# 1247

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# *Visibility Criteria for Signs, Signals, and Roadway Lighting*

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## Contents

# Foreword

The papers included in this Record were originally presented at the Symposium on Visibility Criteria for Signs, Signals, and Roadway Lighting, which was held in Minneapolis, Minnesota, in August 1988. This symposium was the ninth in a series sponsored by the TRB Committee on Visibility.

Except for the paper by Ketvirtis, all of the papers in this Record have been peer reviewed. Although no additional formal discussions are included, the papers as presented here are a result of this peer review and subsequent revisions.

Unique to this symposium was the introduction of emerging philosophies on visibility models. These models will eventually result in accurate predictions of the relative visibility of objects under differing light conditions. Implementation of these models as well as results from current practice are discussed in various papers.

Several papers discuss the relation between color and traffic control devices and the visual effect of headlights on reflectors and objects. A paper that updates current research and research needs and gives appropriate international recommendations will also be of interest to the reader.

The TRB Committee on Visibility encourages comments on this and other visibility publications, as well as suggestions for future symposium topics.

# Effects of Misaimed Low Beams and High Beams on Visual Detection of Reflectorized Targets at Night

HELMUT T. ZWAHLEN, MICHAEL E. MILLER, AND JING YU

**An analytical study was conducted on a microcomputer to assess the effects of misaimed low beams and high beams on the visual detection of reflectorized targets of different brightness, such as reflectorized warning signs, overhead guide signs, license plates, and post delineators. The study was done at night, on a straight and a left-curved section of highway. The model used computed all the geometric distances and angles necessary for a selected driver-vehicle-reflectorized target situation for each headlamp, the amount of beam illumination that is returned to a driver's eyes for selected environmental and vehicle conditions, and a Multiples of Threshold value. Calculations were performed for a matrix containing 25 passenger-side and driver-side beam misaim combinations (5 × 5 points, identical and nonidentical misaims). The results show that both vertical and horizontal beam misaim may have a detrimental effect upon the detection distance of reflectorized targets in the driving environment: however, the use of brighter retroreflective materials can help to offset the detrimental distance effect in most cases.**

This study shows the effect of beam misaim on a driver's ability to detect reflectorized (the use of retroreflective materials) targets of different brightness at night ahead of the vehicle, in the absence of glare from opposing traffic. This paper does not address the glare effects misaimed beams might have on opposing traffic or the effect glare from opposing traffic might have on a driver's detection performance. Detection of reflectorized targets is emphasized since it is the first step in a driver's hazard avoidance process as modeled by McGee et al. (*1*). McGee's model consists of a five-step sequential process during which the driver detects an object causing a hazardous condition, recognizes the condition, decides upon a response, responds to the condition, and successfully maneuvers the vehicle to avoid the hazard. Although this model was suggested for the avoidance of an object on the highway, it might be adapted to describe a driver's response to reflectorized targets, such as traffic signs, at night. It is imperative that the targets be detectable at a sufficient distance to allow a driver to effectively execute the maneuver in a safe manner within the available time period.

Bhise et al. (*2*) investigated the effect of a H4656 low beam misaim on a driver's visual performance using the Comprehensive Headlamp Environment Systems Simulation (CHESS) model, developed at Ford Motor Company. The CHESS model considers the pedestrians detected, delineation visibility, discomfort glare to oncoming drivers, and glare effects by opposing traffic. The model represents its final result as a Figure-of-Merit, which is "the percentage of the total distance traveled by the simulated drivers over the standardized test route for which the headlighting satisfies a certain preselected vision performance level criterion." Also investigated were random beam misaim and combinations of seven horizontal and five vertical identical passenger and driver side beam misaim conditions. The random beam misaim condition was based on low beam misaim data from a 1971 study (*3*). It was assumed that the beam misaims followed a bivariate normal distribution with an average misaim of .08° to the right and .73° below the correct aim position, and with a horizontal standard deviation of .86° and a vertical standard deviation of 1.55°. It was also assumed that the horizontal misaim was independent and the vertical misaim was identical for both low beams. The random beam misaim simulation included about 99.9 percent of the vehicle population (tolerance limits of three standard deviations in both directions). The results showed that the performance of the randomly misaimed low beams produced a significantly lower Figure-of-Merit at the 90 percent confidence level than correctly aimed low beams. For the second condition, both headlamps were aimed at one of seven horizontal levels and one of five vertical aim levels, while all opposing vehicle's headlamps were always correctly aimed. The results showed that the low beam system Figure-of-Merit could be significantly reduced by vertical headlamp misaims of 4 in and 8 in below the correct aim at 25 ft. The performance of the H4656 low beam is less sensitive to horizontal misaims between 4 in left and 12 in right than to vertical misaims between 4 in up and 8 in down at 25 ft.

A more recent survey (*4, 5*) of the aim of a vehicle's low beams indicates that the vertical misaim variability of low beams has a standard deviation of .9°, which is much smaller than the 1.55° used by Bhise et al. The horizontal beam misaim standard deviations are about .8°, which is close to the standard deviation of .85° used by Bhise et al. The effect of horizontal and vertical beam misaim upon a driver's ability to detect reflectorized targets of different brightness at night in the driving environment should be investigated. In addition, the recent vertical misaim variability survey is considerably smaller than Hull et al.'s (*3*) vertical misaim variability, and the CHESS model does not consider detection or recognition of reflectorized targets, such as traffic signs. Further, no study was found that has systematically investigated the effect of nonidentical vertically misaimed headlamps. Since both headlamps contribute to the total reflected illumination which is returned to a driver's eyes, the effect of nonidentical and identical misaimed headlamps and close-to-correct aimed

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headlamps (low beams and high beams) on detection distance for reflective materials of different brightness needs to be investigated.

## APPROACH

An interactive computer program, developed for a Macintosh microcomputer, analytically determined the detection distance of reflectorized targets in the driving environment. This program calculated the illuminance ($E_{ref}$) in footcandles (fc) produced at a reflective target, based upon

$$E_{ref} = I * t^{(a/100)}/a^2 \tag{1}$$

where $I$ is the luminous intensity of the light source (in this case, either the left or right headlamp) in candela (cd), $t$ is the transmissivity of the atmosphere per unit distance (100 ft), and $a$ is the direct distance from the light source to the reflector in feet. Knowing the specific intensity ($SI$) of the reflector at given entrance, observation, presentation, and rotation angles, the same basic relationship can be used to determine the illumination which is returned to a driver's eyes ($E_{eyes}$) in fc. This relationship may be expressed as

$$E_{eyes} = E_{ref} * SI * C * t^{(b/100)}/b^2 \tag{2}$$

where $SI$ is the specific intensity of the reflector in cd/fc/ft$^2$, $C$ is the area of the reflector in ft$^2$, and $b$ is the direct distance from the reflector to the driver's eyes. Combining these relationships into one, the illumination directed to the driver's eyes from either the right or left headlamp can be calculated from

$$E_{eyes} = I * SI * C * t^{(a+b)/100}/(a^2 * b^2) \tag{3}$$

The user inputs the vehicle and driver geometry, highway geometry, and the geometry of the reflector into the computer program. The program then calculates the geometric angles and euclidean distances at user specified rectilinear distances. The user inputs the headlamp aim, beam, and reflector efficiency factors, windshield transmission factor, environmental conditions and selects the headlamp and reflector data files. The program calculates the illumination levels at the driver's eyes due to the right, left, and both headlamps. It then selects the threshold luminance value for a 98 percent probability of detection of a white point source, based upon a user-selected background luminance value from the IES Handbook (*6*,p.3–24). This illumination threshold applies only to point sources, but the program automatically adjusts for sources that are too large to be considered point sources based upon values from the IES Handbook (*6*,p.3–25). To provide a framework where the small illumination values in footcandles (*fc*) at a driver's eyes can be compared on a one-to-one basis with visual backgrounds having different luminance levels, and to obtain numbers tied more closely to human detection performance, the final illumination values and adjusted threshold value are used to calculate a Multiples of Threshold (MOT) value. The MOT is defined as the number of times the illumination level, which is returned to a driver's eyes from the reflector, is above the illumination threshold for a 98 percent probability of detection of a white point source against a uniform background in the laboratory. The program then displays the reflector and beam angles, beam candlepower values, illumination at the reflector and driver's eyes due to the left, right, and both beams and the MOT values for a selected set of distances ahead of the vehicle.

A MOT value must be selected as a criterion value that will be representative for the detection of reflectorized targets in the driving environment. Most published detection threshold values were obtained in the laboratory, against uniform backgrounds, with subjects who were alerted, highly motivated, and had a low information processing work load. Such laboratory threshold values would be unsatisfactory for the detection of targets in the driving environment where the background may contain numerous light sources, the driver is unaware of an upcoming target, and the information work load may be relatively high. For this reason, Zwahlen (*7*) has recommended the use of a MOT value as high as 1,000 (which is between a human brilliancy rating of "satisfactory" and "bright" according to Breckenridge and Douglas (*8*)) for the timely detection of an unexpected reflectorized target (point source) such as a reflectorized pedestrian or bicycle rider at night. A MOT value of 60 ($17.1 \times 10^{-8}$ fc or 1.84 km candles) was selected as a criterion value that corresponds to a human brilliancy rating between faint (.9 km candles) and weak (4 km candles) according to Breckenridge and Douglas. The same MOT value of 60 was used for the fourth post delineator ahead of the car in an earlier study by Zwahlen et al. (*9*) when optimizing the spacing of post delineators.

## ASSUMPTIONS AND ANALYSIS COMBINATIONS

Assumptions include vehicle-driver dimensions for a 50 percent person in a typical large car, when the car is driven in the center of a 12 ft wide right-hand lane, a background luminance of .01 fl., atmospheric transmissivity of .99/100 ft (clear), a windshield transmittance of .9 and a beam efficiency of 90 percent. The halogen 6054 high beams and low beams were investigated in this study.

Selected reflectorized targets included a warning sign located either on the right or left side of the highway, an overhead guide sign, a post-mounted reflective sheeting patch (flexible post delineator) on the right side of the highway, and a reflectorized license plate located on either the left or right side of the highway. According to sections 2E-2 and 2E-4 of the Ohio Manual of Uniform Traffic Control Devices (*10*), warning signs should be placed a minimum of 12 ft from the edge of the highway and the bottom of the sign should be at least 5 ft above the near edge of the pavement on rural roads and at least 6 ft above the near edge of the pavement on expressways and freeways. Therefore, it was assumed the yellow warning sign was 30 in × 30 in, the corner of the sign nearest the highway was 12 ft from the edge line of the highway, and the bottom of the sign was 6 ft above the nearest edge of the highway. Section 2E-4 of the Ohio Manual of Uniform Traffic Control Devices states that overhead guide signs should provide a vertical clearance of not less than 17 ft unless a lesser clearance is used for the design of other structures. Hence, it was presumed that the overhead sign was 12 ft wide, 9 ft tall, and centered in the driver's lane with a vertical clearance of 17 ft. Section 4B-3 and 4B-5 of the manual specifies that the top of the reflecting patch (6 × 3 in) of the post delineator should be placed 4 ft, plus or minus one in, above the near roadway edge. It also states that all delineators should be between 2 ft and 12 ft 6 in from the edge of the pavement and the reflective patch should have a minimum dimension of 3 in. The center of the reflective patch was assumed to be 12 ft to the right and 48 in above the right edge of the pavement, which is 3 in higher than the vertical center of a correctly installed reflective patch. The patch was assumed to have the rectangular dimensions of 3 in wide by 6 in tall. A small random survey of 20 late model vehicles indicated that the center of the rear license plate was located an average of 2.1 ft above the ground. Therefore, it was assumed that the license plate in this study was located at this height above either the right edge or left edge line. It was also assumed that the license plate had a reflectivity of 23 CIL and was 6 in tall and 12 in wide.

It was further assumed that the white/silver reflective material used on post delineators and license plates operated with a 90 percent efficiency due to wear and tear and dirt accumulation. It was assumed that the specific intensity of the yellow reflective material is 60 percent of the specific intensity of the white material (values between 59.6 and 62.5 percent (*11*)) and 90 percent efficient (overall reflectivity was 54 percent). The specific intensity of the green reflective material was assumed to be 15 percent of the specific intensity of the white material and 90 percent efficient (overall reflectivity was 13.5 percent).

Olson and Winkler (*4*) and Olson (*5*) have described a survey of the condition of certain key vehicle safety systems, including lighting equipment, of a sample of 964 vehicles. These reports give horizontal and vertical averages and standard deviations for the misaim of low beams. Since the data collected was obtained at gas stations after the drivers completed refueling, the reports recommend that the standard deviation for the vertical aim be increased from 0.9° to 1.0° as an allowance for this bias. Mechanical aimers were used to measure the misaim of the beams up to 10 in at 25 ft (plus or minus 1.9°) in both directions. The original low beam misaim data (*4*) (on a computer tape) was obtained from the NHTSA in Washington, D.C., and further analysis provided the additional results on low beam misaim which are included in the following section.

Figures 1 through 4 show frequency distributions and statistical calculations of the measured misaim for the horizontal and vertical directions of the driver and passenger side low beams. Figures 1 and 3 show that low beam misaims can be assumed to be normally distributed in the vertical direction for both low beams (based upon a Chi-Square test conducted at the .01 level). However, Figures 2 and 4 indicate that the horizontal misaims for both low beams are not normally distributed (based upon a Chi-Square test at the .01 level). Low-beam misaims of plus or minus 10 in. in both directions at 25 ft were measured a total of 126 times for the driver's side low beam and 123 times for the passenger side low beam (see Figures 1 through 4). Thirteen of the driver's side and 16 of the passenger's side low beams were misaimed by more than 10 in at 25 ft in both the horizontal and vertical directions. These results indicate that the mechanical aimers were unable to measure the exact beam misaim for 13 percent of the low beams.

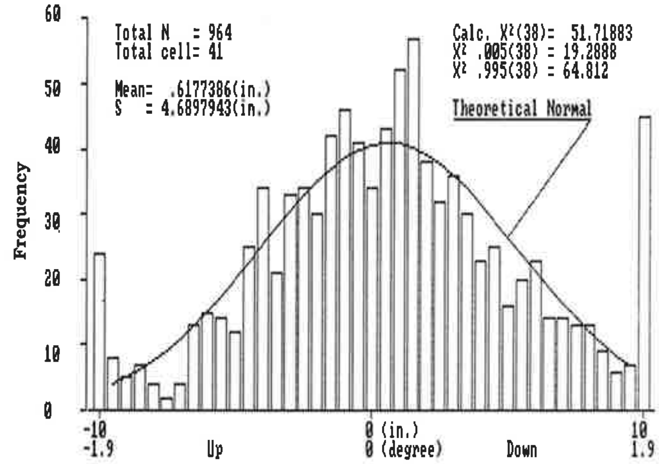


**FIGURE 1 Histogram and statistical calculations of the measured vertical low beam misaims for the driver's side headlamp.**

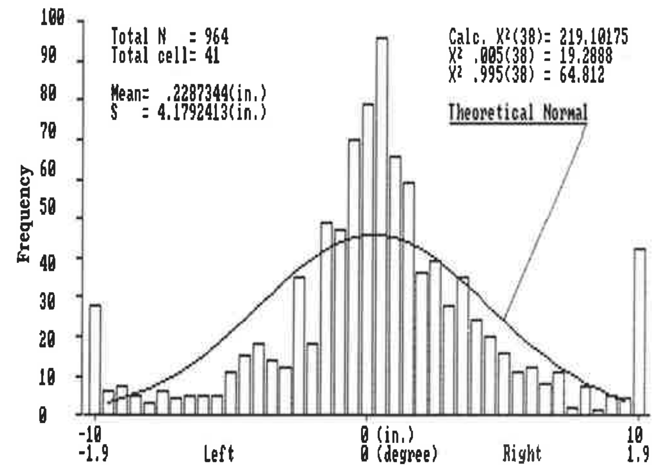


**FIGURE 2 Histogram and statistical calculations of the measured horizontal low beam misaims for the driver's side headlamp.**

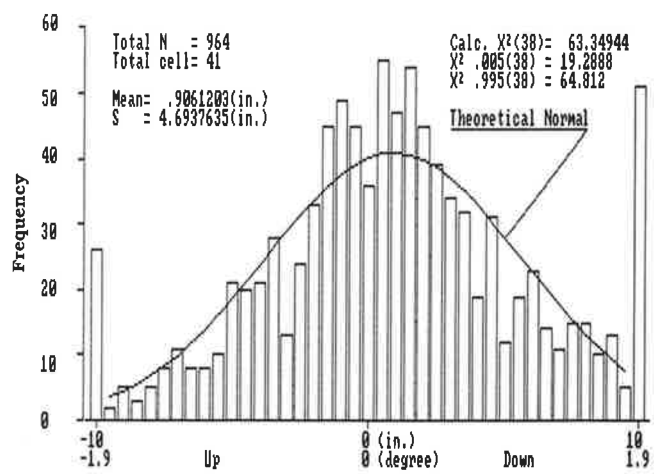


**FIGURE 3 Histogram and statistical calculations of the measured vertical low beam misaims for the passenger's side headlamp.**

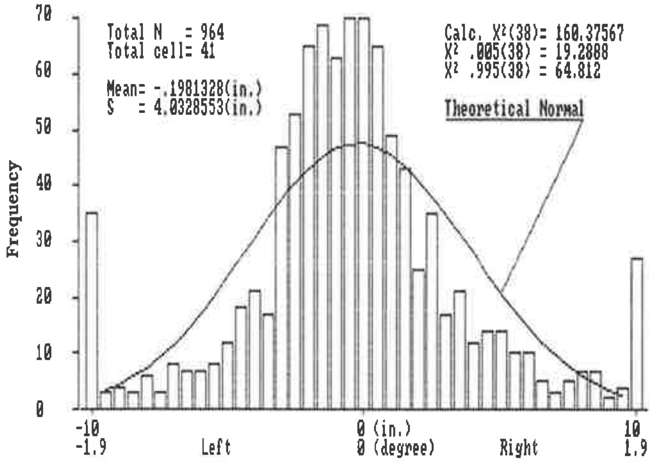


**FIGURE 4 Histogram and statistical calculations of the measured horizontal low beam misaims for the passenger's side headlamp.**

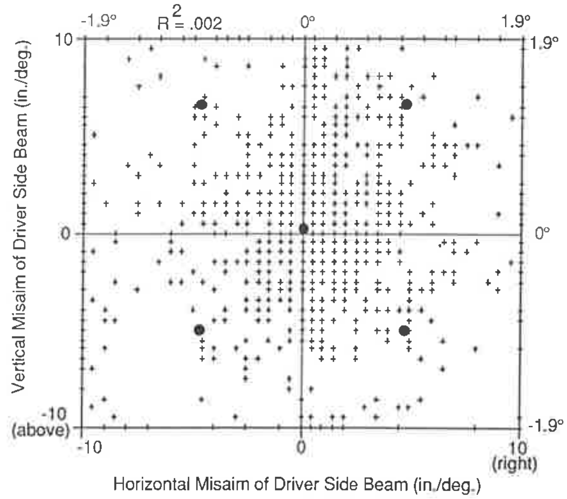


**FIGURE 5 Selected low beam misaim positions overlaid on the beam misaim plot for the driver's side headlamp.**

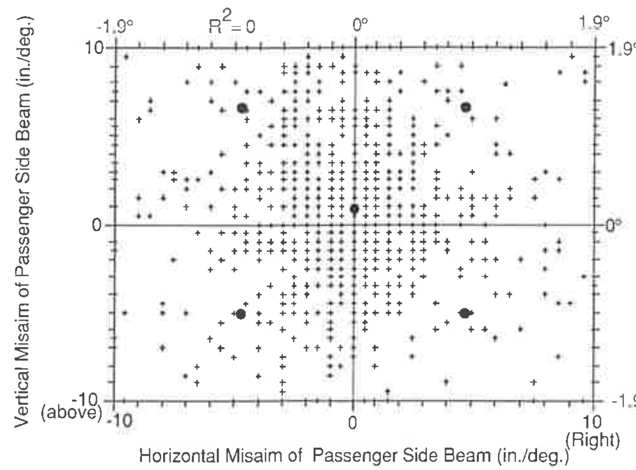


**FIGURE 6 Selected low beam misaim positions overlaid on the beam misaim plot for the passenger's side headlamp.**

The low beam misaim data was also used to determine if any relationships exist between the two low beams or between the horizontal and vertical directions of either beam. A small correlation coefficient ($R$) of 0.18 ($R^2 = .031$) was found for the horizontal misaims of the driver and passenger side low beams, and a small to moderate correlation coefficient of 0.63 ($R^2 = .392$) was found for the vertical misaim. There is practically no correlation between the vertical and horizontal misaim of the driver's side low beam ($R = 0.04$, $R^2 = .002$) or between the vertical and horizontal misaim of the passenger side low beam ($R = 0.00$, $R^2 = 0$).

