, implies that visibility for the task represented in that figure is about the same whether the luminance contrast of the relevant visual target is 0.9 or 0.5. However, people will generally have very little difficulty differentiating a target with a luminance contrast of 0.9 from one with a luminance contrast of 0.5.

For example, Goodspeed and Rea (1999) measured the ability of subjects to correctly identify the orientation of symbols on simulated highway signs. The speed with which subjects could make correct identifications was closely predicted by the RVP model (Figure 7), but subjects' ratings of the contrast of the symbols was linearly related to the actual luminance contrast (Figure 11). Freyssinier et al. (2006) also reported that individuals reported contrast values that were linearly related to luminance contrast. Similarly, Rea (1989) presented visual performance and subjective data to the same targets (Figure 12) and showed that visual performance followed the plateau and escarpment trend, while ratings of apparent contrast were linearly related to contrast. The linear function in Figure 12 does not reach a value of zero when the luminance contrast is zero, however; once the luminance contrast is lower than the threshold contrast required for a target to be visible, it will be rated as having no contrast, even though it still has a non-zero value of luminance contrast.

The data in Figures 11 and 12 (Goodspeed and Rea, 1999; Rea, 1989) correspond to a relatively large range of luminance contrast values (e.g., from 0.0 or 0.2 to a value approaching 1.0). Inspection of the luminance contrast data in Tables 1 and 3 show that the entire range of luminance contrasts between the highest and lowest measured signs is 0.10 to 0.13 luminance contrast units, including the type III signs that were measured during nighttime session 2. In order to assess whether individuals can reliably discern among luminance contrasts differing by these amounts, the LRC project team conducted a series of subjective evaluations of luminance contrast.

Apparatus

The apparatus used for the evaluations consisted of two main systems: a tower with a dynamic presentation system and a computer control system.

The physical apparatus is illustrated in Figure 13. It was comprised of a 15 foot tall free-standing radio tower mounted to a weighted base. The various experimental conditions were presented to the subjects by means of a pentagonal rotating drum. Each of the five sides was equipped with a sign panel with a different luminance contrast (defined below). A non-reflective black shield with a window in the center was used to shield the other sides of the pentagon from the subjects' view. A reference sign panel, when used, was applied to this shield immediately adjacent and to the left of the test condition.

Sign panels were constructed from 12-inch-square pieces of green and white proposed type XI material. An 8-inch high uppercase letter "E" was cut into the green panel, which was affixed to the front of the white panel. Measurement of the luminance contrast of this panel under a lighting/observer geometry simulating the same angles as a driver from 100 m showed the luminance contrast of this panel to be 0.83. Reduced-contrast panels were constructed by inserting 12-inch square sheets consisting of neutral density filters (Rosco, Filter #00) between the green and white pieces. Insertion of one, two, three and four filter sheets resulted in luminance contrast values of 0.78, 0.72, 0.65 and 0.56, respectively, when measured in the same way as the unfiltered sign panel. Other than the gradual reduction in the resulting luminance of the white letter "E," the use of multiple sheets did not result in any other changes in the appearance of the character, such as the possibility of spectral shifts or creation of multiple reflections among the individual filter sheets.

The pentagonal drum was rotated by an electrical gear motor. A system of limit switches was used to stop the drum when the desired test condition was in the proper viewing position. When the limit switch for the test condition was activated, the gear motor was used as an electrical brake to ensure that the drum did not “coast” past the correct position. Electrical braking also helped to insure repeatable positioning of the test conditions.

The computer control system used consisted of a microcontroller (to act as an interface with the electrical hardware of the experimental apparatus) and laptop computer (used to interact with the observers and to control the microcontroller). The following briefly explains how the two components worked together.

The computer software routine (written using National Instruments LabVIEW software) first acquired some information about the observer and experimental conditions, which was inputted using the laptop computer. When the experimental sequence was initiated by the experimenter, the software communicated to the microcontroller which condition to display. The microcontroller, in turn, started the electrical motor and monitored the limit switches. When the correct limit switch was activated, the motor was immediately stopped (as described above). The microcontroller then performed a check to ensure that the drum had not overshot the correct stopping position. If the check passed, then the microcontroller reported success to the laptop computer. If the check resulted in failure, the software would be notified of this and would prompt the experimenter for intervention.

If the software received confirmation that the correct condition was being displayed, it prompted the experimenter to obtain a rating from the observer. The experimenter then entered the rating into the software, which in turn stored it and communicated the next condition to the microcontroller. This process continued for all of the experimental conditions.

At the end of a set of experimental conditions, the experimenter was prompted to save or discard the observers’ responses before the software restarted the experimental sequence for the next observer. If the experimenter opted to save the data, a unique file was created for that observer’s responses. These files contained the observer’s initials, any notes the experimenter included, and the paired contrast and response data.

Condition Presentation Sequences

Two display sequences were used for the subjective ratings. The observers were asked not to watch as the drum rotated during transitions between conditions so that they would not be biased.

In the first sequence (denoted *side-by-side* viewing), the reference condition (defined as the sign panel with a luminance contrast of 0.83) was continuously displayed (as shown in Figure 13) to the left of the condition presented. The test conditions (with luminance contrasts of 0.56, 0.65, 0.72, 0.78, and 0.83) were presented to and rated by the observers in a randomized order as many times as specified by the experimenter.

In the second sequence (denoted *sequential* viewing), the fixed reference sign was removed. The experimental sequence started by displaying the reference condition (i.e., the panel with the luminance contrast of 0.83). Next, each of the contrast conditions (luminance contrasts of 0.56, 0.65, 0.72, 0.78, and 0.83) were displayed in random order and rated by the observers. The reference was then shown again before repeating the randomized display of the five luminance contrast conditions. This process was repeated as many times as specified by the experimenter.

From a practical point of view, sequential viewing is probably more representative of what a driver would experience while driving along a highway and viewing individual signs in sequence. One would not expect highway signs to be located adjacent to a standard sign type of known visibility characteristics. If individuals are judging the appearance of signs while driving, judgments of signs might be made in comparison to the remembered appearance of previously viewed signs. However, one would expect that side-by-side viewing would result in greater sensitivity to luminance contrast differences among signs, since a reference condition would always be visible against which any other conditions could be compared directly.

Response Scale

Observers were told that the reference sign panel (having a luminance contrast of 0.83) was defined as having a contrast rating value of 10, and that for the test panels in each sequence, they should provide their estimate of the contrast rating for each test panel. Contrast ratings greater than 10 were permitted if an observer felt that a particular sign panel had a higher contrast than the reference, even though the luminance contrast of all of the test panels was either lower than, or equal to, the reference panel.

Results: Side-by-Side Viewing

Side-by-side observations were conducted during two nighttime sessions. During the first session (which took place on November 7, 2007 along an unused runway at the Schenectady County Airport), observers sat in a vehicle parked behind a properly aimed halogen headlamp set (General Motors, projector headlamps) located 100 m from the apparatus shown in Figure 13. Some of the observers during the first session included individuals from NYSDOT. During this first session, several observers noted that the letter "E" on the sign panels seemed difficult to read. For this reason, a subsequent side-by-side observation session (which took place on November 13, 2007 in the parking lot of the Lighting Research Center building) occurred using a viewing distance of 60 m from the sign panels. Subsequent analysis of the data from these two sessions revealed no substantial differences in rating values between the 100 m and 60 m distances, so the rating data from both sessions were combined.

Ten observers provided ratings to the test sign panels at each contrast. Three repetitions at each luminance contrast were planned; mechanical issues brought on by cold temperature made it impossible to complete all of the repetitions for all subjects. Figure 14 shows the mean rating values along side a linear function that represents "perfect" ratings whereby a rating of 10 is associated with a luminance contrast of 0.83, and a rating of zero is associated with a threshold luminance contrast of 0.06 (this is the average threshold contrast value from Tables 5 and 6 for nighttime viewing. In general, the rated values are very close to the predictions based on a linear relationship between luminance contrast and rating values.

A within-subjects, one-way analysis of variance (ANOVA) performed on the side-by-side rating data, revealing a statistically reliable ($p<0.05$) effect of luminance contrast on the rating values. Since a one-way ANOVA only indicates that at least two luminance contrasts resulted in reliably different contrast ratings, pairwise comparisons using Student's t-tests (applying the Bonferroni [McGuigan, 1990] correction using a reliability criterion of $p<0.05$) were used to identify which luminance contrasts resulted in reliably different ratings. In general, adjacent luminance contrasts were not reliably different from one another. The average minimum contrast difference required to obtain statistically significant differences in ratings was found to be 0.13.

Results: Sequential Viewing

Sequential observations were conducted during the same two nighttime sessions as the side-by-side observations. The same headlamp set was used, but both sessions used a viewing distance of 60 m from the sign panels. Some of the observers during the first session included individuals from NYSDOT.

Nine observers provided ratings to the test sign panels at each contrast. Three repetitions at each luminance contrast were planned; as in the side-by-side conditions, mechanical issues brought on by cold temperature made it impossible to complete all of the repetitions for all subjects. Figure 15 shows the mean rating values along side a linear function that represents "perfect" ratings. The rated values tend to be lower than the predicted values based on the dotted line in Figure 15, but still follow a largely linear function.

A within-subjects ANOVA of the sequential data revealed a statistically reliable ($p<0.05$) effect of luminance contrast on the rating values. Pairwise, Bonferroni-corrected (McGuigan, 1990) Student's t-tests were used to identify which luminance contrasts resulted in reliably different ratings. As with the side-by-side data, adjacent luminance contrasts were not reliably different from one another; sometimes even the ratings from two contrast steps apart were not reliably different. Inspection of Figure 15 reveals that the standard deviations for the sequential ratings are larger than those for the side-by-side ratings. The average minimum contrast difference required to obtain statistically significant ($p<0.05$) differences in ratings was found to be 0.14, slightly higher than for side-by-side viewing, but consistent with the idea that rating judgments were somewhat more difficult under sequential than under side-by-side viewing.

Discussion of Subjective Evaluations

The results from the subjective observations revealed that either side-by-side or sequential viewing would require a luminance contrast range of at least 0.14 in order to expect drivers to reliably tell signs apart under sequential viewing conditions. Since the measured luminance contrasts for the signs measured along the Gowanus Expressway ranged 0.10 to 0.13 luminance contrast units total, it would be unlikely that subjective evaluations of sign contrast while driving or riding along this highway would reveal that any of the signs using new reflective materials were reliably different from one another. Nonetheless, the data from the present series of observations confirm the expectations from Goodspeed and Rea (1999), Rea (1989) and Freyssinier et al. (2006) that observers can quite reliably estimate luminance contrast of visual targets such as highway sign characters.

5. DISCUSSION AND CONCLUSIONS

Conspicuity of Highway Signs

One consideration outside the scope of the present study is the conspicuity of the signs themselves; that is, the degree to which the sign stands out against its surrounding visual environment. Forbes (1972) summarized research on highway sign conspicuity and reported that the luminance contrast between the sign and its surrounding background, the luminance contrast between the sign and its characters, and the smallest dimension of the sign were the primary factors that determined the distance at which a sign could be recognized as a sign (but not when the message on the sign could be ascertained). The absolute luminance of the sign was reported by Forbes (1972) to be of secondary importance compared to its contrast against its background. Forbes (1972) reported that the distance at which a sign could be detected against its background (not the distance at which the sign is legible) could be estimated by the following equation:

$$D = 600h(C_{sign} + C_{letter}) \qquad \text{(Equation 3)}$$

where D is the predicted detection distance in m, h is the height (or smallest dimension of the sign) in m, C_{sign} is the luminance contrast between the green sign background and its surrounding environment, and C_{letter} is the luminance contrast between the letters and sign background (these contrasts are calculated using Equation 2).

Using a luminance value of 2 cd/m² as a representative value for urban locations (Li et al., 2006), and a sign height of 2.3 m based on information provided by NYSDOT engineering staff, Figure 16 shows the predicted detection distances for a range encompassing the measured nighttime sign luminances and luminance contrasts in the present study given in Tables 1 and 3. It should be noted that the luminances of the signs at distances other than 100 m will be different from those in Tables 1 and 3. Nonetheless, the model from Forbes (1972) predicts that detection distances would always exceed 1000 m, even when the luminance of the sign background equals that of the surrounding visual environment.

There is some evidence that under very complex nighttime visual environments, sign luminances even higher than those resulting from illumination meeting AASHTO (2005) recommendations (i.e., 5.73 cd/m²) would improve detection times for signs (Schieber and Goodspeed, 1997). Only two sign luminances were used in the study by Schieber and Goodspeed (5 cd/m² and 50 cd/m², resulting in detection times of 1.6 and 1.3 seconds, respectively), so the effects for luminances between these values (e.g., 10 cd/m²) are unknown.

Conclusions

The measured luminance values and the resulting calculated luminance contrasts, RVP and visual response values, generally indicate that the unlighted highway signs constructed from new retroreflective materials installed along the Gowanus Expressway are similar, in terms of visual performance, to exterior-lighted signs meeting AASHTO (2005) recommendations for sign illumination, when viewed from 100 m away. Specific factors, including location of the signs relative to the vehicles, headlamp condition, ambient illumination and others will affect the actual luminance of a sign's background and characters. All of the RVP values for the unlighted signs exceeded the value of 0.8 suggested as a possible criterion for urban highways by Rea (1989).

The RVP model (Rea and Ouellette, 1991) has been validated in a number of contexts including a study of simulated highway sign performance (Goodspeed and Rea, 1999). This model provides a tool for *a priori* predictions of visibility of signs to help ensure that they are adequately visible, provided the size of the relevant detail, the luminances of the background and characters, and the observer's age can be defined. Several software packages exist that purport to assist the user in calculating luminance values for retroreflective materials based on geometrical inputs and information about vehicle headlamps provided by the user (Avery Dennison, 2002; University of Iowa, 2004). At least one of these packages was developed by a manufacturer of such materials and only permits assessment of materials from that manufacturer. These software packages were not evaluated as part of the present study. However, if such software packages are reasonably accurate and if manufacturers can provide independent retroreflectivity data for their materials, they could be used in conjunction with the RVP model (Rea and Ouellette, 1991) by a transportation agency to confirm that sign legibility is at or above a specified RVP level (e.g., 0.8) for a range of viewing distances appropriate for a specific roadway location.

For example, if an agency wants to ensure that a sign has sufficient legibility between 50 m and 200 m away from the sign, the predicted luminances of the sign background and characters could be calculated for distances between 50 and 200 m in 10-m steps. By calculating the solid angular size of the letters at each distance, and assuming a particular "design driver" age, RVP values for each distance could be calculated using the equations in Appendix 1. Such calculations could be performed for specific headlamp types or for a market-weighted "average" headlamp (e.g., Schoettle et al., 2002).

Finally, even though the visual performance characteristics for these unlighted signs are all quite similar to lighted signs meeting ASSHTO (2005) recommendations for exterior illumination, the results of the subjective rating observations provide a caveat that people might notice differences in sign appearance before those differences would substantially affect visual performance. Agencies using RVP as a factor in the specification of adequate sign visibility should consider subjective sign appearance as well.

6. STATEMENT OF IMPLEMENTATION

This report describes the photometric conditions of several unlighted retroreflective overhead guide signs installed along a highway in New York State. Through this research project, a potential approach to characterizing the visibility of such signs relative to lighted signs has been developed. NYSDOT intends to disseminate this final report internally to its eleven regions. Although further research and analysis is recommended, the information within the report offers the Regional Offices a starting point in assessing the visibility of unlighted signs in other locations using a variety of different retroreflective materials.

7. REFERENCES AND ANNOTATIONS

American Association of State Highway and Transportation Officials. 2005. *Roadway Lighting Design Guide*. Washington, DC: American Association of State Highway and Transportation Officials.

- Illuminance and luminance levels for lighted signs in areas with low, medium and high ambient luminance conditions are specified.
- The minimum recommended illuminance for signs in medium ambient luminance areas is 200 lx.

American Society for Testing and Materials International. 2007. *Standard Specification for Retroreflective Sheeting for Traffic Control*, D 4956-07. West Conshohocken, PA: American Society for Testing and Materials International.

- Minimum reflectance and retroreflectivity values (in cd/m²/lx) for different material types (designated by Roman numerals) are specified.

Avery Dennison Reflective Products Division. 2002. *ERGO2001 User's Guide.* Pasadena, CA: Avery Dennison.

- A software package that calculates retroreflective sign material luminance for user-specified geometries is described.

Bailey I, Clear R, Berman S. 1993. Size as a determinant of reading speed. *Journal of the Illuminating Engineering Society* 22(2): 102.

- Subjects were presented words that were four, seven and ten letters in length, of varying size and luminance contrast, against backgrounds of varying luminance.
- Results were compared to the relative visual performance model and found to have good agreement; a transformation between visual performance related quantities and reading speed was provided.

Bible RC, Johnson N. 2002. Retroreflective material specifications and on-road sign performance. *Transportation Research Record* (1801): 61.

- For overhead guide signs constructed from Type VII and Type VIII materials, luminances of about 3 cd/m² are obtained from large truck headlamps at a 105 m viewing distance.
- Type IX signs under the same viewing conditions had luminances of about 6 cd/m².

Carlson PJ, Hawkins G. 2003. Legibility of overhead guide signs with encapsulated versus microprismatic retroreflective sheeting. *Transportation Research Record* (1844): 59.

- Subjects viewed signs constructed of Type III and Type IX materials (same material for both background and characters) under sealed-beam and replacement-bulb headlamps; legibility distances were 5% longer for Type IX under sealed-beam illumination and 16% longer for Type IX under replacement-bulb illumination.
- Legibility distances were 15% longer under sealed-beam illumination than under replacement-bulb illumination.

Carlson PJ, Hawkins HG. 2002. Minimum retroreflectivity for overhead guide signs and street name signs. *Transportation Research Record* (1794): 38.

- For drivers older than 55 years, the minimum necessary luminance for legibility at a 640 ft viewing distance was 2.3 cd/m².
- For the same observers at a viewing distance of 480 and 320 ft, the minimum luminances for legibility were 0.9 and 0.3 cd/m², respectively.

Carlson PJ, Holick A. 2005. Maximizing legibility of unlit freeway guide signs with Clearview font and combinations of retroreflective sheeting materials. *Transportation Research Record* (1918): 26.

- Sign material combinations providing the best to worst legibility distances in that order were (material combinations are given as background/characters): Type IX/VIII, Type III/IX, Type IX/IX, Type III/VIII, Type III/III.
- Legibility distances were assessed under low-beam headlamps on a passenger car; older subjects had shorter legibility distances than younger subjects.

Carlson PJ, Urbanik T. 2004. Validation of photometric modeling techniques for retroreflective traffic signs. *Transportation Research Record* (1862): 109.

- Estimates of luminance of retroreflective signs based on calculations were generally close to measured values (goodness of fit r^2 values from 0.63 to 0.90).
- Indirect illuminance (reflected from pavement) had little contribution to sign luminance for typical viewing geometries.

Eklund NH, Boyce PR, Simpson SN. 2001. Lighting and sustained performance: Modeling data-entry task performance. *Journal of the Illuminating Engineering Society* 30: 126.

- Speed and accuracy of visual processing of alphanumeric characters of varying sizes, contrasts and under varying light levels was found to be closely predicted by the relative visual performance model.

Federal Highway Administration. 2003. *Manual on Uniform Traffic Control Devices.* Washington, DC: Federal Highway Administration.

- Guide signs along highways are required to be either illuminated or retroreflective.

Forbes TW (ed.). 1972. *Human Factors in Highway Traffic Safety Research*. New York, NY: Wiley.

- Primary factors determining a highway sign's conspicuity are luminance contrast of the sign against its visual surround, luminance contrast of the letters against the sign background, and the size of the sign.
- Luminance of the sign was a relatively minor factor in determining its conspicuity.

Freyssinier JP, Rea MS, Bullough JD. 2006. Brightness contrast perception in the mesopic region. *Ophthalmic and Physiological Optics* 26(3): 300.

- Judgments of brightness contrast of various colored chips against white backgrounds, at several light levels in the mesopic range (between 0.1 and 3 cd/m²) were found to be closely linearly related to the measured luminance contrasts.

Garvey PM, Pietrucha MT, Meeker D. 1997. Effects of font and capitalization on legibility of guide signs. *Transportation Research Record* (1605): 73.

- Signs constructed from encapsulated lens material (ASTM type III) and from microprismatic material had no difference in terms of recognition distance (the distance at which subjects could correctly identify which of three words on a sign was the one they were trying to identify) during daytime and nighttime viewing, for older observers.
- Signs constructed from microprismatic material had marginally longer daytime legibility distances than those from encapsulated lens material, but there were no differences between sign materials for nighttime viewing.

Gibson EJ, Levin H. 1975. *The Psychology of Reading.* Cambridge, MA: MIT Press.

- Depending upon the context, the relevant visual unit in the reading task could be part of a letter, an entire letter, or the shape of an entire word.

Goodspeed CH, Rea MS. 1999. The significance of surround conditions for roadway signs. *Journal of the Illuminating Engineering Society* 28(1): 164.

- Observers (age 50 years), in simulated 200-ft viewing conditions, identified the orientation of a symbol more quickly when a border of at least the symbol width was located around the sign.
- Response times to high contrast symbols were unaffected by border width and were well-predicted by the relative visual performance model.
- Subjects could accurately assess symbol contrast in a linear manner.

Graham JR, Fazal A, King LE. 1997. Minimum luminance of highway signs required by older drivers. *Transportation Research Record* (1573): 91.

- At a viewing distance of 90 m and 6-in. character height, young (≤25 years) subjects required less than 2.7 cd/m² for 50%-correct legibility, and 28.8 cd/m² for 100%-correct legibility; older (≥65 years) subjects required 28.8 cd/m² and more than 40.2 cd/m² for 50%- and 100%-correct legibility, respectively.
- At a viewing distance of 60 m and 6-in. character height, young subjects required less than 1 cd/m² and 1.7 cd/m² for 50%- and 100%-correct legibility, respectively; older subjects required 2.2 cd/m² and 7.8 cd/m² for 50%- and 100%-correct legibility, respectively.