To keep the number of calculations within manageable limits, five beam misaim angles were selected for both the passenger's and driver's side headlamps. These included a beam misaim of .15° below the correct aim position and 0° in the horizontal direction, which is close to the average overall beam misaim given by Olson and Winkler. The remaining four points were obtained by adding and subtracting 1.1° in the vertical direction and .9° in the horizontal direction. These values are close to the standard deviations given by Olson and Winkler, however, small adjustment values were added to account for increased variability possibly present on the highways for cars that had not just refueled and the fairly small increased variability had the mechanical aimers been able to measure beam aims of greater than 10 in at 25 ft. Figures 5 and 6 show the five selected low beam misaim angles overlaid on the beam misaim plot for the driver's side headlamp and the passenger's side headlamp, respectively. If a square were drawn through the four low beam misaim points, it would enclose 63.3 percent of the misaim points for the driver's side low beam and 64.7 percent of the misaim points for the passenger's side low beam. A circle through these four points would enclose 75.3 percent of the misaim points for the driver's side low beam and 75.1 percent for the passenger side.

Based on these assumptions, the computer program was used to determine detection distances for each of the 25 passenger and driver side low beam misaim combinations (5 × 5 points, identical and nonidentical misaims). In addition, the effect of high beams was also determined. Since no data on high beam misaim was available, the percentage of misaim for vehicles with two and four headlamps was found using the same five misaim points. Also determined were three levels of reflectivity (prismatic sheeting material with a specific intensity of 1080 cd/fc/ft² at a −4° entrance angle and a .2° observation angle, encapsulated lens sheeting material with a specific intensity of 309 cd/fc/ft², and enclosed or embedded lens sheeting material with a specific intensity of 105 cd/fc/ft²), and roadway geometry (straight highway or a 2000 ft radius (2.9°) left curve).

## RESULTS

Figure 7 shows detection distances and percentages for a warning sign on the right side of a straight section of highway for high and low beam conditions, three retroreflective sheeting materials, and 25 combinations of beam misaim. The percentages were obtained by dividing the detection distance for each beam misaim combination by the detection distance obtained for the nearly correct aim position (both beams correctly aimed in the horizontal direction and 0.15° below the correct aim in the vertical direction). The shaded matrix cells indicate detection distances that are less than the detection distance for the nearly correct aim position. The lightest shaded area indicates detection distances of 90 to 100 percent for the nearly correct aim position and each successively darker shaded area represents a further 10 percent decrement. The low beam detection distances shown in Figure 7 range from 1,243 ft to 4,104 ft. For the right warning sign, if either low beam is aimed .95° above the correct aim position, the detection distance will be greater than the detection distance for the nearly correct aim position. This is due to the nonlinear characteristics of the low beam isocandela distribution and the location of the hottest point of the low beam (about 2° down and 2° to the right). However, it should be noted that under low beam misaim conditions, where they are aimed above or to the left of the correct aim position, the low beams will produce higher levels of disability and discomfort glare to oncoming drivers. Figure 7 also shows that the detection distances for the high beams range from 2,668 feet to 5,039 feet.

Figure 8 shows detection distances and percentages for a warning sign on the left side of a straight section of highway, for high and low beam conditions, three retroreflective materials, and 25 combinations of beam misaim. The low beam detection distances range from 1,068 feet (point source size correction factor of 1.16) to 3,774 feet. These detection distances are somewhat shorter than for the right side of the highway shown in Figure 7, especially for the low beam. Figure 8 also shows that if either low beam is aimed .95° above the correct aim position, the detection distance for the warning sign on the left side of the highway will be greater than the detection distance for the nearly correct aim position. Further, it shows that the detection distances for the high beams range from 2,509 feet to 4,918 feet. In general, the best detection conditions are obtained when one of the high beams is nearly correctly aimed, and the second best detection distances are obtained when the beam aim is .9° left and .95° above the correct aim position.

| Driver Side \ Passenger Side | | Reflect. Material | ● H .9° V .95° Dist | % | H .9° ● V .95° Dist | % | H 0° V .15° Dist | % | V 1.25° ● H .9° Dist | % | V 1.25° H .9° ● Dist | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lowbeam Straight | ● H .9° V .95° | Pris. | 4104 | 152 | 3770 | 139 | 3655 | 135 | 3605 | 133 | 3591 | 133 |
| | | Enc. | 3159 | 154 | 2893 | 141 | 2805 | 136 | 2760 | 134 | 2748 | 134 |
| | | Encl. | 2498 | 155 | 2292 | 142 | 2213 | 137 | 2182 | 135 | 2174 | 135 |
| | H .9° ● V .95° | Pris. | 3767 | 139 | 3250 | 120 | 3031 | 112 | 2917 | 108 | 2884 | 107 |
| | | Enc. | 2889 | 141 | 2485 | 121 | 2305 | 112 | 2223 | 108 | 2196 | 107 |
| | | Encl. | 2286 | 142 | 1955 | 121 | 1815 | 113 | 1738 | 108 | 1721 | 107 |
| | H 0° V .15° | Pris. | 3644 | 135 | 3017 | 112 | 2704 | 100 | 2522 | 93 | 2460 | 91 |
| | | Enc. | 2793 | 136 | 2297 | 112 | 2056 | 100 | 1917 | 93 | 1871 | 91 |
| | | Encl. | 2201 | 137 | 1809 | 112 | 1612 | 100 | 1506 | 93 | 1470 | 91 |
| | V 1.25° ● H .9° | Pris. | 3592 | 133 | 2895 | 107 | 2514 | 93 | 2259 | 84 | 2170 | 80 |
| | | Enc. | 2746 | 134 | 2208 | 107 | 1905 | 93 | 1701 | 83 | 1646 | 80 |
| | | Encl. | 2170 | 135 | 1727 | 107 | 1494 | 93 | 1336 | 83 | 1287 | 80 |
| | V 1.25° H .9° ● | Pris. | 3577 | 132 | 2864 | 106 | 2449 | 91 | 2167 | 80 | 2072 | 77 |
| | | Enc. | 2736 | 133 | 2179 | 106 | 1856 | 90 | 1646 | 80 | 1569 | 76 |
| | | Encl. | 2162 | 134 | 1709 | 106 | 1456 | 90 | 1287 | 80 | 1243 | 77 |
| Highbeam Straight | ● H .9° V .95° | Pris. | 4670 | 93 | 4646 | 92 | 4866 | 97 | 4557 | 90 | 4530 | 90 |
| | | Enc. | 3603 | 92 | 3591 | 92 | 3762 | 96 | 3503 | 90 | 3490 | 89 |
| | | Encl. | 2865 | 92 | 2862 | 92 | 2991 | 96 | 2772 | 89 | 2769 | 89 |
| | H .9° ● V .95° | Pris. | 4654 | 92 | 4630 | 92 | 4851 | 96 | 4540 | 90 | 4512 | 90 |
| | | Enc. | 3599 | 92 | 3588 | 92 | 3758 | 96 | 3500 | 90 | 3488 | 89 |
| | | Encl. | 2868 | 92 | 2865 | 92 | 2993 | 96 | 2778 | 89 | 2774 | 89 |
| | H 0° V .15° | Pris. | 4872 | 97 | 4851 | 96 | 5039 | 100 | 4780 | 95 | 4757 | 94 |
| | | Enc. | 3768 | 97 | 3757 | 96 | 3902 | 100 | 3685 | 94 | 3673 | 94 |
| | | Encl. | 2997 | 96 | 2993 | 96 | 3106 | 100 | 2923 | 94 | 2919 | 94 |
| | V 1.25° ● H .9° | Pris. | 4558 | 90 | 4531 | 90 | 4773 | 95 | 4429 | 88 | 4398 | 87 |
| | | Enc. | 3504 | 90 | 3491 | 89 | 3679 | 94 | 3387 | 87 | 3374 | 86 |
| | | Encl. | 2773 | 89 | 2770 | 89 | 2916 | 94 | 2663 | 86 | 2661 | 86 |
| | V 1.25° H .9° ● | Pris. | 4538 | 90 | 4511 | 90 | 4756 | 94 | 4407 | 87 | 4378 | 87 |
| | | Enc. | 3498 | 90 | 3486 | 89 | 3673 | 94 | 3383 | 87 | 3369 | 86 |
| | | Encl. | 2776 | 89 | 2774 | 89 | 2918 | 94 | 2669 | 86 | 2668 | 86 |

—|— Correct Aim of Headlamp ● Actual Aim of Headlamp

Dist. - Distance (ft.) From the Object to the Driver for an Illuminance of 60 MOT

% - Distance Obtained for Actual Headlamp Misalignment Expressed as a Percentage of the Distance Obtained for the Average Headlamp Position

Pris. - Prismatic Sheeting Material Enc. - Encapsulated Lens Sheeting Material

Encl. - Enclosed or Embedded Sheeting Material

**FIGURE 7 Detection distances and percentages for a warning sign on the right side of a straight section of highway for high and low beam conditions, three different retroreflective materials, and 25 passenger's and driver's side beam misaim combinations.**

| Driver Side | Driver Side aim | Reflect. Material | Passenger Side ● H.9° V.95° Dist | % | H.9° ● V.95° Dist | % | H 0° V.15° Dist | % | V 1.25° ● H.9° Dist | % | V 1.25° H.9° ● Dist | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lowbeam Straight | ● H.9° V.95° | Pris. | 3774 | 160 | 3397 | 144 | 3323 | 140 | 3283 | 139 | 3263 | 138 |
| | | Enc. | 2764 | 160 | 2477 | 144 | 2411 | 140 | 2375 | 138 | 2351 | 136 |
| | | Encl. | 2014 | 154 | 1813 | 139 | 1747 | 134 | 1728 | 133 | 1710 | 131 |
| | H.9° ● V.95° | Pris. | 3361 | 142 | 2727 | 115 | 2572 | 109 | 2485 | 105 | 2429 | 103 |
| | | Enc. | 2413 | 140 | 2019 | 117 | 1889 | 110 | 1840 | 107 | 1791 | 104 |
| | | Encl. | 1804 | 138 | 1537 | 118 | 1436 | 110 | 1401 | 107 | 1363 | 105 |
| | H 0° V.15° | Pris. | 3274 | 138 | 2569 | 109 | 2366 | 100 | 2253 | 95 | 2168 | 92 |
| | | Enc. | 2327 | 135 | 1885 | 109 | 1724 | 100 | 1653 | 96 | 1582 | 92 |
| | | Encl. | 1737 | 133 | 1428 | 110 | 1304 | 100 | 1260 | 97 | 1210 | 93 |
| | V 1.25° ● H.9° | Pris. | 3224 | 136 | 2469 | 104 | 2237 | 95 | 2109 | 89 | 2001 | 85 |
| | | Enc. | 2281 | 132 | 1825 | 106 | 1646 | 95 | 1565 | 91 | 1484 | 86 |
| | | Encl. | 1714 | 131 | 1387 | 106 | 1258 | 96 | 1195 | 92 | 1135 | 87 |
| | V 1.25° H.9° ● | Pris. | 3200 | 135 | 2415 | 102 | 2147 | 91 | 2001 | 85 | 1877 | 79 |
| | | Enc. | 2252 | 131 | 1771 | 103 | 1573 | 91 | 1477 | 86 | 1386 | 80 |
| | | Encl. | 1695 | 130 | 1342 | 103 | 1204 | 92 | 1127 | 86 | 1068 | 82 |
| Highbeam Straight | ● H.9° V.95° | Pris. | 4708 | 96 | 4600 | 94 | 4813 | 98 | 4593 | 93 | 4500 | 92 |
| | | Enc. | 3642 | 96 | 3542 | 94 | 3705 | 98 | 3540 | 94 | 3459 | 92 |
| | | Encl. | 2895 | 97 | 2804 | 94 | 2934 | 98 | 2806 | 94 | 2732 | 92 |
| | H.9° ● V.95° | Pris. | 4607 | 94 | 4491 | 91 | 4722 | 96 | 4483 | 91 | 4374 | 89 |
| | | Enc. | 3548 | 94 | 3441 | 91 | 3623 | 96 | 3439 | 91 | 3342 | 88 |
| | | Encl. | 2812 | 94 | 2704 | 91 | 2854 | 96 | 2708 | 91 | 2616 | 88 |
| | H 0° V.15° | Pris. | 4822 | 98 | 4725 | 96 | 4918 | 100 | 4718 | 96 | 4631 | 94 |
| | | Enc. | 3713 | 98 | 3626 | 96 | 3780 | 100 | 3623 | 96 | 3542 | 94 |
| | | Encl. | 2942 | 99 | 2856 | 96 | 2979 | 100 | 2857 | 96 | 2784 | 93 |
| | V 1.25° ● H.9° | Pris. | 4594 | 93 | 4475 | 91 | 4710 | 96 | 4466 | 91 | 4357 | 89 |
| | | Enc. | 3540 | 94 | 3431 | 91 | 3615 | 96 | 3428 | 91 | 3331 | 88 |
| | | Encl. | 2806 | 94 | 2699 | 91 | 2848 | 96 | 2702 | 91 | 2611 | 88 |
| | V 1.25° H.9° ● | Pris. | 4506 | 92 | 4372 | 89 | 4627 | 94 | 4364 | 89 | 4238 | 86 |
| | | Enc. | 3465 | 92 | 3339 | 88 | 3537 | 94 | 3337 | 88 | 3221 | 85 |
| | | Encl. | 2738 | 92 | 2613 | 88 | 2779 | 93 | 2619 | 88 | 2509 | 84 |

─┼─ Correct Aim of Headlamp ● Actual Aim of Headlamp
Dist. - Distance (ft.) From the Object to the Driver for an Illuminance of 60 MOT
% - Distance Obtained for Actual Headlamp Misalignment Expressed as a Percentage of the Distance Obtained for the Average Headlamp Position
Pris. - Prismatic Sheeting Material Enc. - Encapsulated Lens Sheeting Material
Encl. - Enclosed or Embedded Sheeting Material

**FIGURE 8 Detection distances and percentages for a warning sign on the left side of a straight section of highway, for high and low beam conditions, three different retroreflective materials, and 25 passenger's and driver's side beam misaim combinations.**

Figure 9 shows detection distances and percentages for an overhead guide sign on a straight section of highway for high and low beam conditions, two different retroreflective materials, and 25 combinations of beam misaim. From this figure, it can be seen that the detection distances range from 2,256 (point source size factor of 1.66) to 5,390 ft for the low beams and 4,527 to 6,692 ft for the high beams. These detection distances are surprisingly large, apparently due to the large reflective area (108 $ft^2$) of the sign. Detection distances longer than the detection distance for the nearly correct low beam position are obtained if either low beam is aimed .95° above the correct aim position. Further, Figure 9 shows that low and high beam detection distances of less than 90 percent of the detection distance for the nearly correct beam position are obtained only when both beams are aimed 1.25° below the correct aim position.

Figure 10 shows detection distances and percentages for the post delineator patch along a straight and a left-curved section of highway, two retroreflective sheeting materials, and 25 combinations of low beam misaim. The low beam detection distances range from 701 ft to 1,992 ft on the straight section of highway and from 472 ft (point source size factor of 1.01) to 874 ft on the curved section of highway. It can be seen that for the straight section of highway, if either low beam is aimed .95° above the correct aim position, the detection distance will be greater than the detection distance for the nearly correct beam low beam position. In contrast, for the curved section of highway, detection distances greater than the detection distance for the nearly correct aim position are obtained only if the driver's side low beam or both low beams are aimed .95° above the correct aim position.

Figure 11 shows detection distances and percentages for a 23 CIL license plate located on the right and left side of a straight and a left-curved section of highway for the 25 beam misaim combinations. It can be seen that the low beam detection distances range from 519 ft to 1,116 ft when the license plate is located above the right edge of a straight section of highway, 612 to 1,355 ft when located above the left edge. The distances also range from 327 (point source size factor of 1.17) to 618 ft when the license plate is located above the

| Driver Side | Driver side aim | Reflector Material | Passenger Side: ● H .9°, V .95° — Dist | % | Passenger Side: H .9° ●, V .95° — Dist | % | Passenger Side: H 0°, V .15° — Dist | % | Passenger Side: V 1.25°, ● H .9° — Dist | % | Passenger Side: V 1.25°, H .9° ● — Dist | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lowbeam Straight | ● H .9°, V .95° | Pris. | 5390 | 150 | 4944 | 138 | 4830 | 134 | 4769 | 133 | 4751 | 132 |
| | | Enc. | 4193 | 152 | 3829 | 138 | 3746 | 135 | 3701 | 134 | 3685 | 133 |
| | H .9° ●, V .95° | Pris. | 4934 | 137 | 4166 | 116 | 3929 | 109 | 3781 | 105 | 3732 | 104 |
| | | Enc. | 3816 | 138 | 3181 | 115 | 2997 | 108 | 2896 | 105 | 2847 | 103 |
| | H 0°, V .15° | Pris. | 4810 | 134 | 3913 | 109 | 3592 | 100 | 3390 | 94 | 3313 | 92 |
| | | Enc. | 3728 | 135 | 2984 | 108 | 2767 | 100 | 2622 | 95 | 2562 | 93 |
| | V 1.25°, ● H .9° | Pris. | 4749 | 132 | 3758 | 105 | 3382 | 94 | 3137 | 87 | 3020 | 84 |
| | | Enc. | 3679 | 133 | 2871 | 104 | 2613 | 94 | 2439 | 88 | 2356 | 85 |
| | V 1.25°, H .9° ● | Pris. | 4729 | 132 | 3704 | 103 | 3303 | 92 | 3019 | 84 | 2896 | 81 |
| | | Enc. | 3662 | 132 | 2818 | 102 | 2554 | 92 | 2356 | 85 | 2256 | 82 |
| Highbeam Straight | ● H .9°, V .95° | Pris. | 6389 | 95 | 6322 | 94 | 6544 | 98 | 6182 | 92 | 6128 | 92 |
| | | Enc. | 5074 | 96 | 5017 | 95 | 5183 | 98 | 4878 | 92 | 4840 | 91 |
| | H .9° ●, V .95° | Pris. | 6328 | 95 | 6253 | 93 | 6489 | 97 | 6104 | 91 | 6050 | 90 |
| | | Enc. | 5023 | 95 | 4964 | 94 | 5137 | 97 | 4816 | 91 | 4772 | 90 |
| | H 0°, V .15° | Pris. | 6549 | 98 | 6490 | 97 | 6692 | 100 | 6367 | 95 | 6320 | 94 |
| | | Enc. | 5188 | 98 | 5137 | 97 | 5292 | 100 | 5013 | 95 | 4977 | 94 |
| | V 1.25°, ● H .9° | Pris. | 6182 | 92 | 6097 | 91 | 6361 | 95 | 5921 | 88 | 5855 | 87 |
| | | Enc. | 4878 | 92 | 4808 | 91 | 5007 | 95 | 4623 | 87 | 4572 | 86 |
| | V 1.25°, H .9° ● | Pris. | 6133 | 92 | 6048 | 90 | 6318 | 94 | 5862 | 88 | 5790 | 87 |
| | | Enc. | 4844 | 92 | 4769 | 90 | 4975 | 94 | 4578 | 87 | 4527 | 86 |

┼ Correct Aim of Headlamp
● Actual Aim of Headlamp
Dist. - Distance (ft.) From the Object to the Driver for an Illuminance of 60 MOT
% - Distance Obtained for Actual Headlamp Misalignment Expressed as a Percentage of the Distance Obtained for the Average Headlamp Position
Pris. - Prismatic Sheeting Material
Enc. - Encapsulated Lens Sheeting Material

**FIGURE 9 Detection distances and percentages for an overhead guide sign on a straight section of highway, high and low beam conditions, two different retroreflective materials, and 25 combinations of driver's and passenger's side headlamp misaims.**

left edge of the left-curved section of highway, and 423 and 637 ft when located above the right edge. For the straight section of highway, if either low beam is aimed .95° above the correct aim position, the detection distance will be greater than the detection distance for the nearly correct aim position. For the curved section of highway, detection distances greater than the detection distance for the nearly correct aim position are obtained only if the driver's side low beam or both low beams are aimed .95° above the correct aim position. As indicated by the black shaded area, the detection distance will be reduced to less than 70 percent of the detection distance for the nearly correct low beam aim position if the driver's side low beam is aimed .9° to the right and 1.25° below the correct position and the passenger's side beam is aimed 1.25° below the correct aim position with a horizontal misaim of either .9° left or .9° right of the correct aim position.

In reviewing Figures 7 through 11, a few general observations may be made. For a given retroreflective material, the longest detection distance for the low beams is always observed when both low beams are identically aimed 0.9° left and 0.95° above the correct aim position. The longest detection distance for the high beams is always observed when both high beams are identically and nearly correctly aimed, and the shortest detection distances for both low and high beams are observed when both beams are identically aimed 0.9° right and 1.25° below the correct aim position. With the exception of the warning sign on the left side of the highway, the detection distances for the reflective targets investigated are always reduced to less than 90 percent if both beams (either high or low beams) are misaimed 1.25° below the correct aim position. Further it can be seen that the relative effect of beam misaim on detection distance is about the same for each of the three types of retroreflective sheeting materials.

Figure 12 shows maximum, minimum, and nearly correct aimed detection distances for all targets and investigated conditions. It can be seen that the shortest distances for the high beam condition are always higher than the longest distances for the low beam and that the high beam is much less sensitive to the horizontal and vertical misaim conditions investigated in this study than the low beams. Comparing the reflective materials shows that the shortest distance obtained for the encapsulated lens sheeting material is always about equal to the distance obtained for the nearly correct aim position for the enclosed or embedded lens sheeting material. Further,

| Driver Side | | Reflector Material | Passenger Side: ● H .9° V .95° | | H .9° ● V .95° | | H 0° ● V .15° | | V 1.25° ● H .9° | | V 1.25° H .9° ● | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Dist | % | Dist | % | Dist | % | Dist | % | Dist | % |
| Lowbeam Straight | ● H .9° V .95° | Pris. | 1992 | 154 | 1827 | 142 | 1763 | 137 | 1734 | 134 | 1726 | 134 |
| | | Enc. | 1500 | 154 | 1375 | 141 | 1325 | 136 | 1299 | 134 | 1295 | 133 |
| | H .9° ● V .95° | Pris. | 1822 | 141 | 1575 | 122 | 1462 | 113 | 1401 | 109 | 1388 | 108 |
| | | Enc. | 1374 | 141 | 1196 | 123 | 1129 | 116 | 1092 | 112 | 1086 | 112 |
| | H 0° ● V .15° | Pris. | 1755 | 136 | 1454 | 113 | 1291 | 100 | 1196 | 93 | 1175 | 91 |
| | | Enc. | 1320 | 136 | 1093 | 112 | 972 | 100 | 893 | 92 | 880 | 91 |
| | V 1.25° ● H .9° | Pris. | 1723 | 133 | 1386 | 107 | 1185 | 92 | 1045 | 81 | 998 | 77 |
| | | Enc. | 1292 | 133 | 1042 | 107 | 881 | 91 | 769 | 79 | 743 | 76 |
| | V 1.25° H .9° ● | Pris. | 1714 | 133 | 1373 | 106 | 1162 | 90 | 998 | 77 | 957 | 74 |
| | | Enc. | 1288 | 133 | 1030 | 106 | 862 | 89 | 738 | 76 | 701 | 72 |
| Lowbeam Left Curve | ● H .9° V .95° | Pris. | 874 | 117 | 868 | 116 | 833 | 112 | 799 | 107 | 797 | 107 |
| | | Enc. | 698 | 118 | 693 | 117 | 666 | 113 | 642 | 108 | 638 | 108 |
| | H .9° ● V .95° | Pris. | 866 | 116 | 860 | 115 | 820 | 110 | 788 | 105 | 786 | 105 |
| | | Enc. | 689 | 116 | 682 | 115 | 649 | 110 | 629 | 106 | 626 | 106 |
| | H 0° ● V .15° | Pris. | 805 | 108 | 796 | 107 | 747 | 100 | 703 | 94 | 698 | 93 |
| | | Enc. | 633 | 107 | 626 | 106 | 592 | 100 | 560 | 95 | 555 | 94 |
| | V 1.25° ● H .9° | Pris. | 745 | 100 | 730 | 98 | 665 | 89 | 616 | 82 | 605 | 81 |
| | | Enc. | 591 | 100 | 575 | 97 | 538 | 91 | 514 | 87 | 503 | 85 |
| | V 1.25° H .9° ● | Pris. | 735 | 98 | 719 | 96 | 637 | 85 | 585 | 78 | 564 | 76 |
| | | Enc. | 572 | 97 | 555 | 94 | 514 | 87 | 479 | 81 | 472 | 80 |

┼ Correct Aim of Headlamp
● Actual Aim of Headlamp
Dist. - Distance (ft.) From the Object to the Driver for an Illuminance of 60 MOT
% - Distance Obtained for Actual Headlamp Misalignment Expressed as a Percentage of the Distance Obtained for the Average Headlamp Position
Pris. - Prismatic Sheeting Material
Enc. - Encapsulated Lens Sheeting Material

**FIGURE 10 Detection distances and percentages for a post delineator on a straight and a curved section of highway, for low beam conditions, two retroreflective materials, and 25 combinations of driver's and passenger's side headlamp misaims.**

the shortest distances obtained for the prismatic sheeting material are about equal to or longer than the distances obtained for the encapsulated lens sheeting material for the nearly correct beam misaim condition. Therefore, it would seem that the detrimental effect of misaimed beams on the detection distance of reflectorized targets may be almost totally offset by the use of brighter reflector material. However, Sivak and Olson (*12*) have discussed a number of studies which have shown that legibility is generally an inverted U-shaped function of luminance. Thus, there is concern that the selection of brighter reflectorized materials, which would increase detection distances, might have a negative effect upon recognition distance. In a recent study, Zwahlen et al. (*13*) has concluded that based upon average correct recognition distances and the number of correct and incorrect responses, the use of high reflective sheeting materials, such as prismatic sheeting material, combined with fairly high beam illumination conditions have only a small effect upon shape recognition. Therefore, it would appear that the use of brighter reflective materials, encapsulated lens or prismatic sheeting materials, in the design of reflectorized targets will likely offset the detrimental effect of misaimed beams on detection distance while causing only a small, practically negligible negative effect upon recognition distance.

Figure 12 also shows decision sight distance (DSD) for a selected design speed of 55 mph (interpolated from decision sight distances for design speeds of 50 and 60 mph (*1*)) and stopping sight distance (SSD) for a design speed of 55 mph (interpolated from stopping sight distances for design speeds of 50 and 60 mph (*14*)). The decision sight distance is defined as the distance required for a driver to detect a hazard in a cluttered roadway environment, recognize its threat potential, select an appropriate speed and path, and safely perform the necessary avoidance maneuver. The stopping sight distance (SSD) is defined as the distance which is traversed by a vehicle from the instant a driver sights an object for which a stop is necessary until the vehicle is stopped. Looking at Figure 12, it can be seen that, with the exception of detection distances for a vertical beam misaim of .95° above the correct aim position for the license plate on a straight section of highway, all of the distances obtained for the license plate (the only object investigated in this study which might require an immediate stop) are shorter than the minimum decision sight distance for an approach speed of 55 mph. The longest detection

| Driver Side | | License Position | ● H .9° V .95° Dist | % | H .9° ● V .95° Dist | % | H 0° V .15° Dist | % | V 1.25° ● H .9° Dist | % | V 1.25° H .9° ● Dist | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lowbeam Straight | ● H .9° V .95° | Right* | 1355 | 159 | 1238 | 145 | 1197 | 141 | 1182 | 139 | 1178 | 138 |
| | | Left** | 1116 | 168 | 999 | 150 | 978 | 147 | 969 | 146 | 962 | 145 |
| | H .9° ● V .95° | Right | 1220 | 143 | 1047 | 123 | 979 | 115 | 947 | 111 | 937 | 110 |
| | | Left | 966 | 145 | 789 | 119 | 750 | 113 | 729 | 110 | 711 | 107 |
| | H 0° V .15° | Right | 1168 | 137 | 949 | 112 | 851 | 100 | 792 | 93 | 779 | 92 |
| | | Left | 923 | 139 | 713 | 107 | 665 | 100 | 641 | 96 | 617 | 93 |
| | V 1.25° ● H .9° | Right | 1144 | 134 | 893 | 105 | 769 | 90 | 685 | 80 | 662 | 78 |
| | | Left | 902 | 136 | 681 | 102 | 618 | 93 | 590 | 89 | 572 | 86 |
| | V 1.25° H .9° ● | Right | 1138 | 134 | 881 | 104 | 743 | 87 | 649 | 76 | 612 | 72 |
| | | Left | 890 | 134 | 654 | 98 | 579 | 87 | 549 | 83 | 519 | 78 |
| Lowbeam Left Curve | ● H .9° V .95° | Right | 637 | 117 | 634 | 117 | 615 | 113 | 596 | 110 | 593 | 109 |
| | | Left | 618 | 120 | 613 | 119 | 590 | 115 | 565 | 110 | 564 | 110 |
| | H .9° ● V .95° | Right | 630 | 116 | 626 | 115 | 603 | 111 | 580 | 107 | 575 | 106 |
| | | Left | 609 | 118 | 604 | 118 | 577 | 112 | 554 | 108 | 553 | 108 |
| | H 0° V .15° | Right | 583 | 107 | 573 | 106 | 543 | 100 | 519 | 96 | 511 | 94 |
| | | Left | 551 | 107 | 546 | 106 | 514 | 100 | 478 | 93 | 477 | 93 |
| | V 1.25° ● H .9° | Right | 539 | 99 | 529 | 97 | 480 | 88 | 461 | 85 | 453 | 83 |
| | | Left | 477 | 93 | 470 | 91 | 422 | 82 | 381 | 74 | 376 | 73 |
| | V 1.25° H .9° ● | Right | 525 | 97 | 511 | 94 | 465 | 86 | 437 | 80 | 423 | 78 |
| | | Left | 469 | 91 | 460 | 89 | 395 | 77 | 342 | 67 | 327 | 64 |

(Column headings: Passenger Side; row headings: Driver Side)

—|— Correct Aim of Headlamp
● Actual Aim of Headlamp
Dist. - Distance (ft.) From the Object to the Driver for an Illuminance of 60 MOT
% - Distance Obtained for Actual Headlamp Misalignment Expressed as a Percentage of the Distance Obtained for the Average Headlamp Position
*Right - License Plate Located Above Right Edge Line
**Left - License Plate Located Above Left Edge Line

**FIGURE 11 Detection distances and percentages for a 23 CIL license plate located on the right and the left side of a straight and a curved section of highway, for 25 combinations of driver's and passenger's side headlamp misaims.**

distances observed for the license plate in a left-curved section of highway are 250 ft shorter than the minimum decision sight distance. Further, the shortest distances for a license plate located along either edge of a 2,000 ft radius (2.9°) left curve are equal to or below the required stopping sight distance for 55 mph. The rear of most motor vehicles is equipped with prismatic retroreflective devices in addition to a reflectorized license plate which would aid in the detection of a disabled vehicle along the edge of the highway if one is approaching from the rear. However, it should be noted that the results obtained would appear to indicate that if a driver were to approach the front of a disabled vehicle, which is usually not equipped with any retroreflective device other than possibly a reflectorized license plate, a driver may not be able to detect its presence until it is too late to bring his or her vehicle to a complete stop, especially if the vehicle is disabled in a 2,000 ft radius left-curved section of highway.

In the systematic study of horizontal and vertical misaim conducted by Bhise et al. (*2*), the horizontal misaim of low beams was found to have less effect upon the driver visibility criterion than the vertical misaim. Considering the isocandela distribution of the halogen 6054 beam used in this study, or any sealed low beam headlamps commonly used in the United States, this finding would be expected. The maximum horizontal dimension of each isocandela contour is 2 to 3 times larger than the corresponding maximum-vertical dimension. Comparing the detection distance calculated for a low beam misaim of .9° to the right and .95° up for the warning sign on the left side of a straight section of highway and the license plate on the same section of highway (see Figures 8 and 11) to a low beam misaim angle of .9° to the left and .95° up for the same targets (a horizontal shift of 1.8°), it can be seen that the differences between the two percentages are about 45 percent for the warning sign (3,774 ft or 160 percent down to 2,727 ft or 115 percent for prismatic sheeting material) and about 49 percent for the license plate (1,355 ft down to 1,047 ft). Comparing the detection distances calculated for a beam misaim of .9° to the left and .95° up with a beam misaim of .9° to the left and 1.25° down (a vertical shift of 2.2°) for the same signs, it can be seen that the difference between the two percentages is about 36 percent (2,727 ft down to 1,877 ft for prismatic sheeting material) for the warning sign on the left side of the highway and about 41 percent (789 ft down to 519 ft) for the license plate. It can be seen that the difference

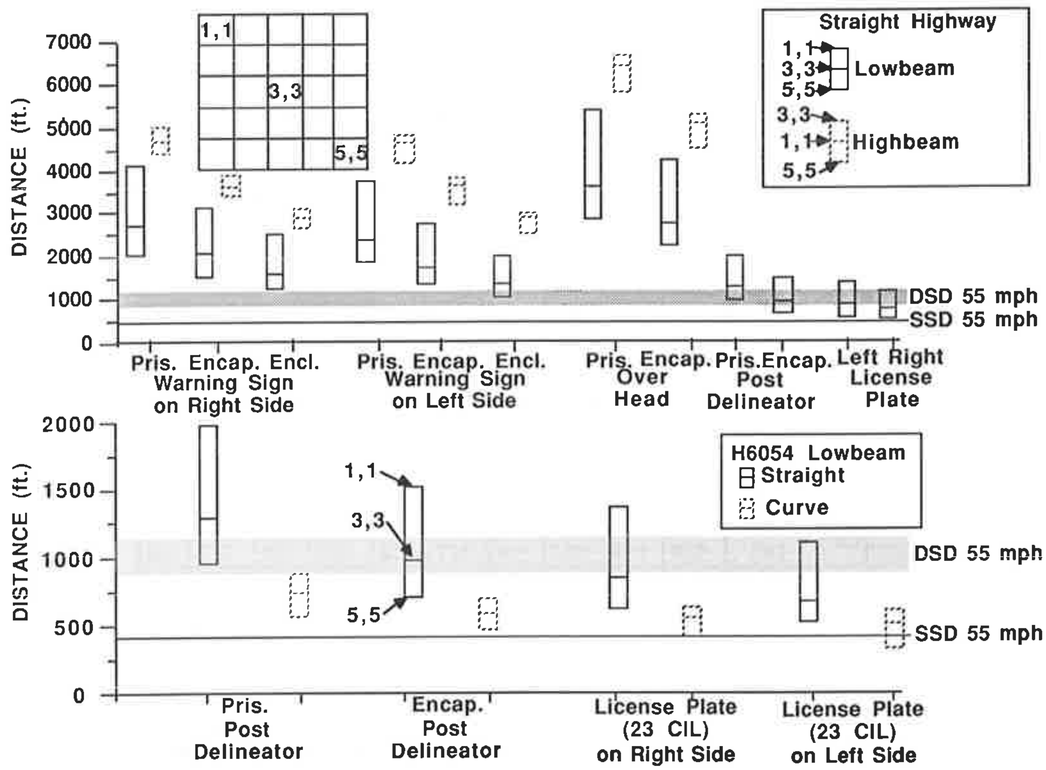


**FIGURE 12 Maximum, minimum and nearly correct aimed beam detection distances for the five targets, three retroreflective sheeting materials (prismatic, encapsulated lens, and enclosed lens), high and low beam conditions, and for straight and left-curved sections of highway.**

between the two percentages is 45 percent for the warning sign and 49 percent for the license plate when the horizontal misaim was changed by 1.8° and the percentages decreased by 36 percent for the warning sign and 41 percent for the license plate when the vertical misaim was changed by 2.2°. Conducting this same analysis for the overhead guide sign shows that a horizontal shift of 1.8° would result in a difference of 34 percent for the low beams and a vertical shift of 2.2° would result in a difference of 35 percent. Therefore, it appears that detection distance can be more sensitive to horizontal misaim than vertical misaim for specific geometric conditions: however, this seems to be the exception to the rule since the vertical misaim is, in general, more sensitive than the horizontal misaim for the majority of conditions.

Figure 11 shows that when both low beams are aimed 1.25° below the correct aim position, and the horizontal beam misaim is moved from .9° to the left to .9° to the right of the correct aim position, the horizontal change of 1.8° will reduce the detection distance by 38 ft for the license plate on the right side of the highway in the left-curved section, and 54 ft for the license plate on the left side of the highway in the left-curved section of highway. For a license plate in a 2,000 ft radius left-curved section, the detection distance is less than the decision sight distance for all the low beam misaim conditions. The decrease in the detection distance, due to this horizontal misaim, reduces the detection distances to those that are shorter than the stopping sight distance. These short reductions may be significant from a practical or safety point of view.

## CONCLUSIONS

Vertically misaimed high and low beams have a larger effect on the detection distance of reflectorized targets than horizontally misaimed beams. However, the influence of horizontal beam misaims may not be negligible, suggesting that a correct aiming position of the beams in both the vertical and horizontal directions would be desirable. The detrimental effect of misaimed beams on detection distance can, in most cases, be totally or almost totally offset by the selection of a brighter reflector material (prismatic or encapsulated material). When measuring the aim of beams, it would appear to be important to measure both low beams and high beams (for vehicles with 4 headlamps), to determine the horizontal and vertical misaim and frequency distributions beyond plus or minus 1.9° (maybe up to 3° or 5°) and also to investigate any possible aiming relationships between the passenger side and driver side beams.

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# Visibility Criteria and Application Techniques for Roadway Lighting

M. S. Rea

**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-

National Research Council Canada, Institute for Research in Construction, Ottawa, Ontario, Canada K1A 0R6.

**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*).

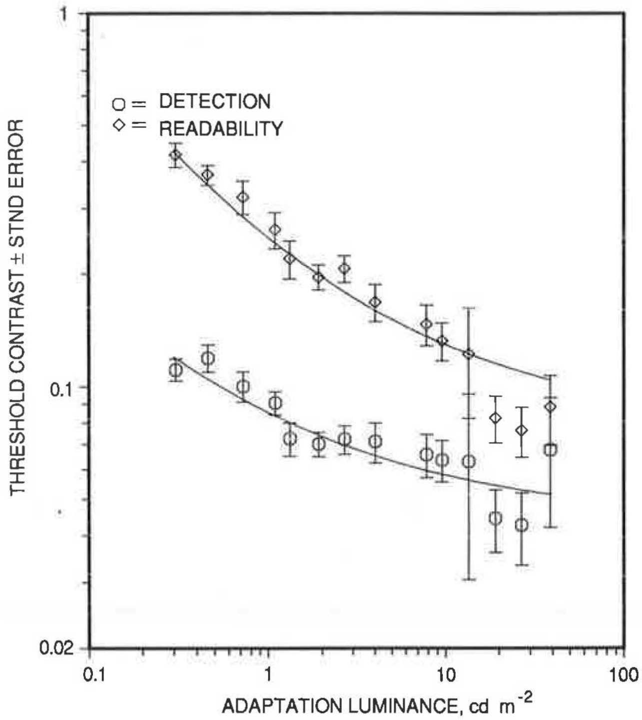


**FIGURE 3 Detection and readability threshold data for steady viewing of five-digit numbers (*16*).**

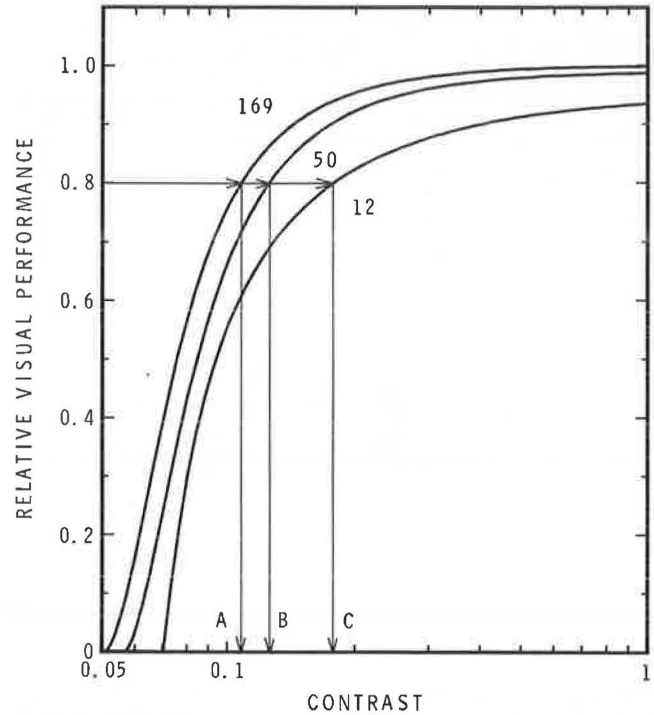


**FIGURE 4 Constant luminance lines from the Relative Visual Performance (RVP) model developed by Rea (*11*). The curves are labelled in units of background luminance, cd/m². Points labelled A, B, and C are derived from a constant criterion of 0.80 from the RVP model for 169, 50, and 12 cd/m², respectively.**

## 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).

### *Appearance*

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

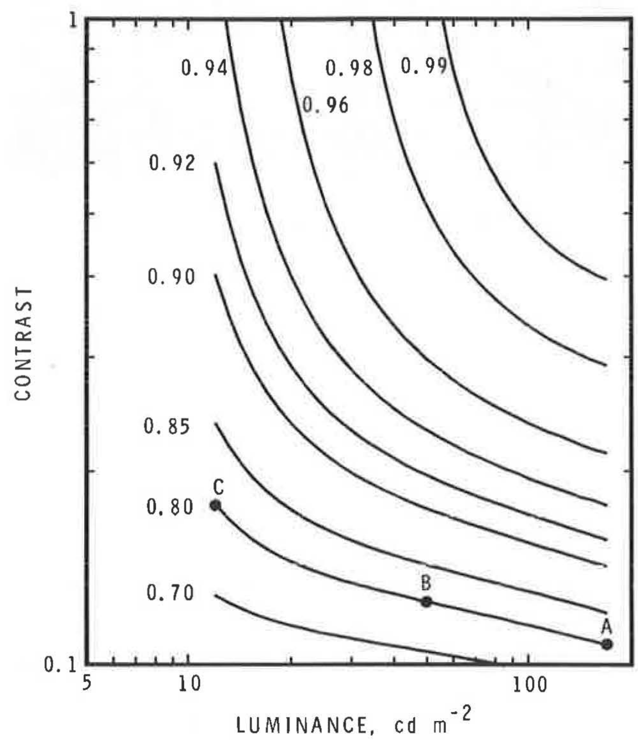


**FIGURE 5 Constant performance lines through the Relative Visual Performance (RVP) model developed by Rea (*11*). The curves, labelled in units of RVP, are comparable to threshold functions. Points labelled A, B, and C correspond to those derived in Figure 4.**