Hildebrand ED. 2003. Reductions in traffic sign retroreflectivity caused by frost and dew. *Transportation Research Record* (1844): 79.

- Frost caused reductions in Type I and III sign material retroreflectivity of 79%, on average.
- Dew caused reductions in Type I and III sign material retroreflectivity of 60%, on average.

Holick AJ, Carlson PJ. 2002. Model of overhead-sign luminance needed for legibility. *Transportation Research Record* (1801): 80.

- From a model developed in the paper, it is predicted that a sign luminance of 5 cd/m² will provide legibility distances up to 325 ft for 16-in. letters for a 65-year-old driver with 20/40 visual acuity.
- A luminance of 7 cd/m² under the same conditions and observer is predicted to provide 350 ft of legibility distance.
- A luminance of 10 cd/m² under the same conditions and observer is predicted to provide 375 ft of legibility distance.

Illuminating Engineering Society of North America. 2000. *IESNA Lighting Handbook: Reference and Application*, 9th Edition (Rea MS, editor). New York, NY: Illuminating Engineering Society of North America.

- An average sky luminance value of 8000 cd/m² is described.
- The relative visual performance model is described as a valid method for assessing visibility produced by a lighting installation.

Li Q, Yang G-X, Yu L-H, Zhang H. 2006. A survey of the luminance distribution in the nocturnal environment in Shanghai urban areas and the control of luminance of floodlit buildings. *Lighting Research and Technology* 38(3): 185.

- A background luminance of 2 cd/m² is proposed as a representative luminance value for typical urban environments, based upon a survey of luminances in various locations.

McGuigan FJ. 1990. *Experimental Psychology: Methods of Research,* 5th Edition. Englewood Cliffs, NJ: Prentice Hall.

- The procedure for adjusting the criterion probability level when conducting multiple pairwise Student's t-tests using the Bonferroni correction is presented.

Nuber L, Bullock D. 2002. Comparison of observed retroreflectivity values with proposed FHWA minimums. *Transportation Research Record* (1794): 29.

- For sign materials (blue, red, green, white and yellow Type III, and white Type I) in service for 10 or 11 years, cleaning resulted in increases in retroreflectivity of up to 8%.
- On average, Type III sign materials lost between 2 and 3 retroreflectivity units (cd/m²/lx) per year.

Rea MS. 1989. Visibility criteria and application techniques for roadway lighting. *Transportation Research Record* (1247): 12.

- A relative visual performance value of 0.8 is suggested as a criterion for visibility along urban highways.
- Visual performance tends to exhibit asymptotic behavior once it reaches a high level, but subjective appearance (e.g., judgments of luminance contrast) tend to follow a more linear function of contrast.

Rea MS, Ouellette MJ. 1991. Relative visual performance: A basis for application. *Lighting Research and Technology* 23(3): 135.

- The speed and accuracy of visual processing is related to the size and luminance contrast of a relevant visual target, the background luminance and the age of the observer.
- A mathematical procedure for calculating relative visual performance (RVP) is provided in Appendix 1.

Schieber F, Goodspeed CH. 1997. Nighttime conspicuity of highway signs as a function of sign brightness, background complexity and age of observer. In *Proceedings of the Human Factors and Ergonomics Society* (pp. 1362-1366). Santa Monica, CA: Human Factors and Ergonomics Society.

- Simulated sign luminances of 5 cd/m^2 or 50 cd/m^2 were presented in scenes of varying visual complexity.
- Higher sign luminances resulted in shorter detection times and more accurate color identification only for the most visually complex backgrounds.

Schnell T, Aktan F, Li C. 2004. Traffic sign luminance requirements of nighttime drivers for symbolic signs. *Transportation Research Record* (1862): 24.

- For high contrast signs (in negative contrast, with black symbols on colored backgrounds), sign luminances higher than 82 cd/m^2 did not improve recognition.
- For very low negative contrast signs, luminances up to 942 cd/m^2 continued to improve recognition, but low contrast signs are atypical for symbolic signs such as pedestrian crossing signs.
- Neither background complexity nor observer age significantly affected the results of this study.

Schoettle B, Sivak M, Flannagan MJ. 2002. High-beam and low-beam headlighting patterns in the U.S. and Europe at the turn of the millennium. In *Advanced Lighting Technology for Vehicles*, SP-1668 (pp. 71-92). Warrendale, PA: Society of Automotive Engineers.

- Luminous intensity distributions for low- and high-beam headlamps were measured and weighted according to the penetration in the market.
- A "median" headlamp beam distribution is presented for U.S. and European vehicles.

University of Iowa Operator Performance Library. 2004. *User Manual for the Target Visibility Predictor Computer Model.* Iowa City, IA: University of Iowa.

- A software package that calculates retroreflective sign material luminance for user-specified geometries is described.

Van Derlofske J, Bullough JD, Lingard R, Rea MS. 2001. Roadway lighting: A systems approach. *Illuminating Engineering Society of Australia and New Zealand Annual Convention* (p. 183), Auckland, New Zealand, April 20-22. Auckland, New Zealand: Illuminating Engineering Society of Australia and New Zealand (New Zealand).

- Components of different systems for providing roadway visibility can interact with one another.
- For example, the addition of roadway and vehicle lighting can reduce contrast of some objects relative to the presence of only one of these forms of lighting.

Zwahlen HT, Russ A, Vatan Ş. 2003. Nighttime expert panel and photometric evaluations of unlighted overhead guide signs. *Transportation Research Record* (1844): 67.

- Experts rated the following four unlighted overhead sign material combinations as best to worst in the following order (material combinations are given as background/characters): Type III/IX, Type III/VII, Type IX/IX, Type III/III.
- Tests were made under clear, dark, straight- and flat-road conditions under one type of vehicle headlamps.

Zwahlen HT, Schnell T. 1998. Legibility of traffic sign text and symbols. *Transportation Research Record* (1692): 142.

- For a variety of signs (text, symbolic, Landolt ring) and contrast polarities, average nighttime legibility was 32.5 ft per in. of character/symbol height.
- Text signs resulted in slightly longer legibility distances (40 ft/in.) than symbolic signs (30 ft/in.).

TABLES AND FIGURES

Table 1. Mean luminances (and standard deviations of three measurements) of the backgrounds and characters for each sign measured during nighttime session 1, along the Gowanus Expressway.

Sign and type	Background luminance, cd/m² (std. deviation)	Character luminance, cd/m² (std. deviation)	Luminance contrast
#1 - IX	3.4 (0.7)	19.7 (3.1)	0.83
#2 - IX	1.4 (0.1)	7.4 (0.4)	0.81
#3 - IX	1.6 (0.2)	9.6 (3.3)	0.83
#4 - IX	0.9 (0.1)	5.0 (1.4)	0.81
#5 - $VIII_a$	6.0 (0.1)	27.0 (1.1)	0.78
#6 - $VIII_a$	6.9 (2.3)	26.9 (5.1)	0.75
#7 - proposed XI	6.9 (0.6)	37.4 (6.4)	0.81
#8 - $VIII_b$	2.5 (0.8)	9.6 (0.4)	0.73
#9 - $VIII_b$	4.9 (1.6)	15.9 (1.2)	0.70

Table 2. Mean luminances (and standard deviations of three measurements) of the backgrounds and characters for each sign measured during daytime session 1, along the Gowanus Expressway.

Sign and type	**Background luminance, cd/m² (std. deviation)**	**Character luminance, cd/m² (std. deviation)**	**Luminance contrast**
#1 - IX	540 (24)	1574 (24)	0.66
#2 - IX	501 (17)	1225 (44)	0.59
#3 - IX	468 (50)	1243 (31)	0.62
#4 - IX	393 (10)	1013 (5)	0.61
#5 - VIII_a	483 (16)	1157 (75)	0.58
#6 - VIII_a	497 (13)	1212 (43)	0.59
#7 - proposed XI	806 (119)	1678 (144)	0.52
#8 - VIII_b	995 (6)	3492 (1)	0.71
#9 - VIII_b	988 (32)	3878 (226)	0.74
#10 - III	540 (6)	1103 (65)	0.51
#11 - III	599 (44)	1437 (110)	0.58

Table 3. Mean luminances (and standard deviations of three measurements) of the backgrounds and characters for each sign measured during nighttime session 2, along the Gowanus Expressway.

Sign and type	Background luminance, cd/m² (std. deviation)	Character luminance, cd/m² (std. deviation)	Luminance contrast
#1 - IX	2.5 (0.7)	12.1 (3.6)	0.79
#2 - IX	0.8 (0.2)	4.3 (0.4)	0.83
#3 - IX	0.8 (0.1)	5.1 (1.4)	0.83
#4 - IX	0.5 (0.1)	3.4 (0.8)	0.84
#5 - $VIII_a$	2.1 (0.4)	9.4 (0.7)	0.78
#6 - $VIII_a$	1.9 (0.1)	10.1 (0.3)	0.81
#7 - proposed XI	2.3 (0.7)	10.9 (2.4)	0.79
#8 - $VIII_b$	3.6 (0.7)	14.3 (3.2)	0.74
#9 - $VIII_b$	3.4 (0.5)	15.7 (2.9)	0.79
#10 - III	1.3 (0.3)	6.7 (3.7)	0.78
#11 - III	0.5 (0.1)	2.8 (0.4)	0.83

Table 4. Luminances of the backgrounds and characters for each sign material measured during the control nighttime session, along an unused runway at the Schenectady County Airport.

Material type	Background luminance, cd/m²	Character luminance, cd/m²	Luminance contrast
IX	2.52	11.32	0.78
VIII_a	1.49	7.38	0.80
proposed XI	2.63	18.81	0.86
VIII_b	1.76	10.06	0.83
III	2.63	8.66	0.70

Table 5. RVP values, visual response times and threshold contrast values for the signs measured along the Gowanus Expressway during nighttime session 1, as well as for a reference sign illuminated to AASHTO (2005) guidelines for locations with medium ambient luminance. All calculations assume a 60-year-old observer and a visual target consisting of a 16-inch uppercase "E."

Sign and type	**Threshold luminance contrast**	**Visual response time (milliseconds)**	**RVP value**
#1 - IX	0.05	373	0.94
#2 - IX	0.06	394	0.91
#3 - IX	0.06	390	0.92
#4 - IX	0.07	409	0.89
#5 - VIII_a	0.05	365	0.95
#6 - VIII_a	0.05	364	0.95
#7 - proposed XI	0.05	362	0.96
#8 - VIII_b	0.06	384	0.93
#9 - VIII_b	0.05	373	0.94
AASHTO illuminated	0.05	366	0.95

Table 6. RVP values, visual response times and threshold contrast values for the signs measured along the Gowanus Expressway during nighttime session 2, as well as for a reference sign illuminated to AASHTO (2005) guidelines for locations with medium ambient luminance. All calculations assume a 60-year-old observer and a visual target consisting of a 16-inch uppercase "E."