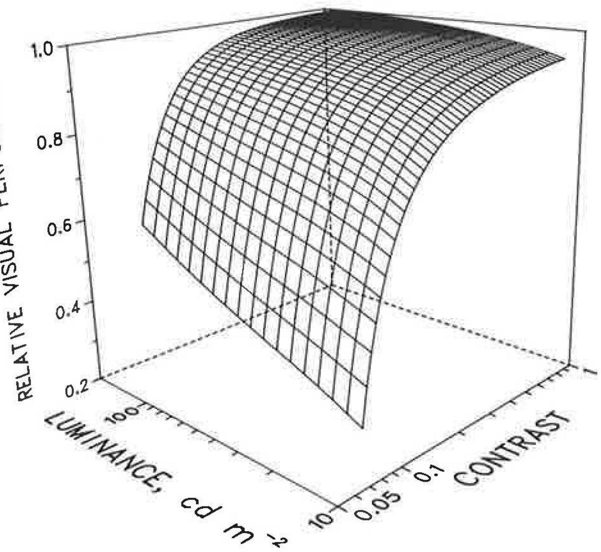


**FIGURE 6 A three-dimensional representation of the Relative Visual Performance (RVP) model developed by Rea (*11*).**

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., $2 \times 10^{-6}$ steradians) targets will require more time to process at 1 cd/m² than at 10 cd/m². 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/m² the 20 year old has a retinal illuminance of about 18 trolands and at 10 cd/m² 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/m² in this experiment. Figure 7 compares the functions derived from the two experiments at 20 cd/m² 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

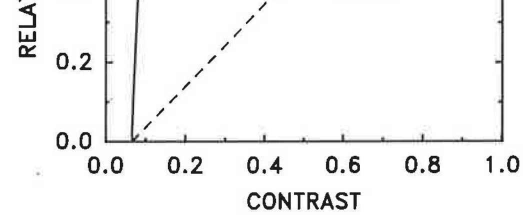


**FIGURE 7 Two types of suprathreshold response to the same stimulus: printed five-digit numbers of different contrast. The solid line is based upon responses of speed and accuracy from the RVP model developed by Rea (*11*); the dashed line is from unpublished data using magnitude estimations of apparent contrast. Adaptation luminance was 20 cd/m² 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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# Effect of Luminaire Arrangement on Object Visibility

Merle E. Keck

**The visibility of small objects is affected more by the contrast between the outline of the object and the background than by the adaptation level produced by the pavement luminance. Because the object luminance is likely to be produced by a different luminaire than most pavement luminances, the contrast can be controlled by the lighting system designer. Both the pavement and the object have distinct directional light reflectance properties; hence, the luminaire arrangement is one of the major factors used in determining the direction from which light reaches both the object and its background. The substantial changes in visibility that occur as the result of the choices made in luminaire arrangement and light distribution are explored. These explorations are made by studying the visibility of a small standard target placed on a grid overlay on the pavement. The resulting Small Target Visibility can be calculated and summarized to serve as a criterion for the quality of the roadway lighting system.**

There is no question that some light is required to drive a vehicle safely. The light may come from the sun, the moon, vehicle headlights, or fixed lighting, but there must be some light to make our human visual system effective. The questions are, "how much light?" and "how does one determine the quality of the lighting?" One answer is, "enough to make things visible."

A measure of the quantity of light reaching the road surface or reflected from it has been used to determine the amount of light required from a fixed lighting system. A candlepower/angle specification of headlight output distribution for vehicle headlights has also been used.

The use of a visibility measure is gaining acceptance by both the fixed roadway lighting community and by the headlighting group. One such measure, loosely called "Small Target Visibility" (STV), will probably be used to specify the quality of fixed roadway lighting in the next edition of ANSI RP-8 (*1*). In vehicle headlighting the tendency is to use several targets, such as a stylized pedestrian, a small object, and a lane line. Such objects are used in the Chess Headlighting Evaluation Program (*2*).

It is necessary for the designer of a lighting system or luminaire to understand the interaction of the various factors that improve or degrade such a surrogate measure. The purpose of this paper is to discuss those factors with regard to the measure called STV.

## SMALL TARGET VISIBILITY

STV, as defined by the Roadway Lighting Committee (RLC) of the Illuminating Engineering Society (IES), is the measurement or calculation of the visibility level of an 18-cm (7-in) square, flat target located on a flat, level roadway 273 ft from an observer that is 1.45 m above the pavement and on a line parallel to the center line of the roadway. The target surface has a diffuse reflectance of 20 percent and is located at 90° to both the observer's line of sight and the roadway surface. The visibility level (VL) is the amount the target is above threshold for a standard observer (*3*). A lighting installation is given an STV rating by evaluating the visibility of such a target located at many points in the installation. It is common to use the 20th percentile as the rating number.

STV, like other measures such as horizontal lux, pavement luminance, vertical lux, hemispherical lux, or semicylindrical lux, is measured or calculated at a large number of grid points over the roadway surface. STV has been correlated to driver performance by Gallagher (*4*), and top vehicular accidents by Janoff (*5*). It is a surrogate measure, however, and does not necessarily correlate with all of the different visual tasks a driver encounters. It is not the purpose of this paper to discuss the merits or deficiencies of STV, but to discuss the ways a designer can improve the STV rating of a lighting system. The factors that determine the VL of a small target are as follows:

- The adaptation level of the human visual system: Adaptation determines the sensitivity of the visual system to both contrast and glare.
- The contrast between the target and its background: In the arrangement previously discussed, the background behind the small target is always the luminance of the roadway pavement surface. Both the luminance of the target and the roadway surface can be calculated.
- The size of the small target: In the definition previously mentioned, size is constant.
- Transient adaptation, the result of the adaptation change from the point last fixated by the moving eye: This is neglected in current calculations because the research defining it is still ambiguous.

To improve or degrade STV, as previously defined, it is necessary to consider only three factors—adaptation level, contrast, and glare—because the target size is constant.

### Adaptation Level

Adaptation level is roughly defined by the horizontal lux over footcandle (fc) level. The average level on the roadway from the observer to 500 ft ahead may be as much as 5,000 fc from daylight; a fixed lighting system provides from 0.5 to 4.0 fc

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and a headlighting system from 0.001 to 0.1 fc. A more accurate method of defining adaptation level is by measuring the luminance over a given angular field. A circular field of 1.5°, centered on the point of visual fixation, is often used to determine adaptation level in visibility calculations.

The adaptation level produced by a fixed lighting system (streetlights) can be changed by several means. The most common is to change the lamp size or the number of units per mile (spacing). If the light output is varied by means of a dimming system with no change in the arrangement of the lighting system, then STV will increase as light level increases. The relationship for a typical street lighting system is shown in Figure 1 (the contrast is constant at 0.5 and the Lv is constant at 0.2). Doubling the light level from 1 to 2 cd/m$^2$ increases the target VL by about 20 percent, provided the luminaire arrangement and luminaire distribution are unchanged.

### Contrast

Contrast is the most powerful factor in determining the visibility of a small target. Contrast is usually defined as the luminance of the target minus the luminance of the background with the quantity divided by the luminance of the background.

$$\text{Contrast} = \frac{L\ (\text{target}) - L\ (\text{background})}{L\ (\text{background})}$$

Contrast may be either positive or negative depending on whether the luminance of the target is greater than or less than the luminance of the background. Less obvious is that negative contrast can vary only between 0 and $-1$ whereas positive contrast can vary from 0 to infinity. Figure 2 shows the relationship between STV and contrast with all other factors held constant (the adaptation level is constant at 1 cd/m$^2$ and the Lv is constant at 0.2). Doubling the contrast doubles the target VL.

The human visual system easily detects and recognizes object shape under either positive or negative contrast situations. Negative contrast is often called "silhouette" vision. Black printing on white paper or white printing on black paper can be read with no particular problems.

### Glare

The eye is not hollow and the material between the lens and the retina is not perfectly clear. Light that enters the eye is scattered by imperfections in the aqueous humor and acts as a luminous veil that reduces the contrast to the receptors on the retina. The severity of this scattering normally increases with the age of the individual. The effect of veiling luminance (Lv) is a function of the amount of light entering the eye and the angular location relative to the line of sight. The relationship between STV and Lv, with other factors constant, is shown in Figure 3 (the contrast is constant at 0.5 and the adaptation level is constant at 1 cd/m$^2$). It is easily seen that the effect is relatively mild with an adaptation level of 1 cd/m$^2$.

Glare from oncoming headlights is particularly severe if the adaptation level is very low. The angle between the driver's line of sight and the oncoming vehicle is small and the amount of light entering the eye from the oncoming headlights may be high. In daylight, or even under a fixed lighting system, the adaptation level may be sufficiently high so that the same

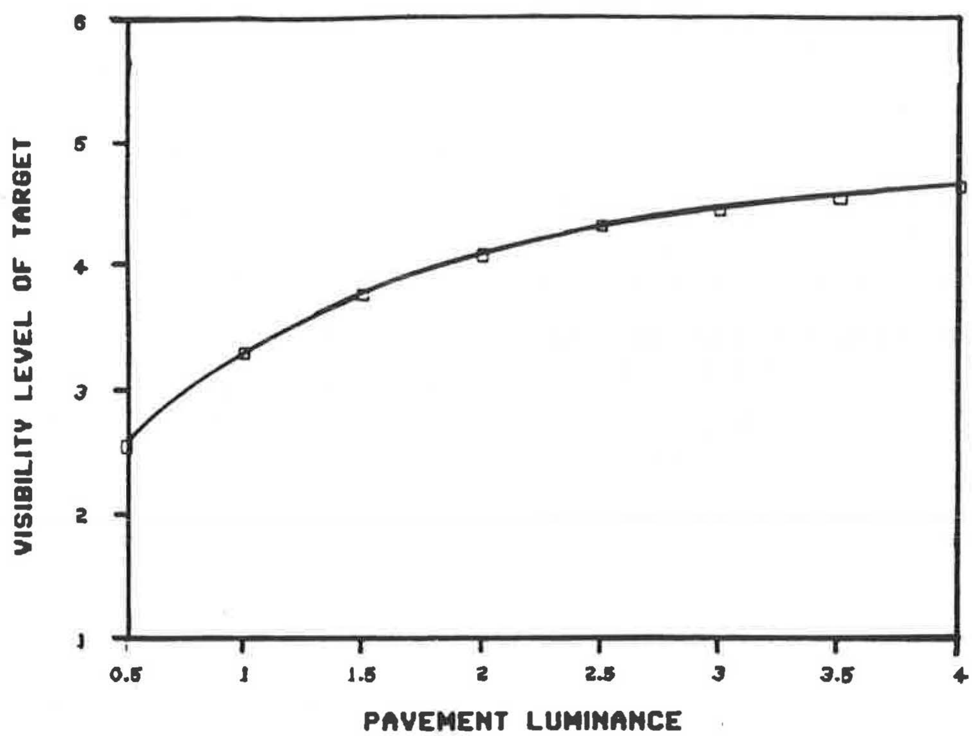


**FIGURE 1 Relationship of target visibility level to adaptation: pavement luminance in candles/m$^2$.**

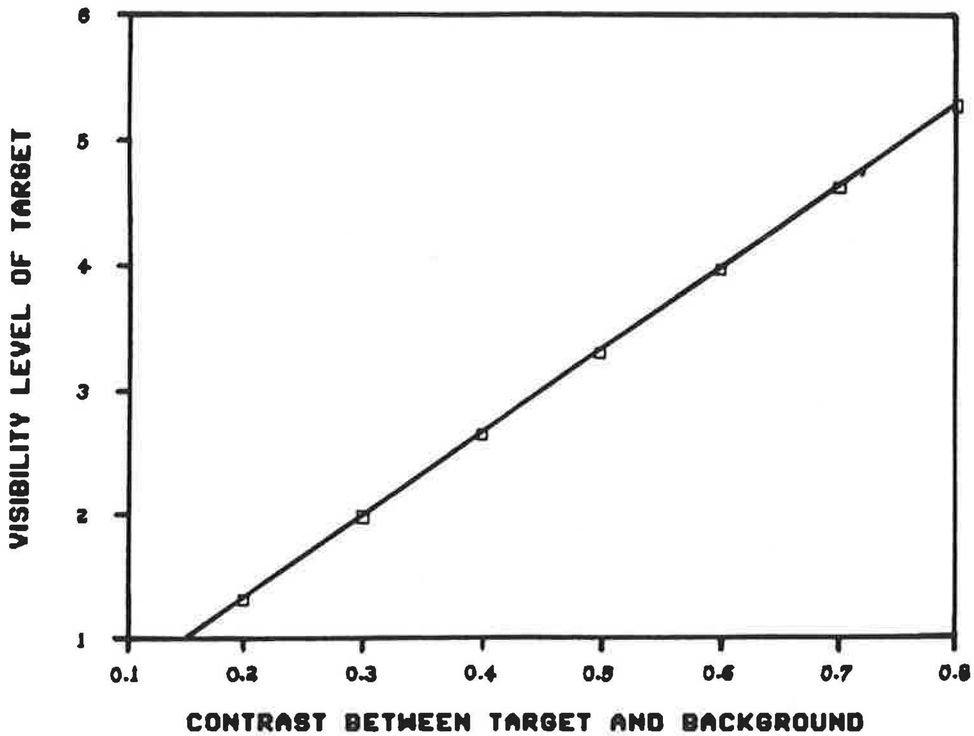


**FIGURE 2** **Relationship of target visibility level to contrast between target and its background.**

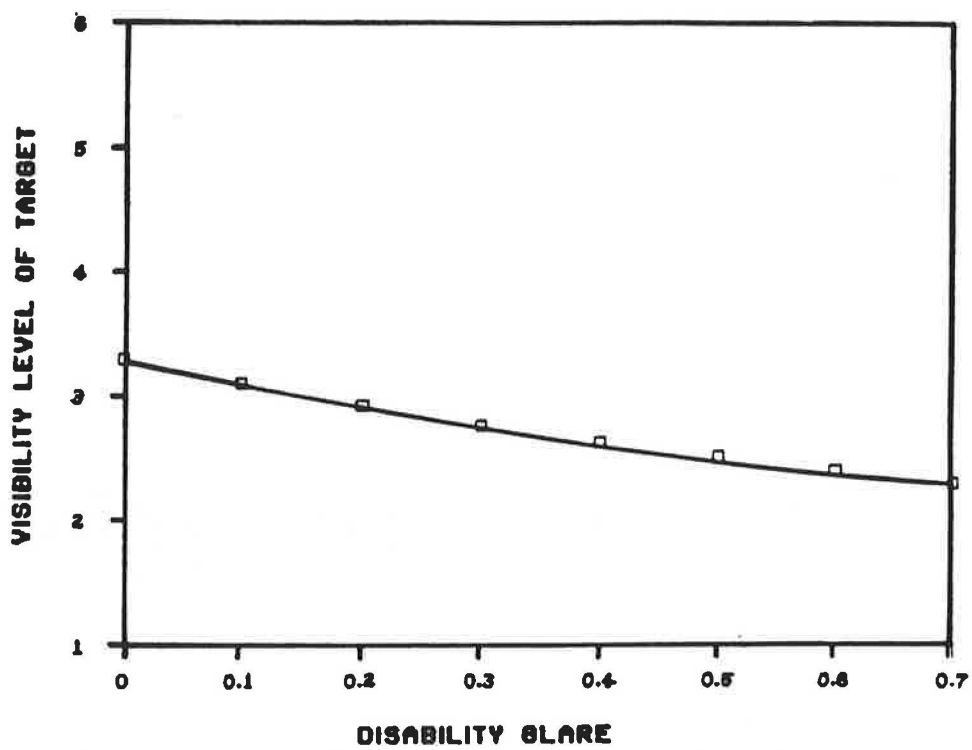


**FIGURE 3** **Relationship of target visibility level to veiling luminance (disability glare).**

quantity of Lv from oncoming headlights has little effect on STV.

## LUMINAIRE ARRANGEMENT AND CONTRAST

Contrast between the object (target) and the background may be altered by changing the reflectance of each. The highway designer has some control over certain reflectances. He specifies the materials used for the pavement, lane markers, signs, and the types of grass or other material used adjacent to the pavement. There is literally no such thing as a perfectly diffuse reflectance material. The reflectance of all practical materials is a function of the angle at which light strikes the material versus the angle of the line of sight of the observer. This is called the bidirectional reflectance-distribution function (BRDF). In the roadway situation, the driver is always located in a vehicle with a small range of height above the roadway, and his line of sight is nearly always directed ahead and slightly down as he looks to determine the run of the road ahead and if it is clear of obstacles and other traffic.

For fixed lighting installations, the lighting designer has a great deal of control over the direction from which light strikes the object (target) and the pavement. As a result, he can exert considerable control over contrast and the resulting small target visibility. The designer or specifier of the luminaire distribution has some control over the amount of light and the angles at which it is emitted in the case both of fixed lighting equipment and headlighting equipment.

The first important concept to understand is that STV may be increased using one technique to increase the light level and that it may be decreased if an alternate technique is used.

### Bidirectional Lighting Systems

The vast majority of all fixed lighting luminaires in service today have a bidirectionally symmetric distribution: two equal beams, one pointed upstream towards traffic and one pointed downstream. Consider a situation in which there is a single fixed luminaire distance of 273 ft. If two targets and an observer are located (see Figure 4), one target is seen by negative contrast, because no light from the fixed luminaire reaches the face of the target, and the other target is seen by positive contrast, because the luminaire is not very effective in producing pavement luminance in this direction due to the BDRF of the pavement surface. There must be some contrast reversal point from negative to positive as the target is moved from one location to another. At and near the point of contrast reversal, the visibility of the target drops below threshold and it is not visible to a standard observer. The location of this contrast reversal point (and disappearance of the flat target) is slightly beyond a point directly under the luminaire. The contrast reversal area below a luminaire is normally narrow for a three-dimensional object and often not recognized by a casual observer.

If two luminaires (with twin beams of equal magnitude) and four targets are used as shown in Figure 5, it is found that there must also be a reversal point between luminaires to regain the negative contrast condition that exists when the target is close to the next luminaire. This area of contrast reversal may be sharp or gradual depending on the relationship between the spacing-to-mounting height ratio and the luminaire distribution. Small three-dimensional objects often completely disappear in this area even though there may be considerable pavement luminance present. In the event the vehicle is using a high beam headlight (or a misaimed low beam headlight), there is often sufficient change in the target luminance to shift or broaden the location of this contrast reversal area of a fixed lighting installation.

The relationship between the spacing-to-mounting height ratio and the luminaire distribution is critical in determining the location and sharpness of the contrast reversal area between luminaires. Figure 6 shows that excessive overlap between the upstream and downstream beams of a conventional luminaire may result in nearly equal luminances of the target face and the pavement over a broad area. In practice, this means that the decision to increase the amount of pavement luminance by reducing the spacing is likely to cause such a severe reduction in contrast that the overall STV will be reduced in spite of a rise in adaptation level.

The second concept to note is that the relationship between luminaire spacing and vertical light output must be coordinated. In order to optimize STV, it is essential to choose the combination of luminaire locations and light distribution that creates short abrupt areas of contrast reversal. Figure 7 uses the same luminaire spacing but, by selecting a luminaire with a lower angle of emitted light, the excessive overlap is eliminated.

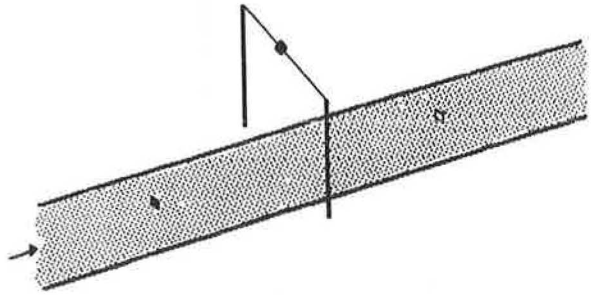

**FIGURE 4 With a single luminaire and two targets, one target will have negative contrast and the other will have positive contrast.**

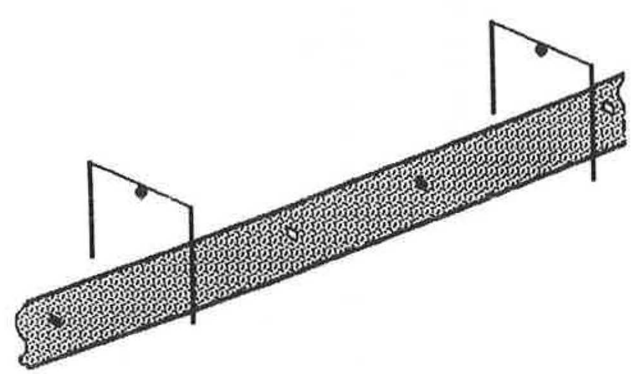

**FIGURE 5 With multiple luminaires and multiple targets, contrasts will reverse below each luminaire and between luminaires.**

Figure 8 indicates the probable location of contrast reversal with center-mounted luminaires and an opposite arrangement of luminaires. The lines of contrast reversal are short and perpendicular to the roadway centerline. Figure 9 indicates that the pattern of contrast reversal can become quite complex for staggered and one-side arrangements. In such arrangements, the below threshold area adjacent to the long contrast reversal lines may be quite large compared to the total roadway area. The third concept is to choose luminaire locations that produce short, abrupt lines of contrast reversal when using conventional twin beam streetlighting luminaires.