Sign and type	Threshold luminance contrast	Visual response time (milliseconds)	RVP value
#1 - IX	0.06	381	0.93
#2 - IX	0.08	415	0.89
#3 - IX	0.07	411	0.89
#4 - IX	0.09	430	0.87
#5 - VIII_a	0.06	386	0.92
#6 - VIII_a	0.06	386	0.92
#7 - proposed XI	0.06	383	0.93
#8 - VIII_b	0.05	375	0.94
#9 - VIII_b	0.05	375	0.94
#10 - III	0.07	399	0.91
#11 - III	0.09	436	0.86
AASHTO illuminated	0.05	366	0.95

Table 7. RVP values, visual response times and threshold contrast values for the signs measured along the Gowanus Expressway during daytime session 1. All calculations assume a 60-year-old observer and a visual target consisting of a 16-inch uppercase "E."

Sign and type	Threshold luminance contrast	Visual response time (milliseconds)	RVP value
#1 - IX	0.02	322	1.01
#2 - IX	0.02	322	1.01
#3 - IX	0.03	323	1.01
#4 - IX	0.03	324	1.00
#5 - $VIII_a$	0.02	324	1.00
#6 - $VIII_a$	0.02	323	1.01
#7 - proposed XI	0.02	320	1.01
#8 - $VIII_b$	0.02	319	1.01
#9 - $VIII_b$	0.02	318	1.01
#10 - III	0.02	323	1.01
#11 - III	0.02	321	1.01

Figure 1. Map of the Gowanus Expressway (from www.nysdot.gov).

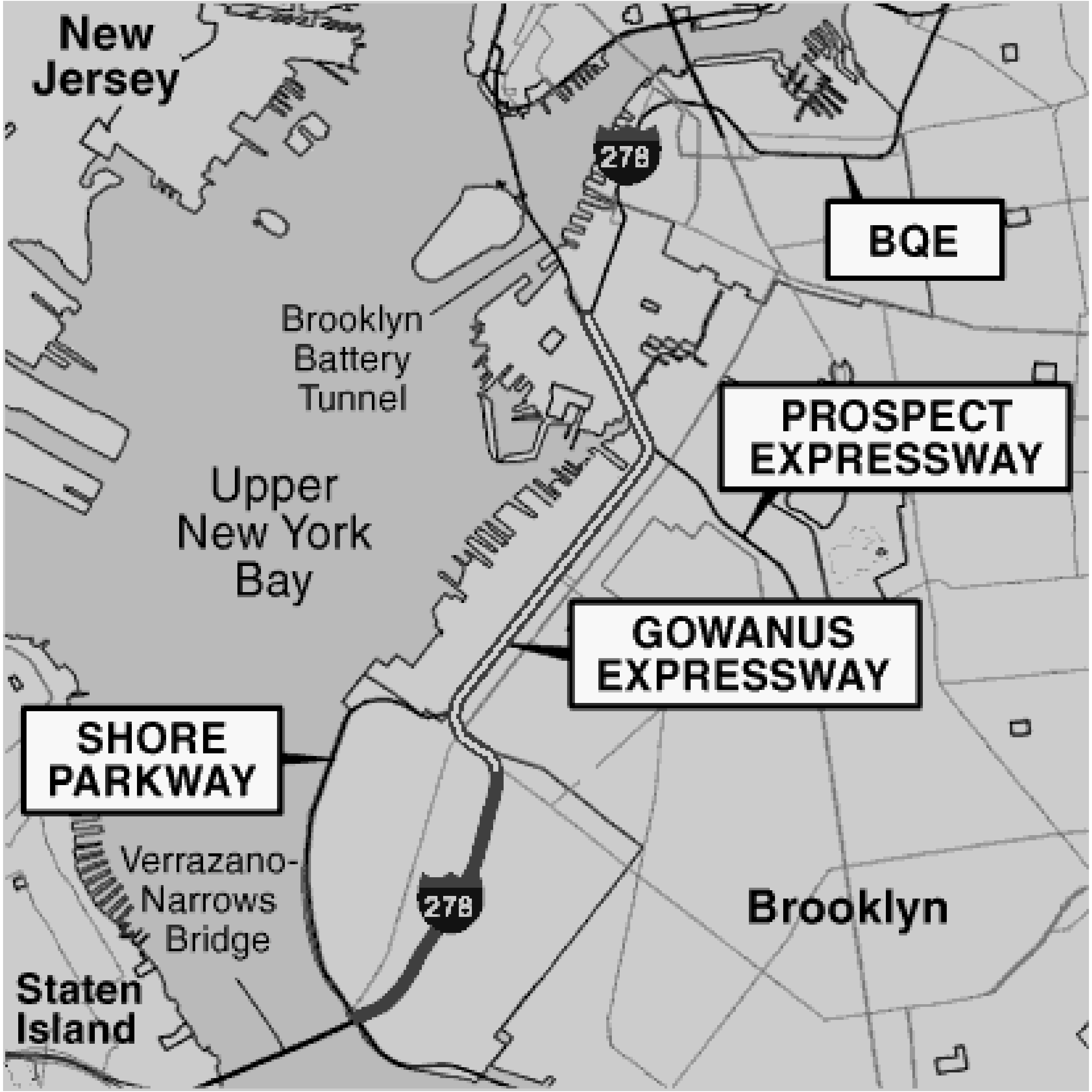


Figure 2. Comparison of the luminance contrast values from nighttime session 1 (along the horizontal axis) with those from nighttime session 2 (along the vertical axis). Despite some variability, the values are moderately (r = 0.54) and positively correlated with one another.

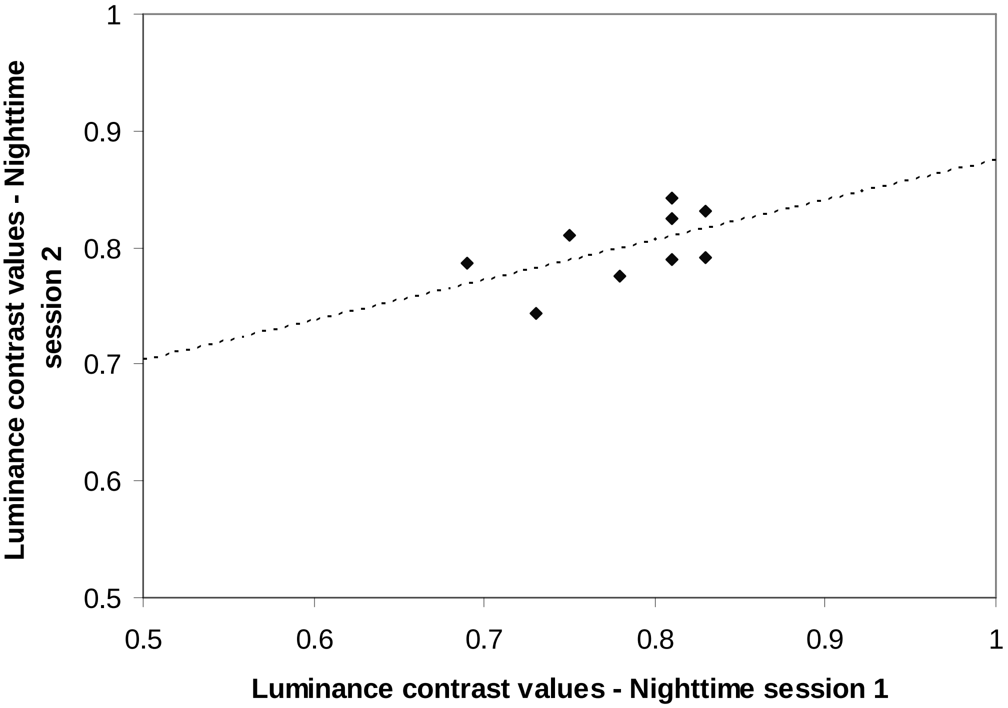


Figure 3. Three-dimensional surface plot of RVP (Rea and Ouellette, 1991) as a function of luminance (left-hand axis) and luminance contrast (right-hand axis), illustrating the plateau and escarpment nature of visual performance.

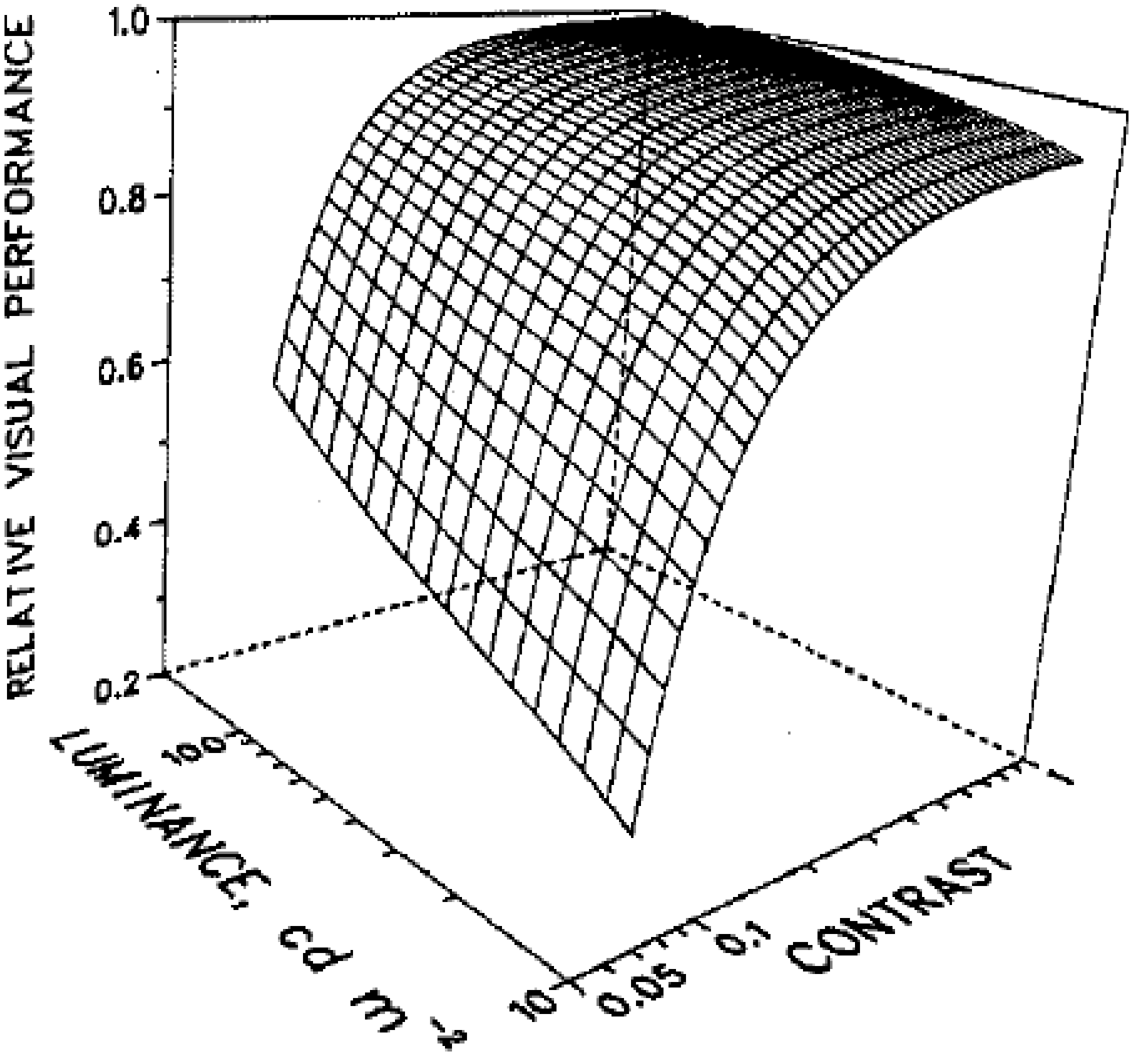


Figure 4. Reductions in light reaching the retina caused by lens thickening/yellowing and pupil size reductions, as a function of age (Rea and Ouellette, 1991).

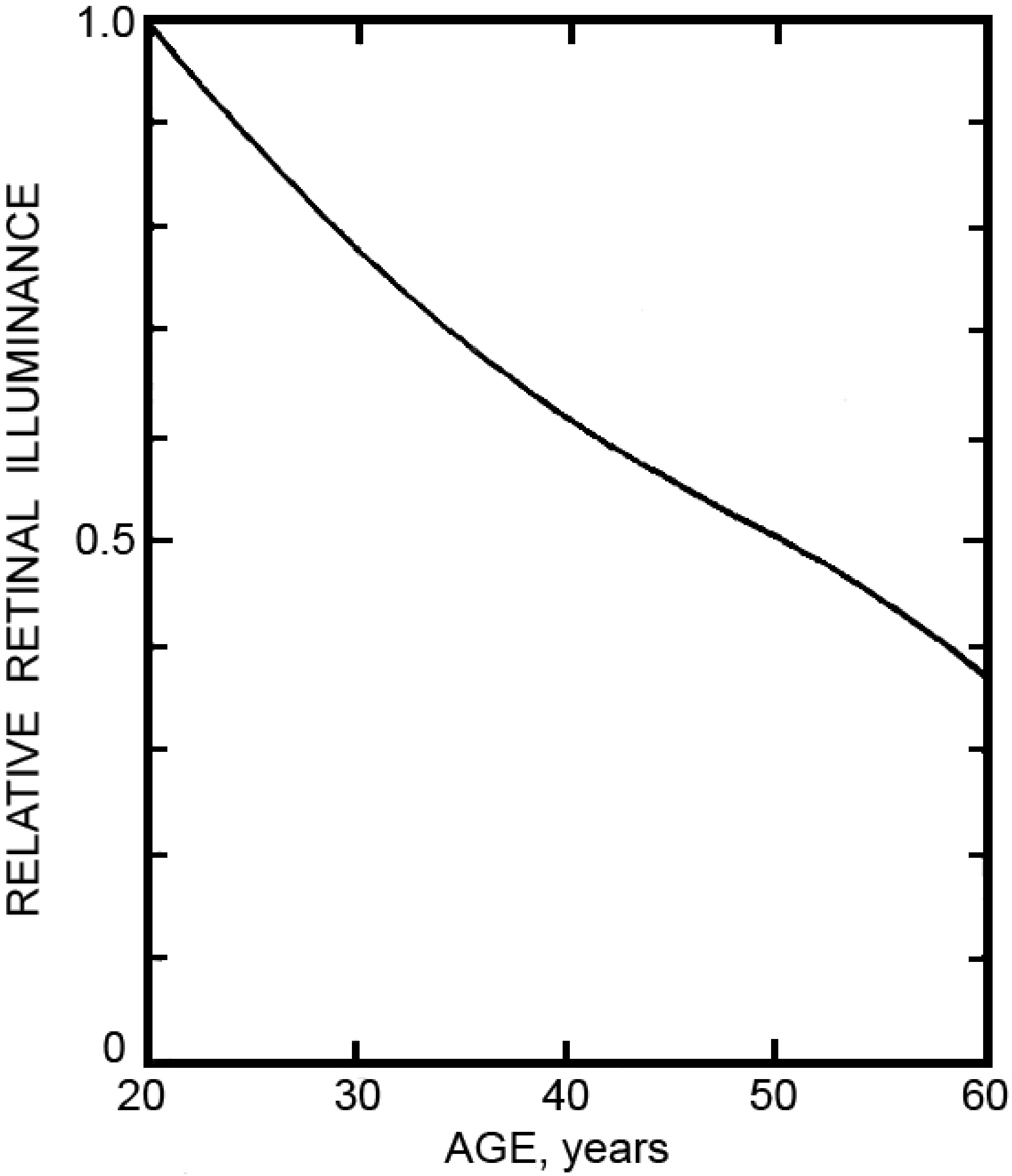


Figure 6. Comparison of measured performance and performance predicted by the RVP model (Rea and Ouellette, 1991) for an experiment involving visual processing of alphanumeric characters at a range of background luminances, luminance contrasts, and sizes (Eklund et al., 1999).

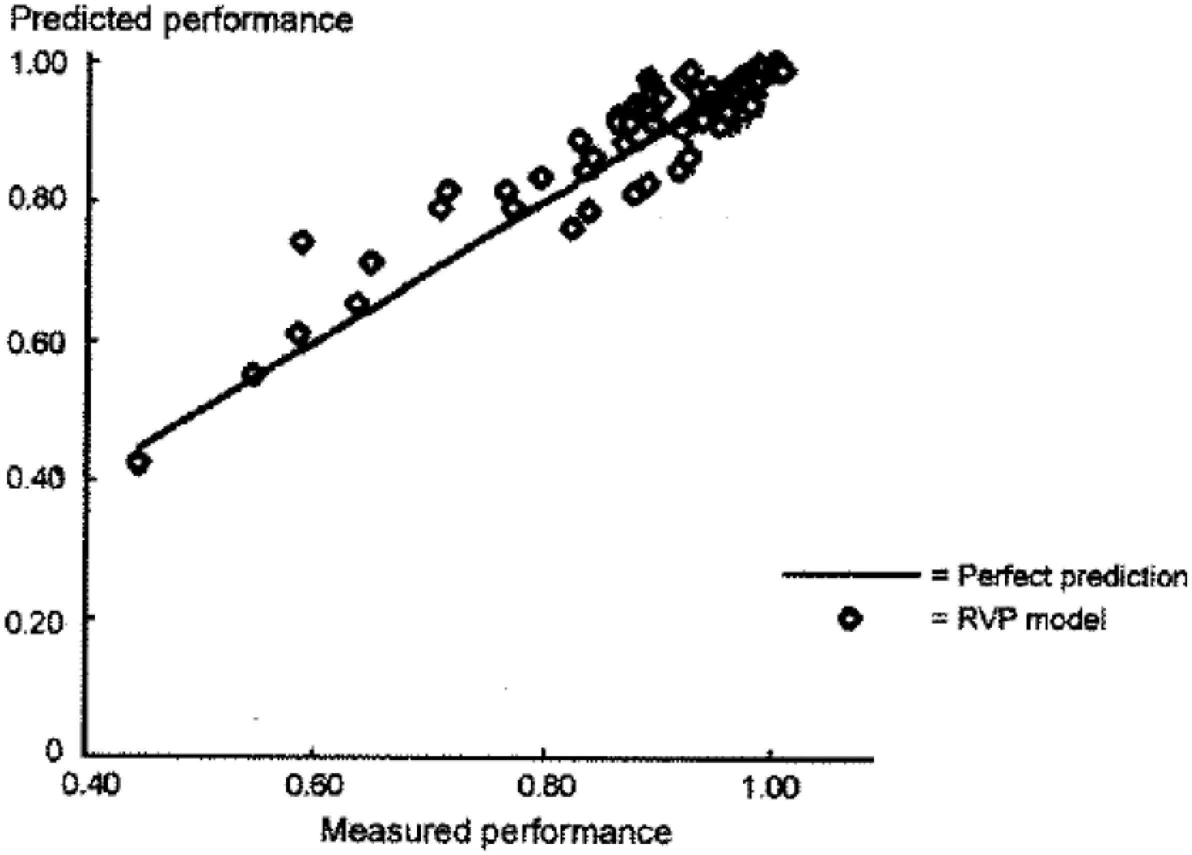


Figure 7. Response times to correctly identify the orientation of Landolt C rings in simulated highway signs (Goodspeed and Rea, 1999) as a function of luminance contrast, alongside the response times predicted from the RVP model (Rea and Ouellette, 1991).

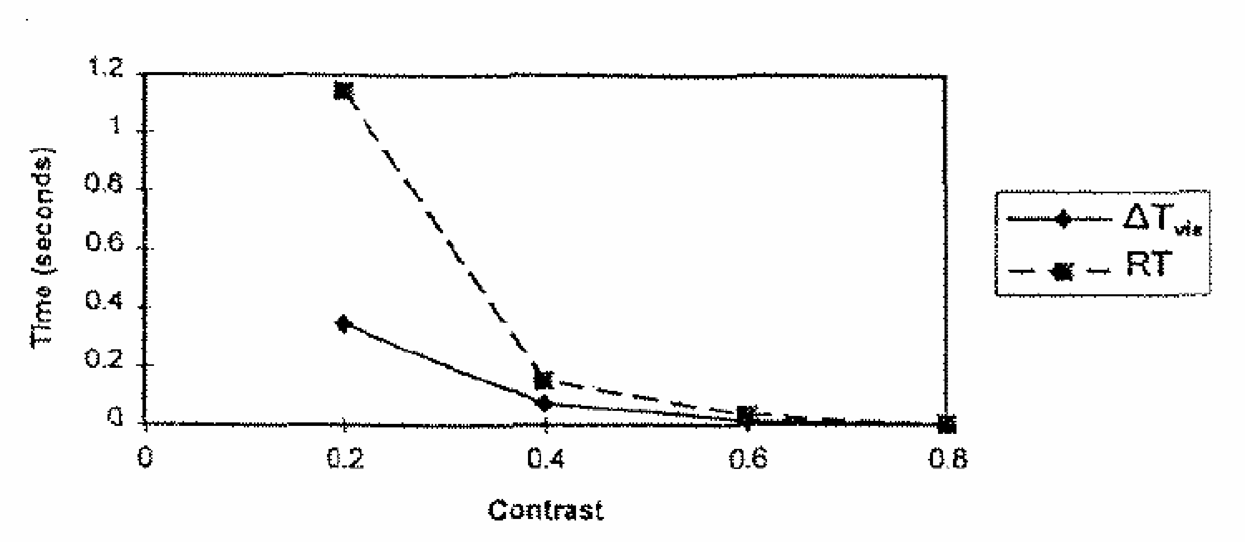


Figure 8. RVP values from Table 5 presented graphically.