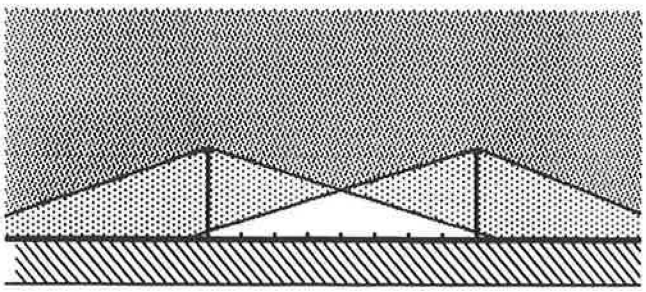

**FIGURE 6 Luminaires with high vertical angle of maximum candlepower and short spacing produce excessive overlap that reduces contrast.**

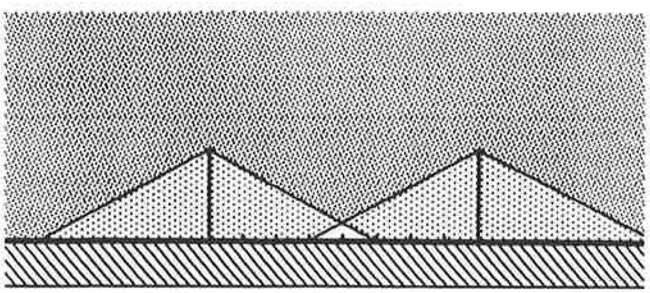

**FIGURE 7 Luminaires with lower vertical angle of maximum candlepower reduce overlap and increase target to background contrast.**

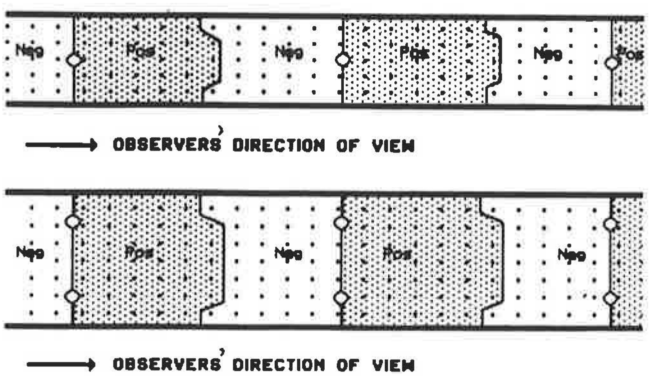


**FIGURE 8 Probable lines of contrast reversal with twin beam luminaires arranged to minimize length of such contrast reversal lines.**

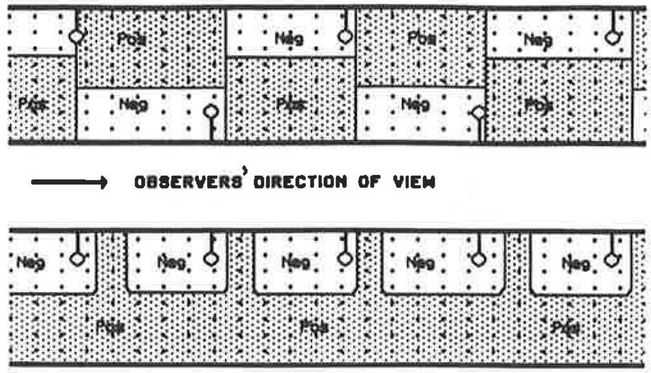


**FIGURE 9 Probable lines of contrast reversal of similar luminaires with staggered and one-side arrangements.**

### Unidirectional Lighting Systems

Automotive headlighting systems are close to the ultimate in terms of a unidirectional lighting system that produces a very high level of small target visibility. The BDRF (directional reflectance) characteristics of the horizontal pavement produce a low background luminance, whereas the high beam candlepower striking the vertical surface of the target produces a high level of target luminance and results in high positive contrast and good STV. There is no contrast reversal under normal situations. The chief problem is the glare from the headlights of oncoming cars on roadways carrying traffic in two directions.

It is possible to design and build luminaires for fixed lighting systems which use the same concepts. If the effects of the automotive headlighting system are disregarded, then the most energy-efficient fixed lighting system would be one that directs the light toward the stream of traffic (upstream lighting) (see Figure 10). Virtually all detection and recognition would be by negative contrast and the BDRF characteristics of the pavement make possible the creation of a high adaptation level with a low level of watts/ft$^2$ of energy. Glare from the fixed lighting units is not an insurmountable problem and would be far less than the glare from the headlights of oncoming cars. The major problem is the interaction of such a lighting system with the vehicle headlamps that are trying to produce visibility in exactly the opposite manner.

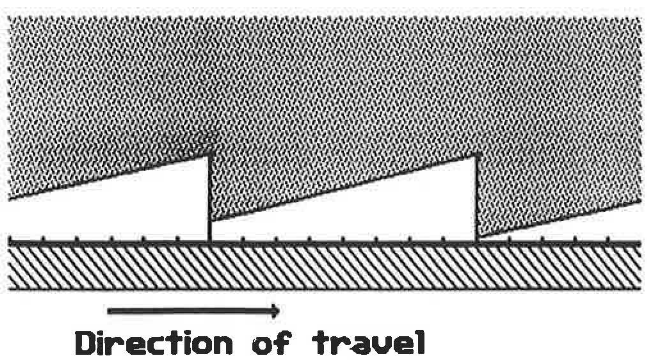


**FIGURE 10 Unidirectional luminaire distribution (single beam) directed upstream produces excellent pavement luminance and negative target to background contrast.**

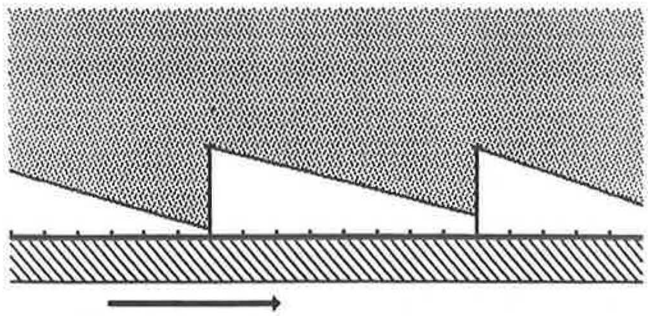


**FIGURE 11 Unidirectional luminaire distribution (single beam) directed downstream produces lower pavement luminance and positive target to background contrast.**

It is also feasible to produce luminaires for a fixed lighting system that direct all of their light in the same direction as the traffic stream (see Figure 11). Such luminaires would be more efficient in producing pavement luminance (adaptation level) than would vehicle headlamps, the STV would all be positive, and the fixed lighting system and the headlights would be working together to produce the same effect. It seems probable that such luminaires will be introduced for one-way streets and roadways in the future.

### Off-Roadway Locations for Luminaires

For many years the conventional twin-beam roadway luminaire has been designed for mounting over the paved area of the road. High mast lighting uses luminaire locations away from the pavement as do some specialized low-mounted luminaires designed to be mounted some distance from the pavement. Such luminaires are less efficient in terms of producing pavement luminance than the conventional twin-beam luminaire mounted over the pavement that directs 50 percent of its light in a more favorable direction. Effective small target visibility, however, is easily generated by using the difference in BDRF characteristics of the target and the pavement to create contrast, which is the most powerful factor in producing visibility level. Computer explorations of existing luminaire distributions for off-roadway luminaires indicate the positive STV contrast that can be generated, without contrast reversal, effectively with such distributions. This can almost certainly be applied to high mast lighting techniques and further increase in the use of these luminaires in providing lighting with high levels of positive STV.

### Zero Reflectance Objects

It should be kept in mind that small target visibility, as defined by the RLC, uses a target with a 20 percent reflectance. Positive contrast cannot be achieved with objects that have zero reflectance. Zero and near-zero reflectance objects can be detected and recognized only in terms of being darker than their background. Pedestrians wearing black raincoats or all-dark clothing are very difficult to detect with only vehicle headlights and, thus, the National Safety Council advises pedestrians walking on or across roadways at night to wear light-colored clothing.

It should be remembered that any principles discussed in this paper that involve contrast reversal do not apply to zero reflectance objects. It is not the purpose of this paper to discuss the extent or probability of zero or near-zero reflectance objects being involved in the cause of automobile accidents.

## SUMMARY AND CONCLUSIONS

The objective of both vehicular headlighting and fixed roadway lighting is to reveal the run of the road ahead and the presence of objects and traffic that may result in an accident. It is important to evaluate the interaction between headlights and fixed lighting in revealing to the driver important visual tasks. Surrogate measures of lighting effectiveness that do not incorporate the principles involved in creating object visibility make it impossible to evaluate this interaction. Small target visibility is a surrogate measure that uses the known principles of visibility modeling. In order to generate high levels of STV, some traditional concepts of fixed lighting design must be revised. In particular, it appears that the following concepts must be incorporated into the design of fixed lighting systems:

- Luminaire placement must be selected to minimize contrast reversal areas.
- Luminaire light distributions must be flexible and available in terms of a variable vertical angle of maximum candlepower.
- Unidirectional luminaire distributions should be considered for one-way traffic areas.
- Consideration should be given to locating luminaires away from the roadway pavement and projecting the light in distributions that optimize object visibility.

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# Color Appearance of Traffic Control Devices Under Different Illuminants

BELINDA L. COLLINS

**Color has traditionally been used to code safety information because of its ability to attract attention and evoke a rapid response. Research on color coding, highway safety color codes, conspicuity, illuminant color shifts, and retroreflective materials has been reviewed to evaluate the effectiveness of the current chromaticity specifications for highway signs and markings. These current specifications require colors of medium lightness and saturation (except yellow), and sometimes can appear quite dark. Data from a previous study were analyzed to compare color appearance data (color name, lightness, and saturation) under seven different illuminants for a set of American National Standards Institute (ANSI) and highway colors. This analysis demonstrated that the ANSI colors, particularly safety yellow, were identified more accurately in terms of color name, lightness, saturation, and primary hue than was the corresponding highway color. A shift toward ANSI safety yellow from highway yellow is suggested.**

Color has traditionally been used to code safety information, organize complex displays, and create moods (*1*). The typical highway application is to color code safety information and directions to allow a motorist to see and recognize a colored sign and respond immediately with the desired action. Thus, on U.S. highways, red is used for stop signs, yellow for caution signs, and blue for directional signs.

The current specifications for highway colors are for 12 highly saturated colors of medium to low lightness (*2*,*3*). The color specifications are different from those in other U.S. standards (*4*) as well as from those given by international standards (*5*,*6*). The colors indicated for use on U.S. highways are somewhat darker, particularly yellow, blue, and green, and may not be recognized as accurately as the colors specified in other standards. In addition, current specifications for highway yellow are very close to orange and red, leading to confusion between yellow and orange.

## BACKGROUND

### Existing Codes and Standards

Use of color coding for highway traffic signs evolved slowly into the modern code now recommended in the Manual on Uniform Traffic Control Devices (MUTCD). Thus, the first highway color code, developed in 1927, recommended only four colors: white, black, yellow, and green (for rest stations) (*7*). Red, orange, and blue were added in various revisions up to 1961, although they were not used consistently.

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The process of adding colors to the highway color code did not always run smoothly. In 1957, the noted colorist Faber Birren commented that color coding should be used so that motorists do not have to think continuously while seeing (*8*). This practice is used in industry where bright colors mark dangerous spots. Birren claimed that the "visual reaction to color is involuntary, while words require deliberation" (*8*, p. 569). He objected to a proposal to use black as a background color for directional or guide signs, because black, although affording high contrast with white lettering, does not have the visual or psychological interest that green has.

In 1967, extensive revisions were proposed for the highway code by the National Joint Committee on Uniform Traffic Control Devices. This committee developed the following criteria for a highway color code:

- The code should contain no more than 10 to 15 colors;
- Present highway colors should continue to be used;
- The separation between colors should maximize discrimination by color-normal viewers; and
- The separation between colors for color-defective observers should be no worse than the worst pair in use, red and green (*7*).

Using these criteria, the committee selected the following set of 12 colors:

- Red—stop or prohibition,
- Yellow—general hazards,
- Blue—information,
- White—regulation,
- Purple—unassigned,
- Coral—unassigned,
- Orange—construction or maintenance,
- Green—permitted movement; directions,
- Brown—recreational and cultural,
- Black—regulation,
- Light blue—unassigned, and
- Strong yellow-green—unassigned.

### Introductory Information on Color Research

Perception of an object's color is the result of the interaction of the visual sensitivity of the observer when the object is viewed, the spectral reflectance distribution of the object being viewed, and the type of illumination (spectral power distribution) under which the object is viewed. For example, a red object cannot preferentially reflect red (longwave) radiation if the light source does not contain long wavelength radiation. Commercially available sources vary widely in their spectral power distribution, with some sources such as low-pressure sodium (LPS), containing light concentrated at about 589 nm with virtually no energy at other wavelengths, and others, such as tungsten, having a continuous spectral power distribution. The CIE uses the term "color rendering" for specifying the ability of a light source to reveal the colors of objects.

The color-rendering index, however, does not provide any information about what color a color is; that it, is the red seen a cherry red, burgundy red, brick red, magenta, or is it really pink? A number of color specification systems, such as the Munsell and CIE systems, have been developed so that one person can understand what another person means by a term such as "red" (*9*). The CIE chromaticity system provides a way of specifying a color in mathematical terms for any light source whose spectral power distribution is known. This approach allowed the development of a two-dimensional chromaticity diagram in which the color of an object is specified mathematically in terms of $x$ and $y$. Because the CIE 1931 chromaticity diagram does not represent a uniform chromaticity space, the CIELAB OR CIE L*a*b* system was developed. In this system, the CIE system was transformed mathematically to a uniform color space so that the human visual response could be approximated more closely (*10*). The CIELAB space is widely used for industrial applications, such as textiles and surface colors.

### Color Codes

There are three major types of colors used for safety alerting: ordinary surface, fluorescent, and retroreflective (as well as combinations of the latter). Ordinary surface colors are neither fluorescent nor retroreflective but rather diffuse (glossy) opaque surfaces. Retroreflective materials reflect light back in the direction from which it came by the use of optical devices such as spherical lenses and prismatic (cube corner) materials. Fluorescent colors, in addition to reflecting light, also absorb light of some wavelengths and reemit the energy at longer wavelengths.

In a set of recommendations for surface colors, the CIE (*5*) suggested that limiting the number of colors in a color-coding scheme would be effective, and stated that the colors most accurately recognized are red, yellow, green, blue, black, and white, with orange, purple, gray, and brown as additional colors. The CIE also recommended that the interrelation among the individual colors of the code, and among the background colors, be considered both in terms of luminance and chromaticity. A comparison of the U.S. and international codes reveals that the largest specification differences occur in the green region of the spectrum. The green specified by the U.S. standards occupies a much smaller region, shifting from yellow toward blue. This was done to minimize red-green confusions by color-defective observers. In addition, several international standards, including ISO, do not provide specifications for orange, whereas in others the yellow is shifted away from red toward green. The FHWA (AASHTO) specifications are probably less similar to those used in international practice. On the other hand, the ANSI specifications are the same as those specified by the U.S. Department of Transportation Office of Hazardous Materials Transport and are referenced by the Occupational Safety and Health Administration (OSHA) for use in all industrial work sites.

## BACKGROUND INFORMATION ON COLOR VISION

### Normal Color Vision

Current research in color vision has confirmed that there are two types of photoreceptors in the human eye: the rods, responsible for reception of low levels of light, and the cones, responsible for reception of higher levels of light and color perception. The rods contain one type of photopigment, maximally sensitive at a wavelength of about 505 nm, whereas it is now believed that the cone photopigments peak at about 419, 531, and 559 nm (*11*). The three types of color receptors in the eye are linked into an opponent color system with two separate color channels: one red and green, and the other blue and yellow (with the yellow response being created by the interaction of red and green photopigments); and one achromatic channel.

Although there is good agreement that there are three types of color receptors in the normal human eye, the ability to discriminate color varies through the visible spectrum. Wyszecki and Stiles (*10*) reported that two relative maxima of $\Delta\lambda$ (the wavelength discrimination threshold) are observed, one at approximately 460 nm in the blue, and the other in the green at about 530 nm, and three relative minima occur at approximately 440, 490, and 590 nm. Wavelength discrimination also depends on luminance level, field size, surround luminance, retinal area studied, and observation technique. Generally, decreasing field size will decrease discriminability.

One way of determining accurate color recognition has been the color-naming approach used by Boynton and his colleagues. They explored the location of "basic" colors in the Optical Society of America (OSA) set of uniform colors using three response measures: consistency of color naming, consensus on names among subjects, and reaction times. Boynton and Olson (*12*) determined that the 424 color samples of the OSA set could be described by a lexicon of 11 basic color terms. These terms include white, black, red, green, yellow, blue, brown, gray, orange, purple, and pink. They found a consistent use of these 11 terms for about 70 percent of the color judgements, and a similar consistency for 5 percent of the nonbasic terms, with response time being shortest for the basic terms. In addition, although observers agreed on color names for the samples, the centroid color for a given color name tended to be close but not the same between observers. Uchikawa and Boynton (*13*) determined that native Japanese observers also divided the color space into 11 categories of colors, very similar to those used by English-speaking observers. They interpreted these results as implying that there is a strong physiological basis for color sensation that is not influenced by genetic or cultural differences between Americans and Japanese. The 11 basic color names that Boynton and his colleagues identified are similar to the safety color codes currently used. Pink is the only "basic" color not in use, although FHWA does provide for a coral. The data strongly suggest that these color codes tap basic color sensations that observers agree on and recognize readily.

### Use of Color Coding to Convey Information

Data from 42 experimental studies published between 1952 and 1973 were reviewed and analyzed for the effectiveness of color coding for visual displays (*14*). It was found that when specific color codes were used for a target, performance was superior for color displays relative to black and white displays. Furthermore, the increase in identification and searching performance could be as great as 200 percent. It was reported that if a subject's task was to identify some feature of a target, color was identified more accurately than size, brightness, and shape, but less accurately than alphanumeric symbols. Nevertheless, color can interfere with the accuracy of identifying achromatic feature attributes, particularly if observers do not know the target color (*15*). Yet, when color is used as a redundant variable (e.g., a particular shape is always associated with a particular color), the accuracy of identifying or locating simple targets is greater than when size or brightness is used. Researchers noted that road traffic signs, which use redundant color coding, are more likely to be located accurately and attract the motorist's attention than achromatic signs (*1*). Studies have also determined that color coding facilitated detection of warning messages that appeared unexpectedly and infrequently (such as traffic signs) (*16*).

These studies reiterate the effectiveness and desirability of color coding for conveying simple, yet critically important information quickly and accurately, particularly under stressful conditions. This is likely to be one of the most effective ways to ensure that motorists receive important, easily recognized information. They must, however, be familiar with the color code for maximum effectiveness.

There have been many attempts to develop color codes that are maximally discriminable from each other, and are immediately recognizable. Most of the research has been done with colored lights rather that surface colors, perhaps because of the need to signal information over long distances for naval and air applications. To this end, Halsey determined that reducing illuminance noticeably decreased the accuracy of identifying colored signal lights, particularly for desaturated blues, purples, and greens (*17*). Because violet was frequently identified as blue, she suggested that these two colors not be used in the same signaling system. In a second experiment, Halsey found that blue lights were identified with much greater accuracy when purple was not a choice (*18*).

### Problems Associated with Defective Color Vision

Determining which colors are appropriate for safety color coding is complicated by the fact that some 8 to 10 percent of the U.S. male population is color-defective from birth. There are three major classes of inherited color defects: anomaly, involving the alteration of a photopigment; dichromatism, involving the loss of one photopigment; and monochromatism (very rare), involving the loss of all color photopigments. According to traditional classifications, protan defects include protanopia and protanomaly (loss or alteration of the long wavelength pigment), deutan defects include deuteranopia and deuteranomaly (loss or alteration of the mid-wavelength pigment), and tritan defects include tritanopia and tritanomaly (loss or alteration of the short wavelength pigment). Hurvich reported that about 6.5 percent of the Caucasian population has deutan-type defects, about 2 percent has protan-type defects, and about 0.001 percent has tritan-type defects (*19*). The majority of males (4.9 percent) with defective color vision are deuteranomalous, as are the few females with defective color vision. Protan observers frequently have a deficit in long-wave luminosity not found in deutan or tritan observers (*19*). This deficit has important implications for the development of an effective safety color code because protan observers tend to see reds (if at all) as very dark.

The variations in color discrimination capabilities make diagnosing color defects difficult and predicting color vision almost impossible. Lantern, wool sorting, color chip sorting, and color plate (pseudoisochromatic) tests have been developed to detect color defects, but each seems to test different aspects of the deficiency so that a person (with a mild defect) can "pass" one test and "fail" another. Most of these tests will diagnose dichromatic individuals, although they may not distinguish between protan and deutan defects (*20*). Diagnosing tritan-type defects is complicated because changes in macular pigment and yellowing of the lens (typical of normal aging and acquired color defects) also result in losses in sensitivity to short-wavelength pigments.

The practical implications of color deficiency are that reds and greens tend to be confused. In addition, protan-type observers tend to have reduced sensitivity to reds, so that they appear very dark. Jameson and Hurvich found that protanopes appear to use lightness differences as cues for colors (*21*). Their color-naming behavior suggests that they follow the rule that if a color is dark, then it should be called "red".

Various color-coding schemes have been proposed to improve the ability of color-defective observers to detect colors. Thus, Sloan and Habel designed two experiments to determine the minimum angular subtense and luminance for a three signal color code that would be distinguishable by both normal and dichromatic observers (*22,23*). Their results indicated that normal observers, and about 74 percent of color-defective observers, could recognize the three colors tested for 1° fields that were 0.7 mL or more in luminance. The chromaticity of the green had to be shifted toward blue rather than yellow to be effective, however. Because the only observers who failed to recognize the colors (and to use color names accurately) were protanopes, Sloan and Habel suggested that protanopes should perhaps be excluded from occupations requiring rapid, accurate recognition of colors. They noted, nonetheless, that the use of the three color code would make it possible to qualify about 75 percent of those with deficient color vision. The color specifications currently used by the CIE and ANSI were chosen to be recognizable by color-defective observers. Thus, the purple boundary for the red chromaticity region was chosen partly to compensate for the reduced sensitivity to the extreme red end of the visible spectrum typical of the protanopic and protanomalous observer. The green was shifted toward blue, away from yellow, to avoid red-green confusions.

### Color Deficiency in the Transport Industry

Cole and Vingrys found that evidence from laboratory experiments concluded that color-defective observers (particularly protanopes) make more errors and have slower reaction times recognizing colored signal lights than do normal observers (*1*). Errors occurred most frequently for orange-red, red, yellow, green, and white colors. In addition, protan observers often failed to see reds. The authors suggested that the orange-red currently recommended for signal red by the CIE is too yellow and is not accurately recognized by color-normal and color-defective observers as red. Yellow is frequently confused with white (of a low color temperature) by normal and color-defective observers, whereas error rates for dichromats can be as high as 30 percent for yellow. If the color code is restricted to three colors (red, green, and blue), color defectives have little difficulty with green, but if more colors are present in the code, then error rates may run as high as 40 to 50 percent. Problems arise in accurate recognition by color-defective observers of colors of highway signs and markings as well as of lights, with protans frequently failing to recognize red signals.

Cole and Vingrys pointed out that, although the laboratory data predict that color-defective observers should encounter problems with codes using three or more colors, this prediction is not always validated in field experiments. They did note six field studies that found that color defectives made more errors identifying colored signal lights than did normal observers. Their analysis indicated further that increasing viewing distance also decreased the accuracy of color naming for the color-defective observers. It was noted that, although anecdotal accounts attributed several railway accidents in the late 1800s to defective color vision and subsequent failure to recognize colored signal lights, there was, unfortunately, no definitive evidence of the kind of color defect present or its role, if any, in these accidents. An examination of six studies of highway accidents also indicated confusion about the type and degree of defect and its contribution to the accident. Cole and Vingrys concluded from one study that protans had almost double the number of rear-end collisions, whereas deutans had twice as many accidents at traffic-light controlled intersections. Although two studies attributed an increase of accidents in general aviation to color deficiency, there was some question about whether the number of flights was equal for both normal- and color-defective pilots. Cole and Vingrys concluded, however, that defective color vision can be a significant risk factor in aviation and road use, and recommended the retention of color vision standards in the transport industry.

## STUDIES OF HIGHWAY SIGN COLORS

MacNeil evaluated the impact of different color combinations on observers' ability to detect caution and warning signs at three light levels (*24*). He determined that black on yellow and white on black were significantly more legible than such combinations as white on red, red on black, or black on red. In addition, white on orange and white on red were completely illegible under low red illumination, whereas red and black were illegible under low white illumination. As a result, MacNeil recommended using black on yellow for caution signs for maximum legibility.

Olson and Bernstein evaluated the nighttime legibility of highway signs and found systematic differences in the luminances required for recognition accuracy with various background colors (*25*). Thus, white, orange, and yellow (in that order) required the lowest luminances for a given level of performance. Increasing the luminance of the surround increased the legibility distance by about 5 to 10 percent and reduced the impact of high luminance for the legend, particularly for low background luminances. Subjects with less contrast acuity required greater luminance contrast—sometimes as much as ten times—as the normal group. Older subjects, regardless of luminance contrast, also had higher error rates.

In a study of the conspicuity of sign materials, Olson (*26*) found that sign color identification distance for retroreflective materials viewed under nighttime conditions varied as a function of SIA (specific intensity per unit area or coefficient of retroreflection) and surround complexity, with distance decreasing with complexity but increasing with SIA, at least for yellow signs. Using more highly reflective materials decreased the effect of complexity, however. Older subjects required signs with an SIA about three times greater. Olson found that red, orange, green, and blue signs had greater sign identification distances than yellow signs with about the same SIA—a very unexpected result that indicated that conspicuity may depend on sign color as well as SIA. Olson attributed this difference to the same phenomenon that underlies heterochromatic brightness matching, in which colored lights equivalent in luminance to white lights are seen as brighter. Results from these studies reinforce the importance of colors in the overall conspicuity of highway traffic control devices.

### Measurement of Retroreflective Materials

Lozano pointed out that it is not likely that the color of retroreflective signs will be the same under both daytime diffuse viewing conditions and nighttime directional viewing conditions (*27*). The results obtained for safety color appearance under different illuminants indicate that the problem of accurate color identification is likely to be even greater when high intensity discharge (HID) illuminants are used (*28*). Eckerle noted that the chromaticity boundary specifications for retroreflectors must take into consideration the fact that the color of a retroreflector will vary with geometry from daytime to nighttime conditions (*29*). One of the few systematic assessments of the color of retroreflective materials was performed by Rennilson, who made detailed chromaticity measures for three types of retroreflective materials, with a spectroradiometer for Illuminant *A* (2856 *K*) using different nighttime geometries (*30*). Rennilson reported that a matrix containing observation angles ($\alpha$) of 0.2, 0.5, 1.0, and 2.0° and entrance angles ($\beta_1$) of $-4$, 15, 30, and 50° was a good way to describe the changes in chromaticity with changing measurement geometry. Data given by Rennilson for blue, green, orange, and red retroreflective samples indicated relatively little change in normalized spectral reflectance factor as a function of changing observation angle, particularly for those angles below 1.0°. Nonetheless, the studies of the chromaticity of retroreflective materials reinforce the idea that their color will vary as a function of both the illuminant and viewing geometry.

## PROBLEMS ASSOCIATED WITH THE ILLUMINANT AND OBJECT COLOR

### Safety Colors

Although the ability to detect safety colors of any type is influenced by the size of the sign, the overall illuminance and luminance, and the background characteristics and clutter, the largest impact may be that of the illuminant. The switch to HID sources with higher energy efficiencies but poor color-rendering capabilities has created major difficulties in the accurate recognition of highway and other types of safety signs.

Thus, a study reported on the identifiability of the ANSI safety colors under different light sources (*28*). The ANSI safety colors include red, orange, yellow, green, blue, purple, black, gray, and white. Six light sources were used—daylight fluorescent, incandescent, metal halide, deluxe mercury, clear mercury, and high-pressure sodium—under low levels of illuminance (5.3 lx). Although major confusions between colors for the HID sources were found, the data for fluorescent, clear mercury, and high-pressure sodium (HPS) are of particular interest for highway applications. Under fluorescent light, the major confusion was that 15 percent of the observers saw black as blue. Under clear mercury, orange, red, and yellow were confused, as were yellow and white, green and blue, and blue and black. Under HPS, red and orange, yellow and orange, green and blue, and black and blue were confused. In fact, red and orange were confused under all light sources except fluorescent, as were blue and green. Jerome concluded that colors must be separated by at least 40 units in color space to be discriminable from one another, and noted that the separation in color space will be differentially affected by the light source.

Thornton pointed out that there are two solutions to the problem of identifying colors under HID illuminants: one, to change the light source, and the other, to change the color (*31*). He addressed the latter approach by noting that the chromaticity of red, orange, and yellow shift toward each other under HPS and that their dominant wavelengths move into the region typically termed orange yellow. Similarly, under clear mercury, the dominant wavelength of ANSI red shifts to orange and the saturation to low. Thornton suggested redesigning the spectral reflectance of the safety colors by suppressing the amount of blue-green and yellow reflectance in each color. This approach is effective for those illuminants that have spectral power distributions across the visible spectrum. However, illuminants such as low-pressure sodium, clear mercury, and, to a lesser extent, high-pressure sodium have little or no energy in the red portion of the spectrum, meaning that they cannot render red (and orange) colors accurately. For these cases, Thornton demonstrated theoretically that the addition of fluorescence to red, orange, and yellow would improve their dominant wavelength under high-pressure sodium (HPS), low-pressure sodium (LPS), and clear mercury. The improvement was less marked for blue and green, particularly under the sodium sources. Although Thornton's approach did not use human observers in a strict experimental protocol, it reinforced the idea that safety colors are unlikely to be identified accurately under many common sources, including those used in highway applications, because of shifts in chromaticity and luminance.

Two studies at the National Bureau of Standards (NBS) (*32,33*) explored the interaction between illuminant and object color. The identifiability of different types of colors (ordinary, fluorescent, and retroreflective) was evaluated under several light sources. Glass et al. (*32*) concentrated on color-naming data for red and orange samples in a pilot laboratory experiment, using seven observers and five light sources including tungsten, metal halide, fluorescent, HPS, and LPS. Their results indicated that ANSI blue, green, and purple were generally identified correctly under all sources except LPS (although green was frequently termed blue under HPS). Yellow was correctly identified under all sources, but serious confusions were seen for orange and red except under tungsten and fluorescent. Nominally, red samples were frequently termed red, orange, or yellow depending on the illuminant. Two fluorescent samples were identified as effective reds with few confusions with orange or yellow, even under LPS. Two ordinary samples, blue and green, were also more accurately identified under all light sources than the corresponding ANSI color. The green fluorescent samples were effective, except under LPS where they were termed yellow, a potentially serious confusion. Glass et al. concluded that there is a set of colors (including red, orange, yellow, green, and blue) that are more likely to be accurately identified than the ANSI set and that should be researched further.

In the second study, Collins et al. (*33*) evaluated the appearance of 58 color samples including 11 red, 10 orange, 8 yellow, 10 green, 6 blue, 5 purple/magenta, 2 brown, 4 white, 1 gray, and 1 black. The 10 ANSI samples were included as well as the "best" blue, green, orange, and red samples from the study by Glass et al. A total of 16 ordinary, 17 retroreflective, 17 fluorescent, and 8 retroreflective, and fluorescent samples were used. In 11 cases, a particular sample was available in both a retroreflective and nonretroreflective version. Each sample was studied under seven illuminants: tungsten (TUN), cool white, fluorescent (CW), metal halide (MH), clear mercury (MER), HPS, LPS, and an equal mixture (in illuminance) of metal halide and HPS (MIX). In addition, the spectral reflectance distribution of all samples was measured with a spectroradiometer for an incandescent source. The spectral reflectance distribution for the non-fluorescent samples was then calculated for the seven illuminants, and each fluorescent sample was directly measured under each illuminant.

Ten color-normal observers viewed each sample twice under all sources. They reported the dominant color name, primary hue, secondary hue, and percentage of secondary hue (if any), as well as lightness and saturation for each sample (in terms of high, medium, and low). The results agreed with previous experiments indicating serious confusion between ANSI red, orange, and yellow for LPS, HPS, and mercury; confusion of green with blue-green under HPS, and nonrecognition of green under LPS. There was no improvement for retroreflective materials compared with nonretroreflective versions of the same color sample. Collins et al. also determined that there was a set of "best" colors which were identified more accurately under the seven light sources than the ANSI colors. This set included the fluorescent red identified by Glass et al., a new fluorescent orange, and three ordinary colors for blue, green, and yellow. The ANSI samples for purple, brown, and white performed better than the comparison samples. Collins et al. converted the spectroradiometric measurements for each sample into chromaticity and luminance data in both CIE $x,y$, and CIELAB coordinates. The data for both the ANSI and "best" samples were plotted in CIELAB $a^*b^*$ space to examine the gamut of coloration under each light source. This analysis demonstrated that the range for the "best" colors was larger for all light sources than for the ANSI colors, thereby supporting the contention that the "best" colors were seen with higher saturations and were therefore more likely to be correctly identified in safety applications.

## Appearance of Highway Colors

Although the research by Collins et al. focused on the ANSI safety colors and attempts to improve their recognizability, their data represent one of the few evaluations that also contained colors similar to the current highway colors. For this paper, the chromaticity data from their study were reanalyzed to determine which colors were similar to the current Federal Highway Administration (FHWA) colors. Performance for these colors was then compared with the ANSI safety colors for each of the seven illuminants. It should be noted that the data were obtained by viewing color samples positioned vertically under diffuse (overhead) illumination conditions so that the experimental conditions simulated signs illuminated by overhead roadway illumination or daylight. They did not simulate nighttime highway conditions in which signs are illuminated directionally by car headlamps.

Similarity between the FHWA and the experimental colors was determined by comparing each of the 58 samples visually with the appropriate set of colors in the Highway Color Tolerance Charts and then graphing those colors that were a reasonable visual match in CIELAB space. Examination of the CIE and CIELAB specifications indicated that several colors used in the study, specifically red No. 11, orange No. 35, yellow No. 21, green No. 25, and blue No. 27, were very similar to those specified by FHWA for highway use. In subsequent paragraphs, these samples will be referred to as "highway" colors because they are close to, but not identical with, the FHWA centroid color specifications.

For the present analysis, the psychophysical results for dominant color name, primary hue, secondary hue, lightness, and saturation were examined for both the ANSI standard color and the color most similar to the current highway specifications for red, orange, yellow, green, and blue. A color sample was considered to be a good example if it had a high percentage of that color name as the dominant color name, medium lightness (except for yellow, which should have high lightness), high saturation, and a high percentage (above 90 percent) of the desired color as the primary hue.

Table 1 presents responses for both the ANSI and highway samples for 20 observations of each color under each illuminant. The frequency of color names, given for two or three possible colors for each light source, is presented first, followed by the name and mean percentage of the primary hue (PH) and secondary hue (SH). (Four hues were used: red, yellow, green, and blue or R, Y, G, and B.) The frequency with which a sample was judged to have high, medium, or low lightness is given next, followed by similar judgments for saturation.

Inspection of the data given in Table 1 indicates that highway red, sample No. 11, was termed red more frequently than ANSI red No. 6 under all sources except LPS and HPS, where neither was termed red. Highway red was also seen as having medium lightness and high saturation more frequently than ANSI red and was given red as a primary hue more frequently for all light sources except LPS and HPS. Nonetheless, $\chi^2$ analyses of the differences in the frequency of color names, medium lightness judgments, and medium saturation judgments were not significant for the two samples. Although one red sample evaluated by Collins et al. had better recognition than either of these two samples under all light sources, it was a fluorescent sample for which extensive durability research should be done before using outdoors. (Both the ANSI and highway colors have been in use for many years with no major problems in durability.)

Examination of Table 1 for the two orange samples suggests that highway orange No. 35 is a better orange than the ANSI orange No. 5. Its primary hue was red rather than yellow. (Only four primary hues were allowed—red, yellow, green and blue.) It did, however, have a tendency to have lower lightness and saturation than the ANSI sample. A $\chi^2$ comparison of the differences in frequency counts was significant for color name, indicating that the highway orange was termed "orange" more frequently than ANSI orange ($p < 0.05$) under all light sources. Thus, these data indicate that the current highway orange was more accurately recognized, although it was seen as somewhat darker and more desaturated. Again, the "best" orange sample from Collins et al. was a fluorescent one, for which the durability concerns noted for red would also apply.

Inspection of the two yellow samples in Table 1 indicates that the ANSI yellow No. 4 was termed yellow more frequently (except under mercury), and had higher lightness and greater saturation than the highway color yellow No. 21 for all light sources. The $\chi^2$ comparisons were significant for color name, lightness, and saturation ($p < 0.05$) for the two samples. These comparisons suggest that highway yellow was significantly less yellow than the ANSI yellow, because of its large number of confusions with orange, and its darker, less saturated appearance.

Inspection of Table 1 for the two green samples suggests that the ANSI green No. 3 was seen as green more frequently than the highway green No. 25. The latter was termed "blue-green" (BG) under HPS, MIX, MH, and TUN, whereas the ANSI green was seen primarily as "green" except under HPS. Both samples had generally medium saturation and medium to low lightness. The $\chi^2$ comparison for color name was significant ($p < 0.05$), indicating that ANSI green performed better than highway green. Table 1 also indicates that the highway green No. 25 tended to have a lower percentage of green as the primary hue and, in fact, was given blue as the primary hue for HPS.

Comparison of the data for the two blue samples suggests that the ANSI blue No. 2 was termed blue slightly less frequently than the highway blue No. 27 (except under mercury light), but was seen as having medium, rather than low lightness. Its saturation was significantly lower (although still "medium"), according to the $\chi^2$ analysis. It should be noted that, although highway blue No. 27 was closest to the FHWA chromaticity specifications of the samples examined, the agreement was not especially good. Finally, inspection of the data in Table 1 for ANSI brown and highway brown indicated little difference in color appearance data for the two samples, perhaps because of the close chromaticity of the two samples.