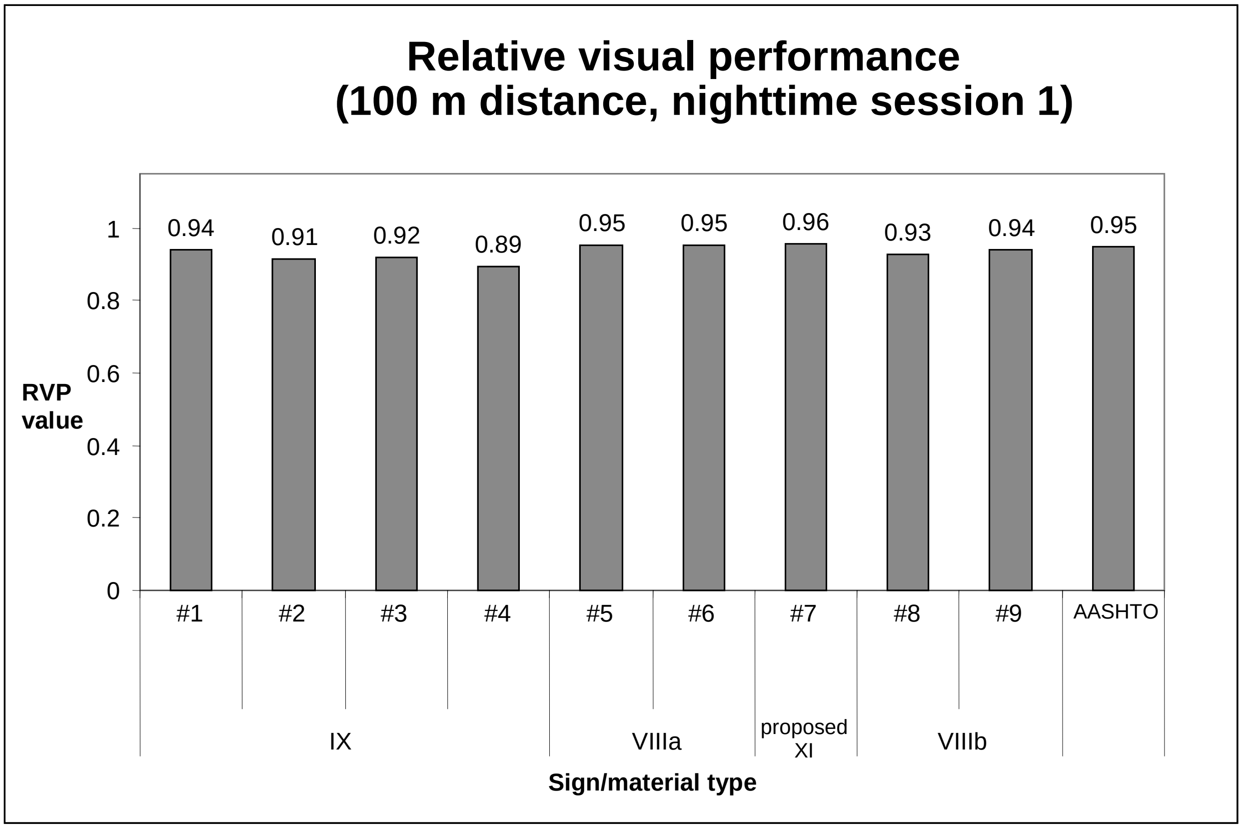


Figure 9. RVP values from Table 6 presented graphically.

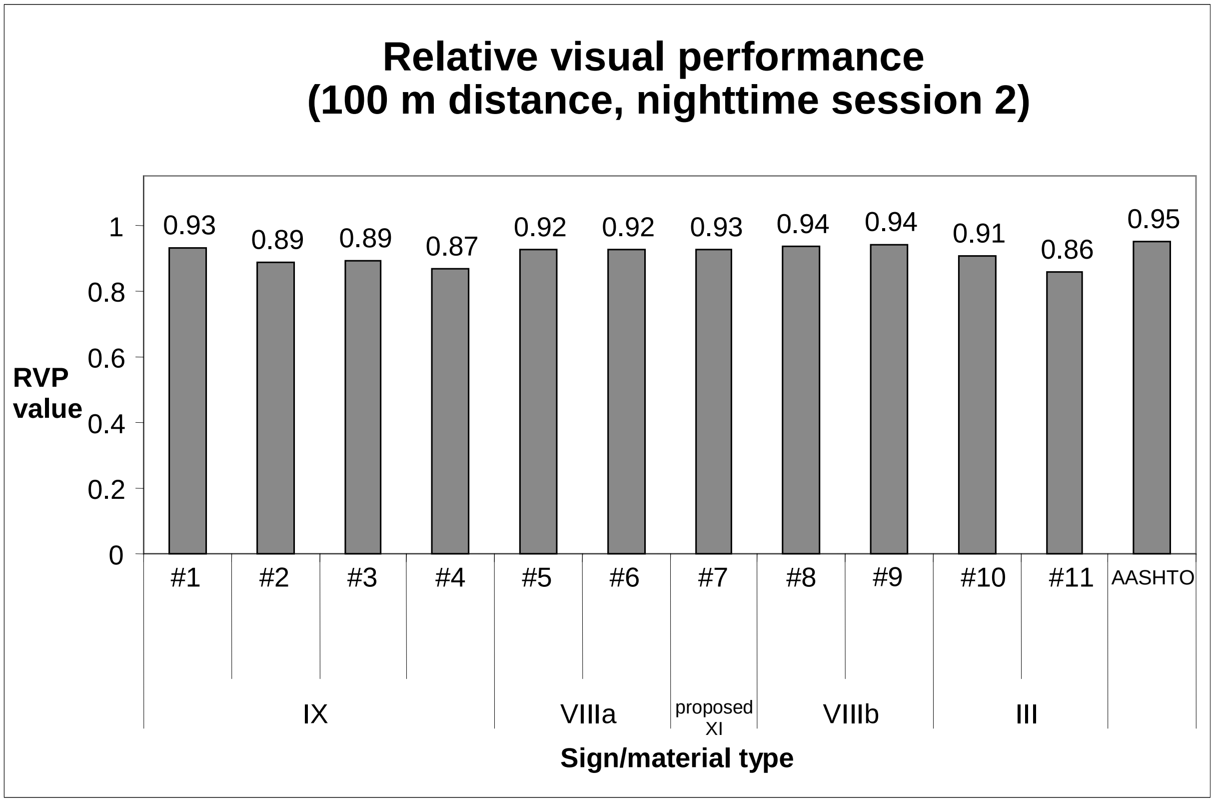


Figure 10. RVP values from Table 7 presented graphically.

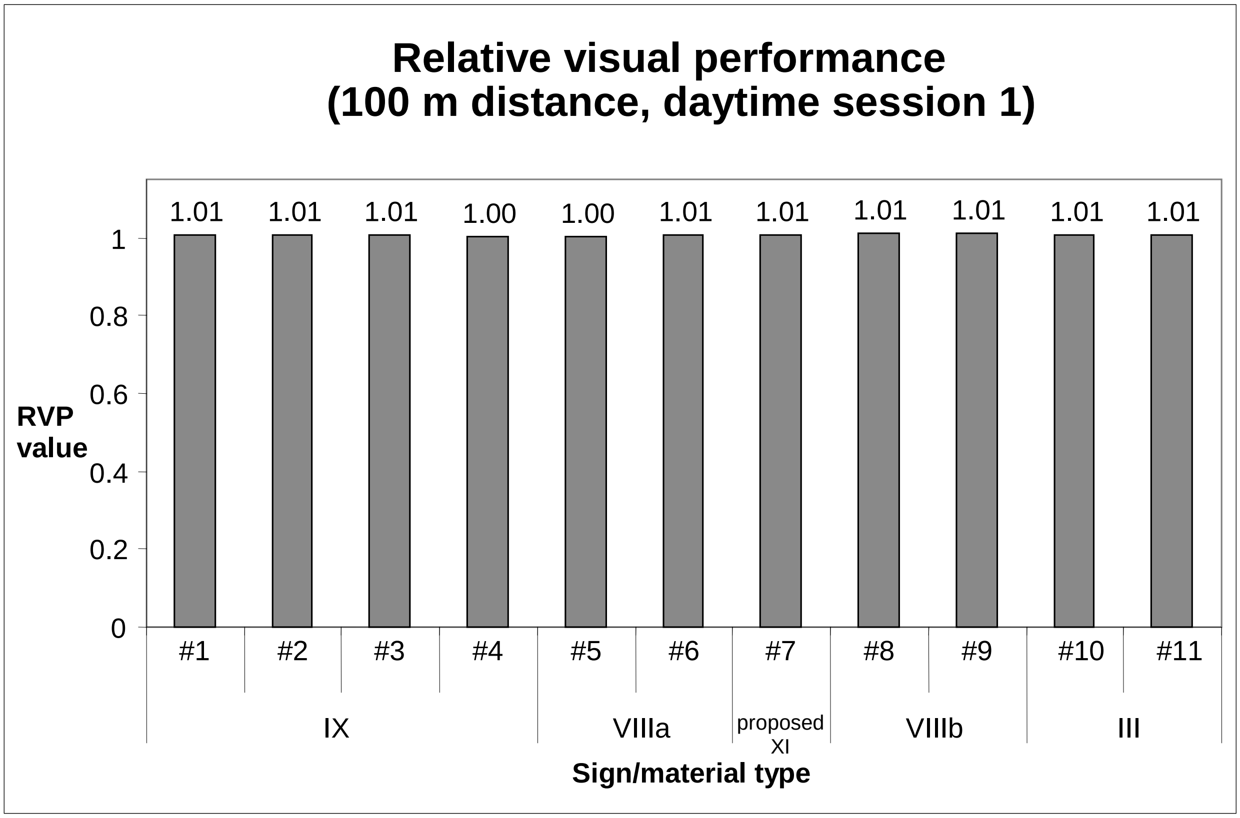


Figure 11. Rated contrast values for the simulated highway sign symbols presented by Goodspeed and Rea (1999).

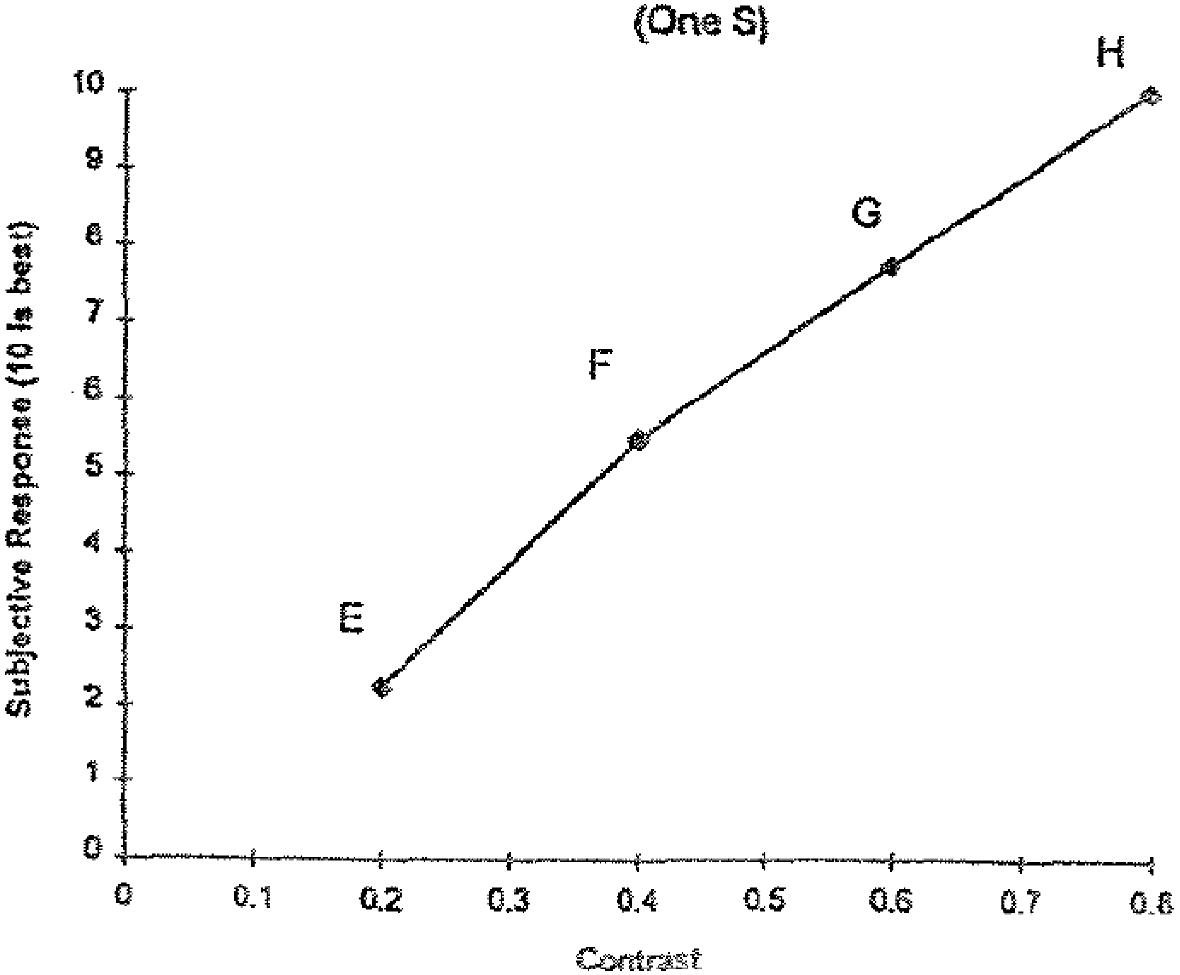


Figure 12. RVP values and subjective ratings of contrast for the same visual targets adjusted as a function of luminance contrast, for a background luminance of 20 cd/m² (Rea, 1989).

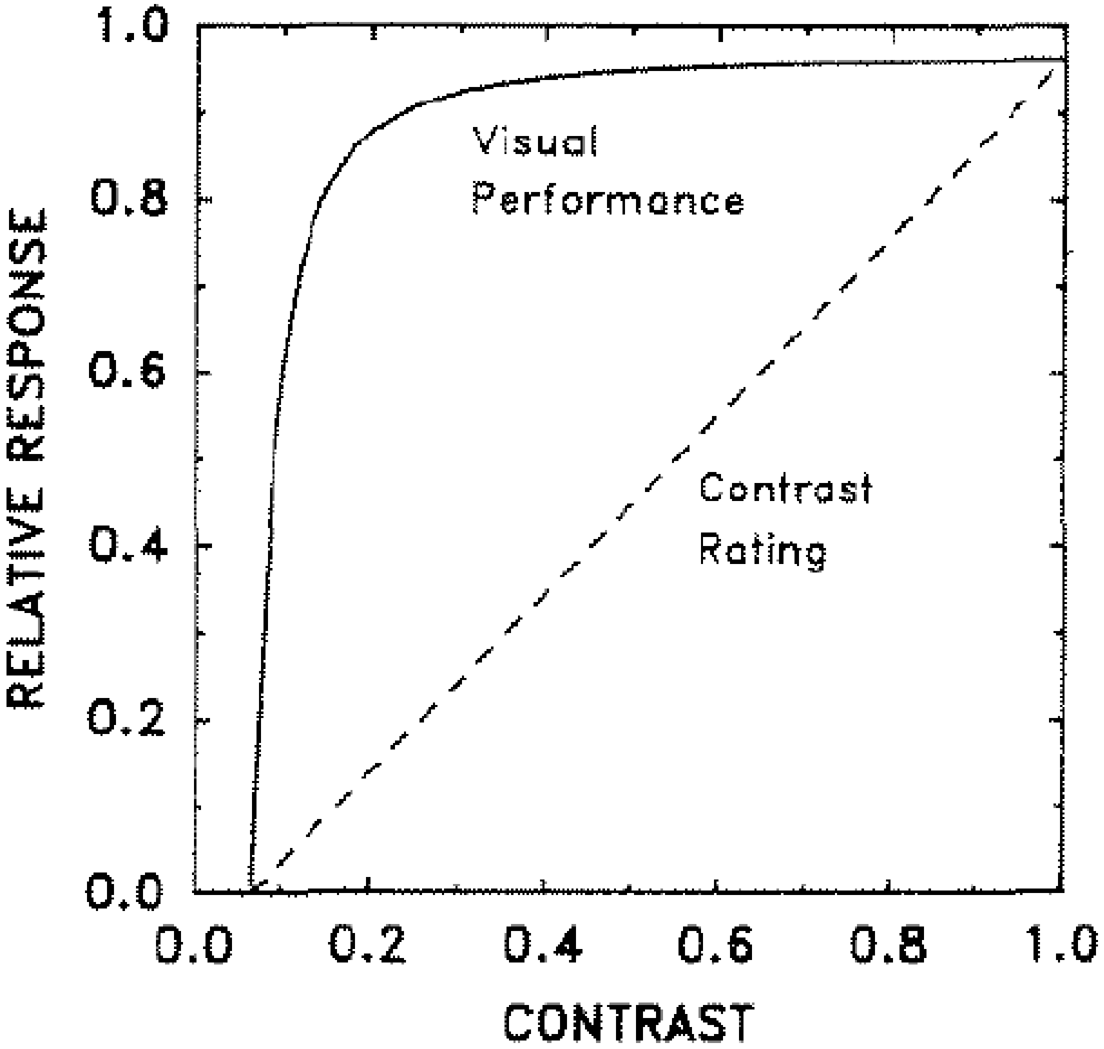


Figure 13. Illustration of apparatus used during the subjective rating observations.

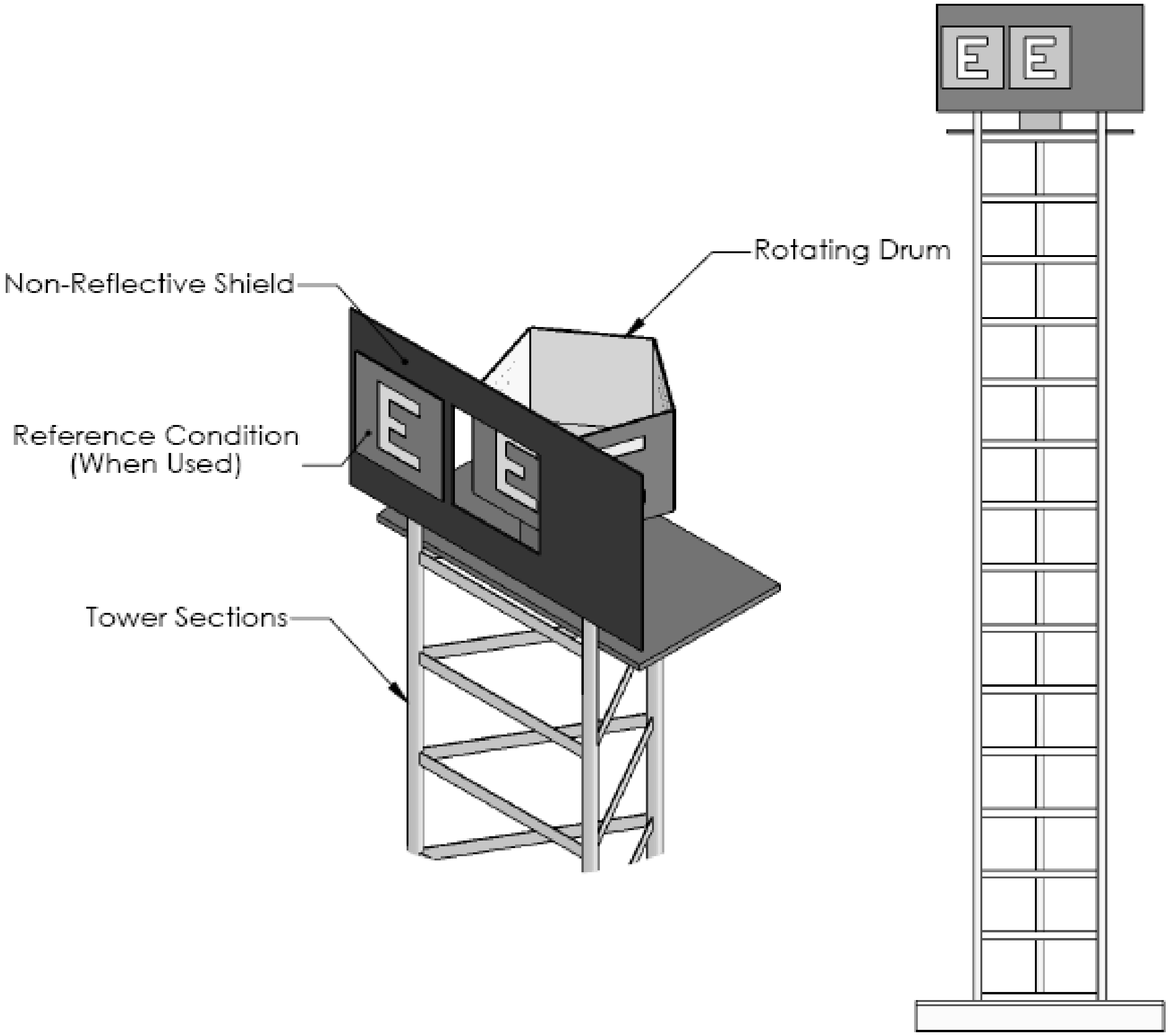


Figure 14. Mean contrast ratings (±standard deviation) for side-by-side viewing conditions. Also shown is a linear function representing "perfect" ratings based on an expected linear response.