## CONCLUSIONS

The detailed analysis of the data collected by Collins et al. for safety color appearance strongly indicates that highway yellow was less accurately recognized than ANSI yellow, with significantly more confusion with orange, and had lower saturation and lower lightness. In addition, highway green was recognized less accurately, and both green and blue were seen

TABLE 1 PSYCHOPHYSICAL COMPARISONS FOR ANSI AND HIGHWAY COLOR SAMPLES

ANSI Red #6 (N=20)

| Source | Color Name Counts: Red | Orange | Brown | Hue: PH% | SH% | Lightness: High | Med | Low | Saturation: High | Med | Low |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CW | 11 | 5 | 1 | R[1] 85 | Y 18 | 0 | 14 | 6 | 5 | 11 | 4 |
| HPS | 0 | 15 | 2 | R 69 | Y 31 | 1 | 10 | 9 | 4 | 13 | 3 |
| MIX | 2 | 9 | 3 | R 74 | Y 26 | 0 | 14 | 6 | 5 | 10 | 5 |
| LPS | 0 | 0 | 0 | Y 77 | G 24 | 2 | 15 | 3 | 1 | 6 | 13 |
| MER | 0 | 0 | 20 | R 82 | Y 20 | 0 | 3 | 17 | 0 | 9 | 11 |
| MH | 6 | 4 | 1 | R 79 | Y 24 | 0 | 14 | 6 | 3 | 14 | 3 |
| TUN | 12 | 3 | 0 | R 85 | Y 17 | 0 | 18 | 2 | 11 | 6 | 3 |

Highway Red #11

| Source | Red | Orange | Brown | PH% | SH% | High | Med | Low | High | Med | Low |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CW | 14 | 2 | 0 | R 86 | Y 17 | 0 | 17 | 3 | 10 | 10 | 0 |
| HPS | 0 | 14 | 1 | R 64 | Y 36 | 0 | 15 | 5 | 6 | 12 | 2 |
| MIX | 4 | 8 | 2 | R 77 | Y 24 | 0 | 16 | 4 | 6 | 12 | 2 |
| LPS | 0 | 0 | 1 | Y 79 | G 22 | 3 | 14 | 3 | 0 | 5 | 14 |
| MER | 6 | 0 | 13 | R 87 | Y 16 | 0 | 1 | 19 | 0 | 14 | 6 |
| MH | 12 | 3 | 2 | R 82 | Y 18 | 0 | 19 | 5 | 8 | 9 | 3 |
| TUN | 13 | 2 | 0 | R 87 | Y 16 | 0 | 15 | 1 | 13 | 7 | 0 |

ANSI Orange #5

| Source | Orange | Yellow | PH% | SH% | High | Med | Low | High | Med | Low |
|---|---|---|---|---|---|---|---|---|---|---|
| CW | 13 | 0 | Y 72 | R 25 | 2 | 18 | 0 | 1 | 19 | 0 |
| HPS | 5 | 13 | Y 88 | R 28 | 6 | 13 | 1 | 10 | 10 | 0 |
| MIX | 10 | 2 | Y 82 | R 22 | 1 | 19 | 0 | 5 | 13 | 2 |
| LPS | 0 | 20 | Y 96 | R 7 | 9 | 11 | 0 | 10 | 6 | 4 |
| MER | 0 | 12 | Y 93 | R 13 | 1 | 17 | 2 | 1 | 12 | 7 |
| MH | 11 | 1 | Y 74 | R 30 | 2 | 17 | 1 | 3 | 13 | 4 |
| TUN | 17 | 1 | Y 76 | R 31 | 3 | 16 | 1 | 3 | 15 | 2 |

Highway Orange #35

| Source | Orange | Yellow | Olive | PH% | SH% | High | Med | Low | High | Med | Low |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CW | 13 | 1 | 0 | Y 70 | R 31 | 2 | 16 | 2 | 4 | 16 | 4 |
| HPS | 16 | 0 | 0 | Y 69 | R 31 | 3 | 17 | 0 | 1 | 15 | 1 |
| MIX | 12 | 1 | 0 | Y 78 | R 22 | 1 | 16 | 3 | 0 | 13 | 4 |
| LPS | 0 | 19 | 1 | Y 96 | G 11 | 7 | 12 | 1 | 7 | 7 | 6 |
| MER | 1 | 6 | 7 | Y 84 | G 18 | 0 | 15 | 5 | 3 | 7 | 13 |
| MH | 16 | 1 | 0 | Y 78 | R 24 | 1 | 16 | 3 | 4 | 14 | 5 |
| TUN | 19 | 0 | 0 | R 61 | Y 39 | 1 | 17 | 2 | 0 | 12 | 4 |

ANSI Yellow #4

| Source | Color Name Counts: Yellow | YG[2] | Hue: PH% | SH% | Lightness: High | Med | Low | Saturation: High | Med | Low |
|---|---|---|---|---|---|---|---|---|---|---|
| CW | 15 | 4 | Y 90 | G 13 | 12 | 8 | 0 | 6 | 14 | 0 |
| HPS | 19 | 1 | Y 93 | G 12 | 14 | 6 | 0 | 11 | 7 | 2 |
| MIX | 17 | 2 | Y 94 | G 12 | 12 | 8 | 0 | 6 | 14 | 0 |
| LPS | 20 | 0 | Y 99 | G 7 | 14 | 6 | 0 | 18 | 2 | 0 |
| MER | 8 | 10 | Y 85 | G 18 | 11 | 9 | 0 | 10 | 9 | 1 |
| MH | 16 | 4 | Y 95 | G 12 | 11 | 9 | 0 | 12 | 8 | 0 |
| TUN | 17 | 2 | Y 94 | G 8 | 9 | 11 | 0 | 5 | 14 | 1 |

Highway Yellow #21

| Source | Yellow | Gold | Orange | PH% | SH% | High | Med | Low | High | Med | Low |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CW | 11 | 3 | 3 | Y 94 | R 8 | 4 | 16 | 0 | 3 | 14 | 3 |
| HPS | 18 | 0 | 1 | Y 95 | G 12 | 7 | 13 | 0 | 8 | 10 | 2 |
| MIX | 10 | 2 | 5 | Y 88 | R 17 | 5 | 15 | 0 | 6 | 13 | 1 |
| LPS | 19 | 1 | 0 | Y 97 | G 9 | 8 | 12 | 0 | 9 | 9 | 2 |
| MER | 13 | 3 | 0 | Y 96 | G 8 | 1 | 19 | 0 | 2 | 16 | 2 |
| MH | 5 | 6 | 7 | Y 85 | R 22 | 4 | 14 | 2 | 2 | 14 | 4 |
| TUN | 6 | 6 | 6 | Y 85 | R 20 | 5 | 14 | 1 | 3 | 13 | 4 |

TABLE 1 (*continued on next page*)

TABLE 1 (*continued*)

ANSI Green #3

| Source | Green | BG | Gray | PH% | SH% | High | Med | Low | High | Med | Low |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CW | 11 | 9 | 0 | G 84 | B 20 | 0 | 12 | 8 | 1 | 16 | 3 |
| HPS | 8 | 10 | 0 | G 81 | B 26 | 0 | 7 | 13 | 1 | 13 | 6 |
| MIX | 10 | 9 | 0 | G 84 | B 22 | 0 | 13 | 7 | 0 | 17 | 3 |
| LPS | 1 | 0 | 13 | G/R | Y 18 | 0 | 2 | 18 | 0 | 3 | 1 |
| MER | 17 | 2 | 0 | G 89 | B19 | 0 | 10 | 10 | 0 | 7 | 13 |
| MH | 12 | 8 | 0 | G 87 | B 17 | 0 | 16 | 4 | 1 | 15 | 4 |
| TUN | 13 | 7 | 0 | G 96 | B 14 | 0 | 17 | 3 | 4 | 14 | 2 |

Highway Green #25

| Source | Green | BG | Black | PH% | SH% | High | Med | Low | High | Med | Low |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CW | 11 | 8 | 0 | G 85 | B 20 | 1 | 13 | 6 | 1 | 17 | 2 |
| HPS | 1 | 17 | 0 | B 67 | G 33 | 0 | 5 | 15 | 4 | 12 | 4 |
| MIX | 4 | 15 | 0 | G 77 | B 27 | 0 | 13 | 7 | 5 | 14 | 1 |
| LPS | 0 | 0 | 14 | 0 | 0 | 0 | 0 | 20 | 0 | 0 | 1 |
| MER | 17 | 1 | 0 | G 92 | B 12 | 0 | 9 | 11 | 1 | 13 | 6 |
| MH | 8 | 12 | 0 | G 79 | B 28 | 1 | 15 | 4 | 3 | 16 | 1 |
| TUN | 7 | 13 | 0 | G 74 | B 28 | 0 | 16 | 4 | 8 | 12 | 0 |

ANSI Blue #2

| | Color Name Counts | | | Hue | | Lightness | | | Saturation | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Source | Blue | Purple | Gray | PH% | SH% | High | Med | Low | High | Med | Low |
| CW | 20 | 0 | 0 | B 99 | R | 0 | 14 | 6 | 6 | 12 | 2 |
| HPS | 20 | 0 | 0 | B 98 | R/G | 0 | 7 | 13 | 4 | 12 | 4 |
| MIX | 20 | 0 | 0 | B 9 | R | 0 | 13 | 7 | 5 | 13 | 2 |
| LPS | 0 | 0 | 12 | R 80 | Y 16 | 0 | 0 | 20 | 0 | 0 | 5 |
| MER | 12 | 8 | 0 | B 85 | R 19 | 8 | 10 | 10 | 3 | 12 | 5 |
| MH | 20 | 0 | 0 | B 98 | R | 0 | 17 | 3 | 4 | 12 | 4 |
| TUN | 20 | 0 | 0 | B 97 | G | 0 | 15 | 5 | 5 | 13 | 2 |

Highway Blue #27

| Source | Blue | Black | | PH% | SH% | High | Med | Low | High | Med | Low |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CW | 20 | 0 | | B 99 | R 5 | 0 | 11 | 9 | 12 | 8 | 0 |
| HPS | 20 | 0 | | B 98 | R/G | 0 | 3 | 17 | 12 | 8 | 0 |
| MIX | 20 | 0 | | B 99 | R/G | 0 | 13 | 7 | 12 | 7 | 1 |
| LPS | 5 | 15 | | B 100 | 0 | 0 | 0 | 20 | 1 | 2 | 8 |
| MER | 19 | 0 | | B 96 | R | 0 | 1 | 19 | 8 | 12 | 0 |
| MH | 20 | 0 | | B 98 | R/G | 0 | 15 | 5 | 11 | 9 | 0 |
| TUN | 20 | 0 | | B 98 | R/G | 1 | 13 | 6 | 12 | 8 | 0 |

ANSI Brown #7

| Source | Brown | Tan | Olive | PH% | SH% | High | Med | Low | High | Med | Low |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CW | 20 | 0 | 0 | R 75 | Y 24 | 0 | 3 | 17 | 0 | 13 | 7 |
| HPS | 11 | 1 | 7 | R 79 | Y 25 | 0 | 7 | 13 | 0 | 10 | 10 |
| MIX | 15 | 3 | 2 | R 79 | Y 21 | 0 | 5 | 15 | 1 | 10 | 9 |
| LPS | 2 | 6 | 6 | G 87 | Y 14 | 3 | 11 | 6 | 0 | 5 | 13 |
| MER | 11 | 1 | 7 | G 86 | Y 10 | 0 | 7 | 13 | 0 | 6 | 14 |
| MH | 18 | 2 | 0 | R 76 | Y 26 | 0 | 4 | 16 | 1 | 9 | 10 |
| TUN | 19 | 0 | 0 | R 79 | Y 20 | 0 | 3 | 17 | 0 | 9 | 11 |

Highway Brown #38

| Source | Brown | Tan | Olive | PH% | SH% | High | Med | Low | High | Med | Low |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CW | 20 | 0 | 0 | R 79 | R/Y | 0 | 4 | 16 | 1 | 11 | 8 |
| HPS | 13 | 1 | 6 | R 80 | Y 23 | 1 | 7 | 12 | 0 | 10 | 10 |
| MIX | 18 | 0 | 2 | R/Y | R 34 | 1 | 5 | 14 | 0 | 10 | 10 |
| LPS | 2 | 4 | 8 | G 88 | Y 17 | 1 | 12 | 7 | 0 | 3 | 14 |
| MER | 14 | 0 | 5 | G 84 | Y 9 | 0 | 3 | 17 | 1 | 8 | 11 |
| MH | 16 | 1 | 1 | R 78 | Y 20 | 0 | 4 | 16 | 1 | 12 | 7 |
| TUN | 20 | 0 | 0 | R 78 | Y 21 | 0 | 6 | 14 | 1 | 9 | 10 |

[1]R=Red, Y=Yellow, G=Green and B=Blue.

[2]YG=Yellow Green; BG=Blue Green

as darker than the comparable ANSI color. On the other hand, highway orange was more accurately recognized than ANSI orange, although both its lightness and saturation were lower. Differences between highway and ANSI red were not significant. The poor performance for both under LPS and HPS is of concern, however. The widespread use of HPS as a roadway illuminant and the importance of red in signalling prohibited actions such as "do not enter," "no right/left turn," and "stop" suggests the potential for serious confusion for red, and the need to develop durable fluorescent colors. The generally better performance for the ANSI colors, particularly yellow, green, and blue, compared with the highway colors, suggests that serious consideration should be given to altering the specifications for highway colors to meet the ANSI specifications. Such a move should increase the general recognizability of traffic sign colors, and increase the unity among standards for safety colors in the United States.

Before specifications for highway materials are changed dramatically, though, there is a need for further research on the recognizability of retroreflective colors viewed in a retroreflective mode. The data collected by Collins et al. were only for color samples viewed by diffuse illumination. Although this represents a major portion of highway viewing, it does not deal with the nighttime situation of signs illuminated by a mixture of headlights and HID (or fluorescent) lamps. The colors identified as more effective should be evaluated as retroreflective materials under both daytime (diffuse) and nighttime (directional) viewing conditions. In addition, the chromaticity of retroreflective colors should be evaluated to determine the extent of shifts as the illuminant is changed from $A$ to $D_{65}$, and to HID sources. Because preliminary indications are that major shifts occur, there is a need to document these changes and develop a field procedure to determine when a sign's chromaticity has shifted beyond tolerance and must be replaced. Finally, because they can be recognized more accurately under HID sources, the durability of fluorescent red and orange pigments under long-term, outdoor use should be assessed.

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# Major Road Accident Reduction by Illumination

PAUL C. BOX

**This paper presents the accident reduction effect found by installing roadway lighting in conformance with the American National Standard Practice for Roadway Lighting. A portion of Ogden Avenue in Naperville, Illinois, had only one block of modern lighting plus a few intersection lights in a length of 2.8 km. This five-lane roadway (two through lanes plus a center two-way left-turn lane) is 18 m wide. Street lighting was installed and maintained at a design level of 15 Lux, as appropriate for a major route in an intermediate area. A 4-year study of accidents was made, with 1984 and 1985 used in the "before" period and 1986 and 1987 in the "after" period. More than 800 accidents occurred during the total study period. Overall, accidents were reduced from 31 percent at night to 23 percent in the "after" period. The greatest reduction was in midblock locations, where the "before" percentage was 35 and the "after" was 21. The night accident reduction was 36 percent, calculated either on a night/day ratio of rates per million vehicle kilometers or by the simpler method of night percent change. If total day plus night accidents are considered, the overall accident reduction was 14 percent. An economic analysis, comparing the installation cost with the estimated cost of accidents prevented, showed payback in one year.**

Naperville is a rapidly growing Chicago suburb with a population of 53,000 in 1984 and 72,000 in 1987. Ogden Avenue is a major east/west route, lined with commercial land uses such as service stations, fast food restaurants and a community-size shopping center. In 1982, a widening was completed from the prior four lanes to the current five-lane cross section, which includes a two-way left-turn operation in the center lane.

Figure 1 shows the route alignment, which extends from a north/south major street (Washington) on the west, to a newly constructed north/south major boulevard (Naper Boulevard) on the east. Accidents involving the latter intersection were not included in the analysis. The route crosses one major street (Naperville Road) on the north and is intersected by three collector streets. Table 1 details the intersections and driveways by general types. During the "before" period of the accident study, average daily traffic was 24,000. In the "after" period, it was 32,000.

Several night/day accident studies were conducted to determine street lighting needs prior to the widening. Table 2 shows the results of one study, which extended further west than the final lighted section. Of particular interest is the high proportion of accidents occurring at night for those intersections without lights and for the midblock sections in general. Because of these findings, lighting was designed to be installed during the widening; however, because of budget restraints, it was not put in until 2 years later.

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The 1975 to 1979 study examined night proportions of accidents by type of collision. The night percentages of both driveway and fixed object accidents were found to be very high (the latter having 74 percent of such collisions in midblock locations). The pedestrian-bicycle night accident rate was also high.

## LIGHTING DESIGN

A mounting height of approximately 15 m was chosen with a setback and mast arm length to provide an overhang of about 0.6 m. Since the ratio of road width to mounting height was approximately 1.2, a one-side arrangement was selected (see Figure 2).

An average maintained design illumination level of 15 Lux was specified (13 Lux is recommended by the Standard Practice (*1*)). A 400-watt high-pressure sodium lamp was used in a Type III. Medium, Cutoff Luminaire (see Figure 3). The calculated maximum spacing to provide the required illumination level was 64 m, which produced a uniformity ratio (average to minimum) of 2.5:1.

The spacing was reduced at intersections, in accordance with recommendations of the Standard Practice, to 44 m at major/local intersections and 38 m at major/collector intersections.

For depreciation calculations, a four-year replacement cycle was used, yielding lower limit of detection (LLD) of 0.83, with an annual cleaning yielding an LLD of 0.95. Thus, the combined maintenance factor was 0.79.

## FIELD MEASUREMENTS AND LUMINANCE CALCULATIONS

The system was energized in January 1986. At the end of six months, illumination measurements were made on a point-by-point basis at a typical location to check the calculated values. The measured average was found to be 5 percent greater than the calculated values for the subject spacing, after correction for lamp depreciation. However, the uniformity ratio was 3.3:1. While less than the design value, this is within 10 percent of the 3:1 illuminance uniformity ratio specified in the Standard Practice. Of particular interest, however, was the location of this low point. The calculated value had found this to be on the far side of midpoint between luminaires, and it actually occurred on the near side.

The Ogden lighting system was designed on the basis of illuminance. While this is one of the two allowable methods in the Standard Practice, many engineers feel that the use of

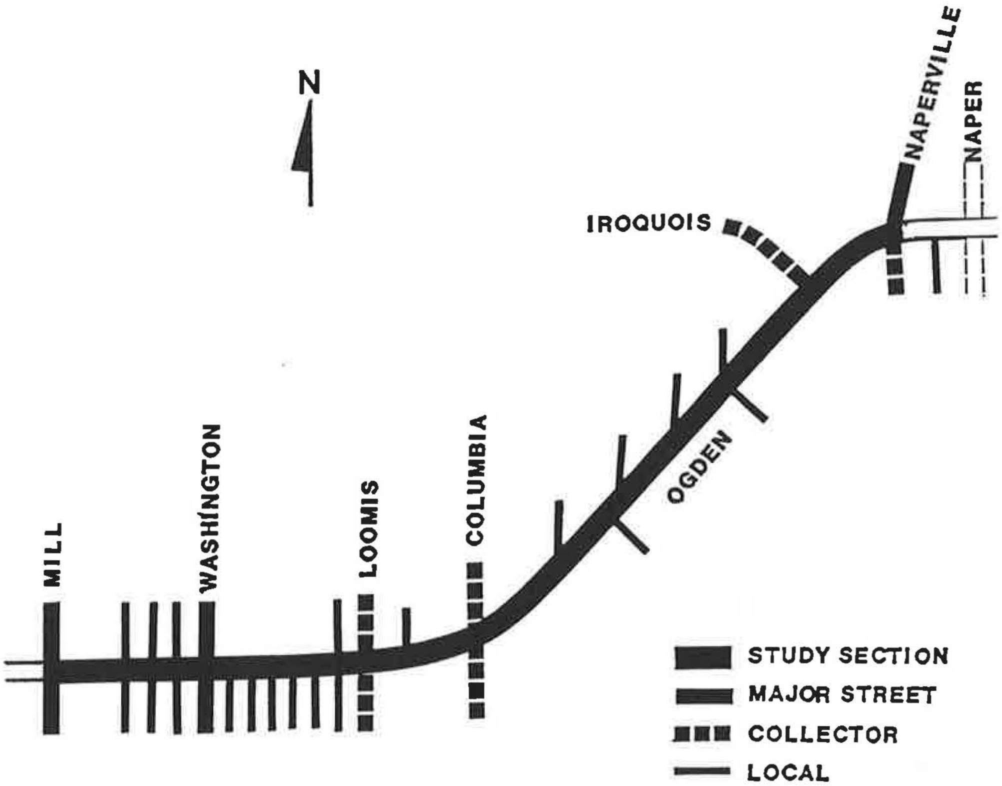


**FIGURE 1 Study section.**

TABLE 1 GENERAL STATISTICS, OGDEN AVENUE, WASHINGTON STREET TO NAPER BOULEVARD

| | |
|---|---|
| Length | 2.8 Km |
| Number of intersections | |
| Cross type | 6 |
| T type | 8 |
| Total | 14 |
| Number of driveways | |
| Service stations | 14 |
| Restaurants & taverns | 24 |
| Auto repair, supply | 16 |
| Real estate offices | 8 |
| Misc. retail stores | 25 |
| Misc. services | 8 |
| Motels | 6 |
| Commercial subtotal | 101 |
| Alleys | 5 |
| Residential driveways | 4 |
| DRIVEWAY TOTAL | 110 |
| Total access points | 124 |

TABLE 2 OGDEN NIGHT ACCIDENT STUDY, MILL-NAPERVILLE ROAD, 1975–1979

| | PDO(1) | | | INJ(2) | | | Total | | |
|---|---|---|---|---|---|---|---|---|---|
| | D(3) | N(4) | N% | D | N | N% | D | N | N% |
| INTERSECTIONS | | | | | | | | | |
| With lights(5) | 447 | 160 | 26% | 93 | 42 | 31% | 540 | 202 | 27% |
| Without lights(6) | 19 | 15 | 44% | 3 | 1 | 25% | 22 | 16 | 42% |
| MIDBLOCK | | | | | | | | | |
| Mill-Washington and Iroquois-Naperville Road(7) | 23 | 19 | 45% | 3 | 2 | 40% | 26 | 21 | 45% |
| Washington-Iroquois(8) | 218 | 133 | 38% | 51 | 36 | 41% | 269 | 169 | 39% |
| OVERALL | 707 | 327 | 32% | 150 | 81 | 35% | 857 | 408 | 32% |
| TOTAL ACCIDENTS | 1034 | | | 231 | | | 1265 | | |

(1)Property Damage Only accidents.

(2)Injury or Fatal Accidents.

(3)Day.

(4)Night.

(5)Having at least one light per intersection.

(6)Having no lights.

(7)Having some midblock lights between intersections.

(8)Having no midblock lights between intersections except for four on curve at Columbia.

FIGURE 2 Lighted study section.

luminance is preferable. Accordingly, Merle Keck, a lighting consultant and former chairman of the Illuminating Engineering Society (IES) Roadway Committee, and long an active member, offered to perform various calculations of illuminance, luminances, and target visibility. Of specific concern was the question of relative effects between the two through traffic lanes on the same side as the luminaires versus the through lanes on the opposite side. Table 3 gives an illuminance comparison among the lanes and among the calculated illuminance values and those measured in the field. These are of interest in two ways. First, there is little difference in average illumination values among the lanes. Second, the computer-calculated average Lux values and uniformity ratio differ from

FIGURE 3 Typical view of Ogden lighting unit.