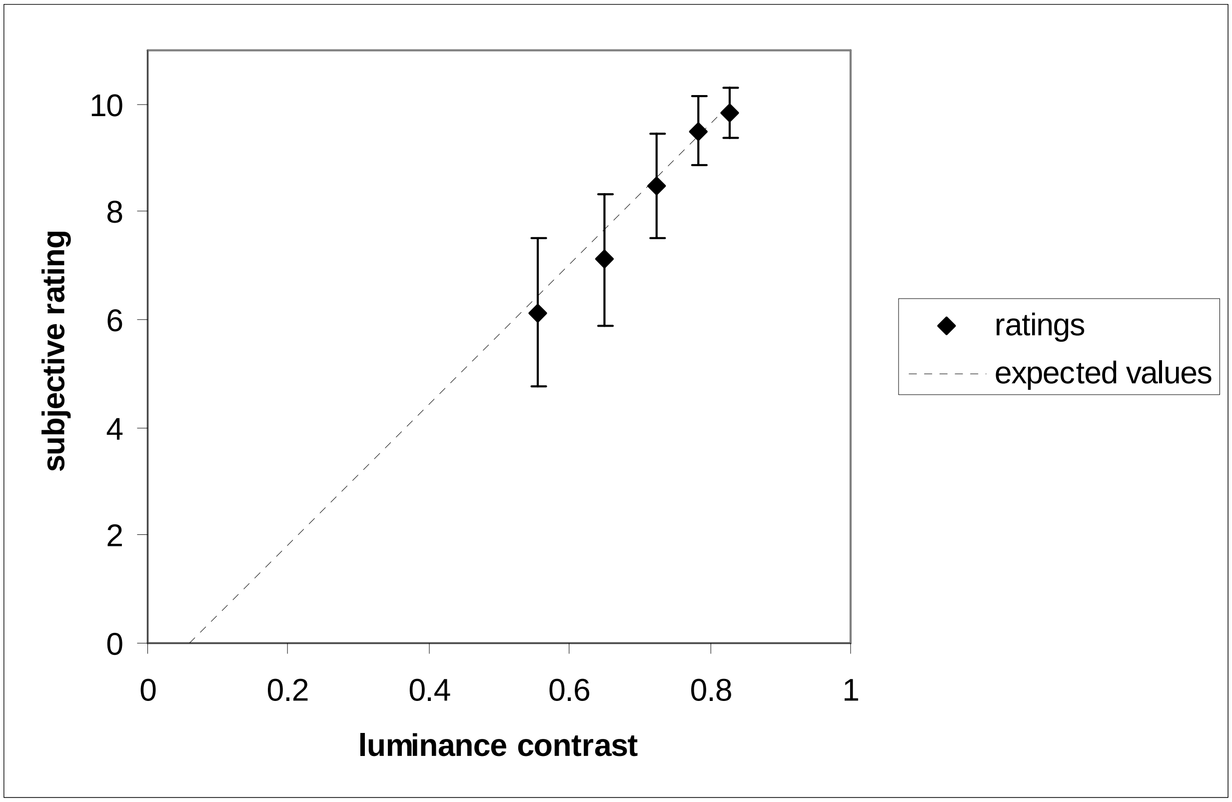


Figure 15. Mean contrast ratings (±standard deviation) for sequential viewing conditions. Also shown is a linear function representing "perfect" ratings based on an expected linear response.

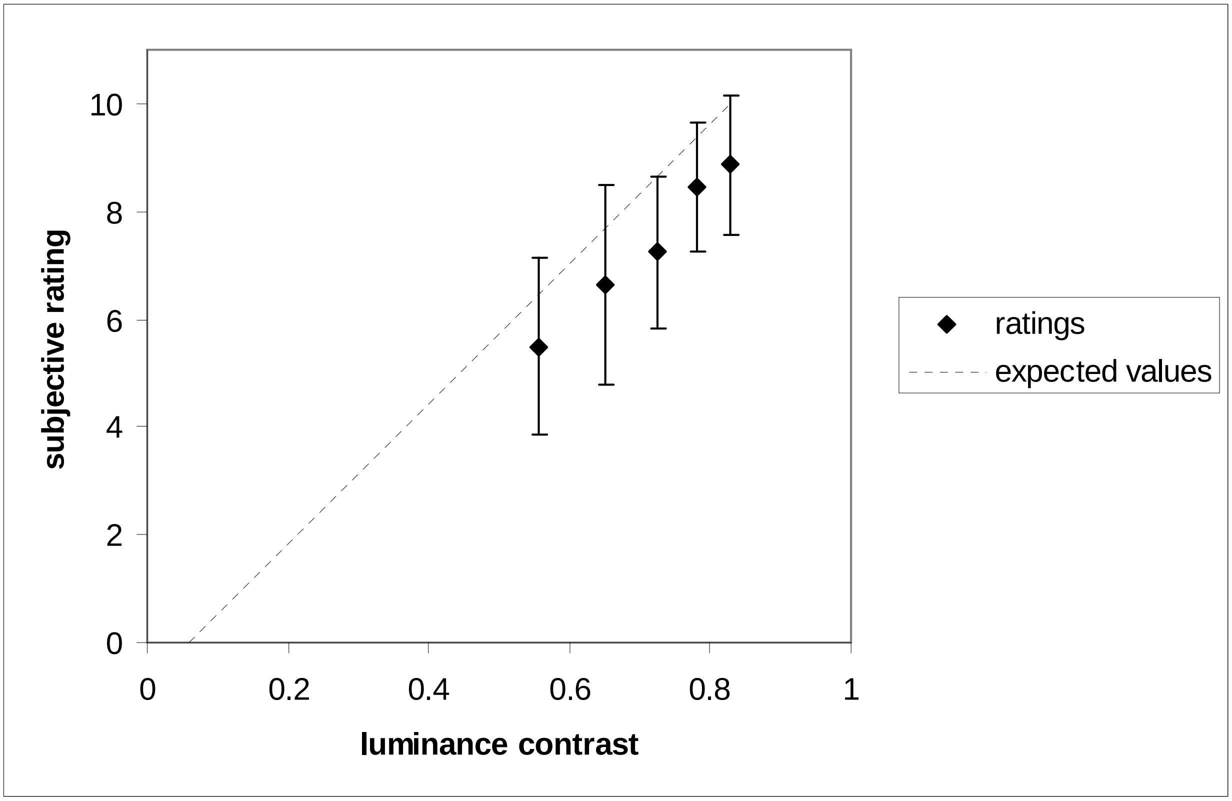
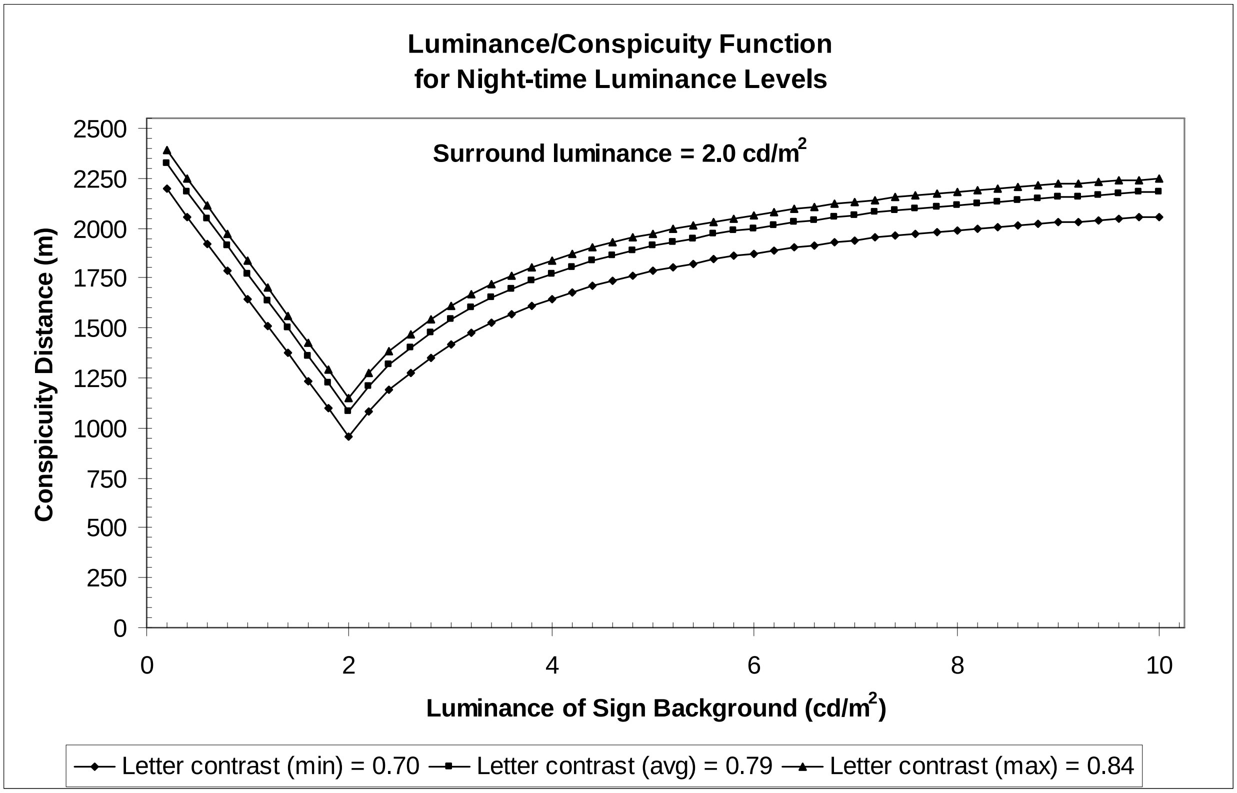


Figure 16. Predicted sign detection distances based on the model presented by Forbes (1972) for the range of nighttime sign luminances encompassing those shown in Tables 1 and 3, assuming a visual surround luminance of 2 cd/m² (Li et al., 2006) and a sign height of 2.3 m, and luminance contrasts for the sign characters



APPENDIX 1: RELATIVE VISUAL PERFORMANCE CALCULATION PROCEDURE

1. Let A be the observer's age in years. Let L be the background luminance in cd/m² (if the illuminance on the task and the reflectance of the background are known, L can be calculated using Equation 1 in the present report). Let C be the luminance contrast (calculated using Equation 2 in the present report). Let S be the size of the target in microsteradians:

   $$S = T/(1{,}000{,}000\,d^2) \qquad \text{(Equation A-1)}$$

   where T is the projected area of the target (in m^2) and d is the viewing distance (in m).

2. Calculate the pupil radius P in millimeters:

   $$P = 2.39 - 1.22\tanh(0.3\log L) \qquad \text{(Equation A-2)}$$

3. Calculate the age-corrected retinal illuminance E_r in trolands:

   $$E_r = \pi P^2 L[1 - 0.017(A - 20)] \qquad \text{(Equation A-3)}$$

4. Calculate five intermediate values x_1, x_2, x_3, x_4 and x_5:

   $$\begin{aligned} x_1 &= \log[\tanh(20{,}000\,S)] \\ x_2 &= \log[\log(10\,E_r/\pi)] \\ x_3 &= 1 + [0.0025(A - 20)] \\ x_4 &= \log[\tanh(5000\,S)] \\ x_5 &= \log[\tanh(0.04\,E_r/\pi)] \end{aligned} \qquad \text{(Equations A-4a through A-4f)}$$

5. Calculate the threshold luminance contrast C_t:

   $$C_t = x_3\,10\hat{}(-1.36 - 0.18x_1 - 0.81x_2 + 0.23x_1^2 - 0.077x_2^2 + 0.17x_1x_2) \qquad \text{(Equation A-5)}$$

6. Calculate the half-saturation constant K:

   $$K = 10\hat{}(-1.76 - 0.18x_4 - 0.031x_5 + 0.11x_4^2 + 0.17x_5^2 + 0.062x_4x_5) \qquad \text{(Equation A-6)}$$

7. Calculate the maximum response R_{max}:

   $$R_{max} = 0.0002\log(E_r) + 0.0027 \qquad \text{(Equation A-7)}$$

8. Calculate the visual response time in milliseconds:

   $$V = [(C - C_t)^{0.97} + K^{0.97}]/[(C - C_t)^{0.97}\,R_{max}] \qquad \text{(Equation A-8)}$$

9. Calculate the relative visual performance (RVP):

   $$RVP = 1.42 - V/778.56 \qquad \text{(Equation A-9)}$$

APPENDIX 2: MANUFACTURERS OF RETROREFLECTIVE MATERIALS USED ALONG THE GOWANUS EXPRESSWAY

Type VIII_a: Avery Dennison

Type VIII_b: Nippon Carbide

Type IX: 3M

Proposed Type XI: 3M