TABLE 3 ILLUMINANCE COMPARISON

| | Calculated(1) | | | |
|---|---|---|---|---|
| | Left Two Lanes(2) | Right Two Lanes(3) | Total Street | Measured Total Street |
| Average Lux | 18.6 | 17.5 | 18.8 | 21.6 |
| Maximum Lux | 46.7 | 34.6 | 46.7 | 40.6 |
| Minimum Lux | 4.3 | 12.2 | 4.3 | 6.5 |
| Avg/Min. ratio | 4.3:1 | 1.4:1 | 4.3:1 | 3.3:1 |

(1)Merle E. Keck, printouts #7, 8, and #2.

the ones measured and previously hand calculated from the manufacturer's data. However, the differences are not major, and more importantly, the actual performance is better than calculated.

Merle Keck's luminance calculations are shown in Table 4. Also indicated are the current recommended Standard Practice values. The calculated performance of the subject system exceeds that of Standard Practice in each measure.

Also calculated was small target visibility in accordance with the IES moving observer method (*2*) (see Table 5). The use of an arbitrary target's visibility is currently under consideration by the Roadway Lighting Committee of the IES for possible inclusion in future Standard Practice.

The visibility data from Table 5 shows little difference among the through lanes on either side of the pavement, as compared with the total pavement. Some engineers have expressed concern regarding the relative visibilities on the near and far sides with one-side luminaire mounting arrangements. Clearly, the luminaire used for Ogden (carefully selected based on isolux curves) provides an excellent lighting arrangement.

## ACCIDENT STUDIES AND FINDINGS

Four years of total accident data were collected, with the "before" period covering calendar years 1984 and 1985, and the "after" period covering 1986 and 1987. More than 800 total accidents occurred within the subject lighted section of the route. Table 6 gives the findings expressed as night percent of total accidents. These are presented separately by intersection versus midblock locations and by property damage only (PDO) accidents versus the more serious injury/fatal type of accidents (I/F). For every condition, the night percentage of accidents was reduced—in some cases dramatically. In other

TABLE 4 LUMINANCE CALCULATIONS VERSUS STANDARD PRACTICE[1]

| | Calculated | Recommended Standard Practice |
|---|---|---|
| L AVG = Avg CD/sq.m | 1.05 | 0.9 minimum |
| Max CD/sq.m | 1.63 | -- |
| Min CD/sq.m | 0.51 | -- |
| Avg/Min ratio | 2.1:1 | 3:1 maximum |
| Max/Min ratio | 3.2:1 | 5:1 maximum |
| LV = Max Veiling Luminance | 0.09 CD/sq.m | -- |
| LV/L AVG ratio | 0.1:1 | 0.3:1 maximum |

NOTES:

R3 pavement.

(1)Source Merle E. Keck, printout #3.
(2)On same side as lights.
(3)In advance of first light checked.

TABLE 5 SMALL TARGET VISIBILITY[1]

| | Near 2 Lanes | Far 2 Lanes | Total Street |
|---|---|---|---|
| LUMINANCE DATA | | | |
| L AVG | 1.17 | 0.85 | 1.04 |
| L MIN | 0.68 | 0.50 | 0.50 |
| L MAX | 1.60 | 1.30 | 1.60 |
| L MAX/L MIN | 2.4:1 | 2.5:1 | 3.2:1 |
| VISIBILITY DATA | | | |
| 80% of points over VL(2) | 3.9 | 3.3 | 3.7 |
| VL MIN | 0.4 | 0.3 | 0.1 |
| VL MAX | 16.2 | 17.4 | 17.6 |

(1)Source Merle E. Keck, printouts #5, #6 and #4.

(2)VL is a contrast multiplier to be applied to the visibility reference function to provide the luminance contrast required at different levels of task background luminance to achieve visibility for specified conditions relating to the task and observer.

Conditions:

Target 18 cm, reflectance 20%.

IES Moving Observer Method, 0.2 sec. @ 84 meters to target.

TABLE 6 OGDEN LIGHTING ACCIDENT EFFECT STUDY, WASHINGTON-NAPER BOULEVARD[1]

| | | Day | Night | Total | Night % |
|---|---|---|---|---|---|
| BEFORE (1984 + 1985) | | | | | |
| Intersection | | | | | |
| PDO | | 117 | 51 | 168 | 30% |
| Injury/Fatal | | 29 | 21 | 50 | 42% |
| | Subtotal | 146 | 72 | 218 | 33% |
| Midblock | | | | | |
| PDO | | 84 | 29 | 113 | 26% |
| Injury/Fatal | | 28 | 15 | 43 | 35% |
| | Subtotal | 112 | 44 | 156 | 28% |
| TOTAL | | | | | |
| PDO | | 201 | 80 | 281 | 28% |
| Injury/Fatal | | 57 | 36 | 93 | 39% |
| | TOTAL | 258 | 116 | 374 | 31% |
| AFTER (1986 + 1987) | | | | | |
| Intersection | | | | | |
| PDO | | 174 | 57 | 231 | 25% |
| Injury/Fatal | | 36 | 15 | 51 | 28% |
| | Subtotal | 210 | 72 | 282 | 26% |
| Midblock | | | | | |
| PDO | | 114 | 23 | 137 | 17% |
| Injury/Fatal | | 31 | 8 | 39 | 21% |
| | Subtotal | 145 | 31 | 176 | 18% |
| TOTAL | | | | | |
| PDO | | 288 | 80 | 368 | 22% |
| Injury/Fatal | | 67 | 23 | 90 | 26% |
| | TOTAL | 355 | 103 | 458 | 23% |

(1)Does not include Naper Boulevard intersection.

studies, approximately 25 percent of the traffic on similar routes has been found to occur during hours of darkness (*3*). Thus, the Ogden Avenue experience in Naperville shows a close correlation between night accidents and night traffic volumes, after lighting installation.

The midblock reduction in the more serious I/F class of accidents, from 35 percent at night to only 21 percent at night, represents the most dramatic improvement produced by the Ogden project.

The accident reduction also can be expressed in the night/day ratio of accident rates. These were 1.35 during the "before" period and 0.87 in the "after" period, representing a 36 percent reduction. Comparison of the differences in night percent of accidents will, of course, calculate to the same value.

On a night accident basis, the expected number of accidents (if the "before" night-to-day ratio had been the same) would be 115 PDO and 42 I/F accidents. The actual night numbers of accidents at night in the "after" period were 80 PDO and 23 I/F. Thus, the apparent effective reduction was 14 percent of total accidents occurring both day and night. This may be compared with the results of lighting freeways, in which an apparent overall reduction of 18 percent was found (*4*).

The accident-reduction effect, during a period when the average illumination was about 20 Lux, may also be compared with the Syracuse study, in which the most favorable night-to-day ratio of accident rates for major streets occurred at a calculated average illumination of 20 Lux (*5*).

The overall Ogden Avenue night accident reductions are statistically significant at the 1 percent level, using the *t* test for the difference in percentages (*6*).

It may also be of interest to compare the proportions of various accident types as they occurred in the "before" versus "after" periods (see Table 7). The largest category of accident reduction at night, as a result of the new lighting, was the fixed object category. Also greatly reduced were pedestrian-bicycle and sideswipe types of accidents.

Because of concern over the relative benefits of one-side lighting for the lanes on the same side as the lighting, (versus those on the opposite side) a separate tabulation of accidents was made by direction of travel. This was done for the first "after" year, 1986. Little difference was found. Pedestrian-bicycle, fixed object, and "other" types had higher night proportions on the lighted side. Driveway and sideswipe accidents were greater on the side opposite the lights. A careful review of the data led to the conclusion that no statistically significant difference existed, and the directional tabulation was discontinued.

It is possible that a one-side lighting design, less sensitive than the Ogden project to visibility elements on the side opposite the lights, might produce different results.

## ECONOMICS

The installation cost for the lighting was $204,000, including engineering. This averages $73,000/km, and $4,250 each for the 48 lights.

The National Safety Council (NSC) makes an annual estimate of the cost of motor vehicle accidents. Using their 1986 figures, the yearly accident savings would be $131,000 (*7*). However, the NSC does not recommend use of these values for computing future benefits because they do not include what people are willing to pay for improved safety (*8*).

Calculation of annual accident cost savings apparently produced by the lighting, using the referenced procedure and 1985 values for average urban accident costs, totals $253,000. By either measure, the Ogden lighting project will pay for

TABLE 7 NIGHT PROPORTIONS OF ACCIDENT TYPES

| Location and Accident Type | Before | After |
|---|---|---|
| INTERSECTIONS | | |
| Pedestrian-bicycle | 50% | 33% |
| Fixed object | 57% | 25% |
| Head-on | 33% | 43% |
| Sideswipe | 32% | 11% |
| Other* | 33% | 25% |
| MIDBLOCK | | |
| Driveway | 18% | 22% |
| Pedestrian-bicycle | 67% | 25% |
| Fixed object | 86% | 0% |
| Head-on | 50% | 0% |
| Sideswipe | 18% | 0% |
| Other | 26% | 12% |
| OVERALL | | |
| Driveway | 18% | 22% |
| Pedestrian-bicycle | 60% | 29% |
| Fixed object | 64% | 25% |
| Head-on | 38% | 43% |
| Sideswipe | 27% | 8% |
| Other | 30% | 22% |

*Turning, rear-end, right angle (not involving private driveways).

itself in one year, after allowance for annual maintenance and energy costs of approximately $10,000.

The Unit Power Density of the design is 0.4 (watts/$m^2$), or only two-thirds of the maximum value recommended by the IES for high-pressure sodium installation (*9*).

## CONCLUSIONS

This study gives yet another example of the benefits of properly designed modern lighting. It shows that the generally accepted proportions of accidents at night used to warrant improved lighting (about 35 percent) might be lowered to values of about 30 percent, with the expectation of pronounced improvement.

The study also shows that a one-side lighting design, using a relatively small street side-mounting height ratio (by use of high-mounting heights on wider streets) can provide an effective lighting design. The one-side location has the clear economic advantage of only requiring wiring along one side of the route. It also offers the opportunity of installing lighting where dense overhead utility lines might prevent use of utility pole attachments on that side or installation of new poles within that wiring area, if using a staggered layout. The study shows that the proper application of illumination techniques can produce an economical and accident-reducing lighting design. It also illustrates a design whose luminance characteristics are within current recommended parameters. Finally, the economic benefits of an accident cost-saving payback of installation cost in less than one year is outstanding.

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# Visibility of Targets

WERNER ADRIAN

**Traffic safety is highly correlated to the amount of visual information that can be obtained from the road and its immediate environment. It is therefore a logical consequence to base any quality judgment for lighting systems on visibility criteria. This development can be observed in indoor lighting as well, where the visibility-related CRF (contrast rendering factor) was introduced as a quality criterion. Visibility as a characteristic of roadway lighting has recently been discussed in Canada. When applying visibility as a criterion, there needs to be a metric to measure it and a method for calculation to predict the visibility level to be achieved in a certain lighting installation.**

Outlined below are the basics arising from the physiology of the visual system. Assuming that achromatic light is in general white or near white, there needs to be a certain luminance difference between the target and background to perceive it.

Figure 1 shows a target subtending the angular size α seen against a background luminance $L_b$. The target can have a higher luminance than the background (positive contrast) or appear darker than $L_b$ (negative contrast). For both cases, a minimal luminance difference is needed to perceive the target with a certain probability level:

$$\Delta L = L_T - L_b$$

where $L_T$ equals target luminance. In this paper, $p = 99.93$ percent.

Figure 2 contains the results of the necessary $\Delta L$ for positive contrast as a function of the target size on a background of $L_b = 10^3$ cd/m². For small targets, this curve shows the following function:

$$\log \Delta L = -2 \log \alpha + k \Big|_{\alpha \to 0}$$

This reflects Ricco's law, for which summation is observed over a receptive field. The size of this field is indicated by the critical Ricco's angle, often taken from the intersection of that line with the abscissa. A more precise value can be obtained from the point of a defined deviation from the law expressed by that line.

For larger α, the threshold $\Delta L$ attains a contrast value independent from the target size:

$$\log \Delta L = \text{const} \Big|_{\alpha \to \infty}$$

This expresses Weber's law, indicating that for larger objects the threshold is dependent only on $L_b$ and approaches

$$\Delta L / \Delta L_b = 1$$

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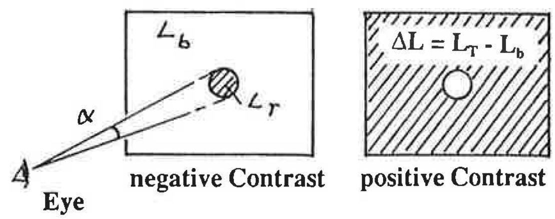


**FIGURE 1 Target with angular size α against background luminance $L_b$. $L_T$ is the luminance of the target.**

The calculation of $\Delta L$ is based on a composite of these two laws. This study introduces two auxiliary functions: the luminous flux function, (ϕ), characteristic for the Ricco process, and the luminance function ($L$), reflecting Weber's law:

Ricco:

$$\Delta L = K \cdot \alpha^{-2} \Big|_{\alpha \to 0}$$

Weber:

$$\Delta L = \text{const} \Big|_{\alpha \to \infty}$$

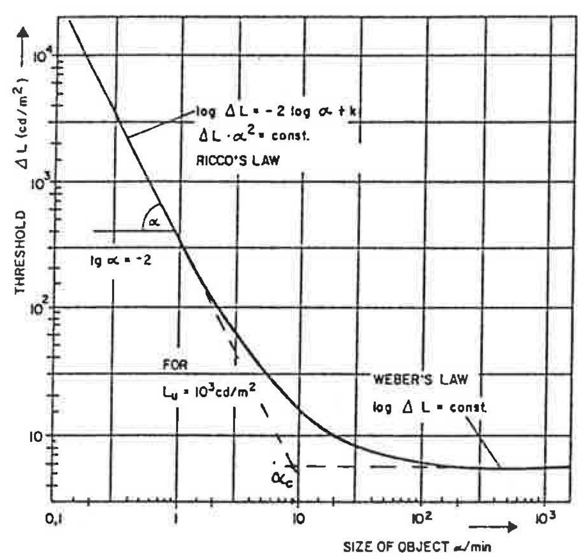


**FIGURE 2 $\Delta L$ threshold as a function of α at a constant background luminance $L_b = 10^3$ cd/m². The intersection of the Ricco and Weber functions is often taken as an indicator of the critical angle $\alpha_c$ over which summation occurs.**

Ricco:

$$\Delta L_{\alpha \to 0} = \Phi(L_b) \cdot \alpha^{-2}$$

Weber:

$$\Delta L_{\alpha \to \infty} = L(L_b)$$

$\Delta L$ is derived from the combination of the two functions in the following form:

$$\Delta L = k \cdot \left(\frac{\sqrt{\phi}}{\alpha} + \sqrt{L}\right)^2$$

From Adrian's (*1*), Aulhorn's (*2*), and Blackwell's (*3*) data, the $\phi$ and $L$ functions have been derived and can be calculated as follows:

Adrian:

$$L_b \geq 0.6 \text{ cd/m}^2$$

$$\sqrt{\phi} = \log (4.1925\, L_b^{0.1556}) + 0.1684\, L_b^{0.5867}$$

$$\sqrt{L} = 0.05946\, L_b^{0.466}$$

Aulhorn:

$$L_b \leq 0.00418 \text{ cd/m}^2$$

$$\log \sqrt{\phi} = 0.028 + 0.173 \cdot \log L_b$$

$$\log \sqrt{L} = -0.891 + 0.5275 \cdot \log L_b + 0.0227 (\log L_b)^2$$

Blackwell:

$$0.00418 \text{ cd/m}^2 < L_b < .6 \text{ cd/m}^2$$

$$\log \sqrt{\phi} = -0.072 + 0.3372 \cdot \log L_b + 0.0866(\log L_b)^2$$

$$\log \sqrt{L} = -1.256 + 0.319 \cdot \log L_b$$

## INFLUENCE OF EXPOSURE TIME

The data are obtained with 2 sec or unlimited observation time. For a shorter exposure time of the target, higher $\Delta L$ values are needed. This influence is measured by the following equation:

$$\frac{a(\alpha, L_b) + t}{t}$$

where $a$ is the Blondel-Rey constant and is a function of the target size and luminance level $L_b$. The following equations to calculate $a$ $(\alpha, L_b)$ are based on experimental data from Schmidt-Claussen (*4*) and Blackwell (*5*):

$$a(\alpha) = 0.36 - 0.0972 \frac{(\log \alpha + 0.523)^2}{(\log \alpha + 0.523)^2 - 2.513 (\log \alpha + 0.523) + 2.7895}$$

$$a(L_b) = 0.355 - 0.1217 \frac{(\log L_b + 6)^2}{(\log L_b + 6)^2 - 10.4 (\log L_b + 6) + 52.28}$$

For small targets ($\alpha < 60$ min of arc), the value of $a(\alpha, L_b)$ can be best approximated by

$$a(\alpha, L_b) = \frac{\sqrt{a(\alpha)^2 + a(L_b)^2}}{2.1}$$

The increase in threshold value $\Delta L$ for a target of $\alpha = 10$ min with a shorter observation time is illustrated below ($L_b = 1$ cd/m²):

| *Observation Time (t sec)* | $\frac{a(\alpha, L_b) + t}{t} = \frac{\Delta L_t}{\Delta L_{t=2 \text{ sec}}}$ |
|---|---|
| 2 | 1 |
| .1 | 2.11 |
| .01 | 12.66 |

$$\Delta L_t = \Delta L_{t=2 \text{ sec}} \cdot \frac{a(\alpha, L_b) + t}{t}$$

## DIFFERENCE BETWEEN $\Delta L$ THRESHOLDS FOR POSITIVE AND NEGATIVE TARGET CONTRAST

So far, only targets of positive contrast have been considered. Aulhorn (*2*) reported that, at the same $\Delta L$, a target in negative contrast could always be seen better than a target in positive contrast. She wrote: "We face this phenomenon whatever visual function we consider" (she had investigated the luminance difference sensitivity and its relationship to the visual acuity). She produced considerable data for both positive and negative contrast. From the data, it can be concluded that the threshold differences between negative and positive targets are dependent on $L_b$ and also on target size $\alpha$. For an explanation of these phenomena, it is helpful to study the results of Remole (*6*). He investigated the border contrast and found inhibitory effects on either side of borders. Figure 3 is taken from Remole's publication. The lengths of the inhibitory zones are different, and the ratio between them varies with the luminance level, which accounts for the dependency on $\alpha$ and $L_b$. The arrows indicate the widths measured. Remole (*6*) has shown that the ratio $a/b$ and the absolute value of $b$ depend on the luminance level.

To obtain the difference between $\Delta L$ for positive and negative contrast, a factor ($F_{CP}$) was derived from Aulhorn's data. $\Delta L_{\text{neg}}$ follows from the term

$$\Delta L_{\text{neg}} = \Delta L_{\text{pos}} \cdot F_{CP}$$

where $\Delta L_{\text{pos}}$ is the value for exposure time $t = 2$ sec. $F_{CP}$ is computed according to the following equation:

$$F_{CP}(\alpha, L_b) = 1 - \frac{m \cdot \alpha^{-\beta}}{2.4\, \Delta L_{\text{pos}_{t=2}}}$$

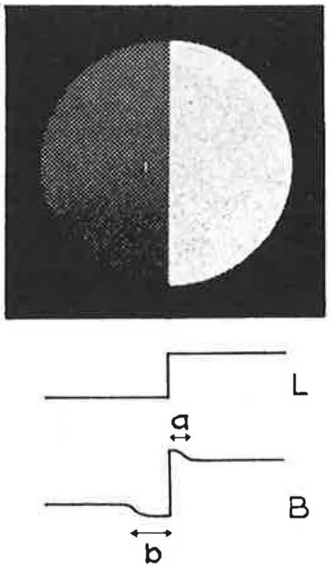


**FIGURE 3 Stimulus field with illuminated portion of hairline visible in the dark field.**

where

$m = 10^{-10^{-(.125(\log L_b+1)^2+.0245)}}$ for $L_b \geq .1$ cd/m$^2$

$m = 10^{-10^{-(.075(\log L_b+1)^2+.0245)}}$ for $L_b > .004$ cd/m$^2$

$\beta = 0.6 L_b^{-.1488} \quad \forall\ L_b$ cd/m$^2$

Threshold $\Delta L$ for a target with negative contrast (darker than the background) is obtained by

$$\Delta L_{\text{neg}} = F_{CP} \cdot \Delta L_{\text{pos}_{t=2}}$$

Figure 4 shows the function for the contrast polarity factor ($F_{CP}$) versus target size for luminance levels as used by Aulhorn in her investigations (she chose the unit asb as a basis, which leads to the odd numbers when expressed in cd/m$^2$). The curves indicate that $F_{CP}$ is always $<1$, which yields smaller $\Delta L$ thresholds for negative contrast. Figures 5, 6, and 7 allow a comparison between Aulhorn's data and the calculated function according to the method described in this paper, which is based on Adrian's and Blackwell's data. $\Delta L_{\text{pos}}$ and $\Delta L_{\text{neg}}$ thresholds are plotted versus the target size for different levels of $L_b$.

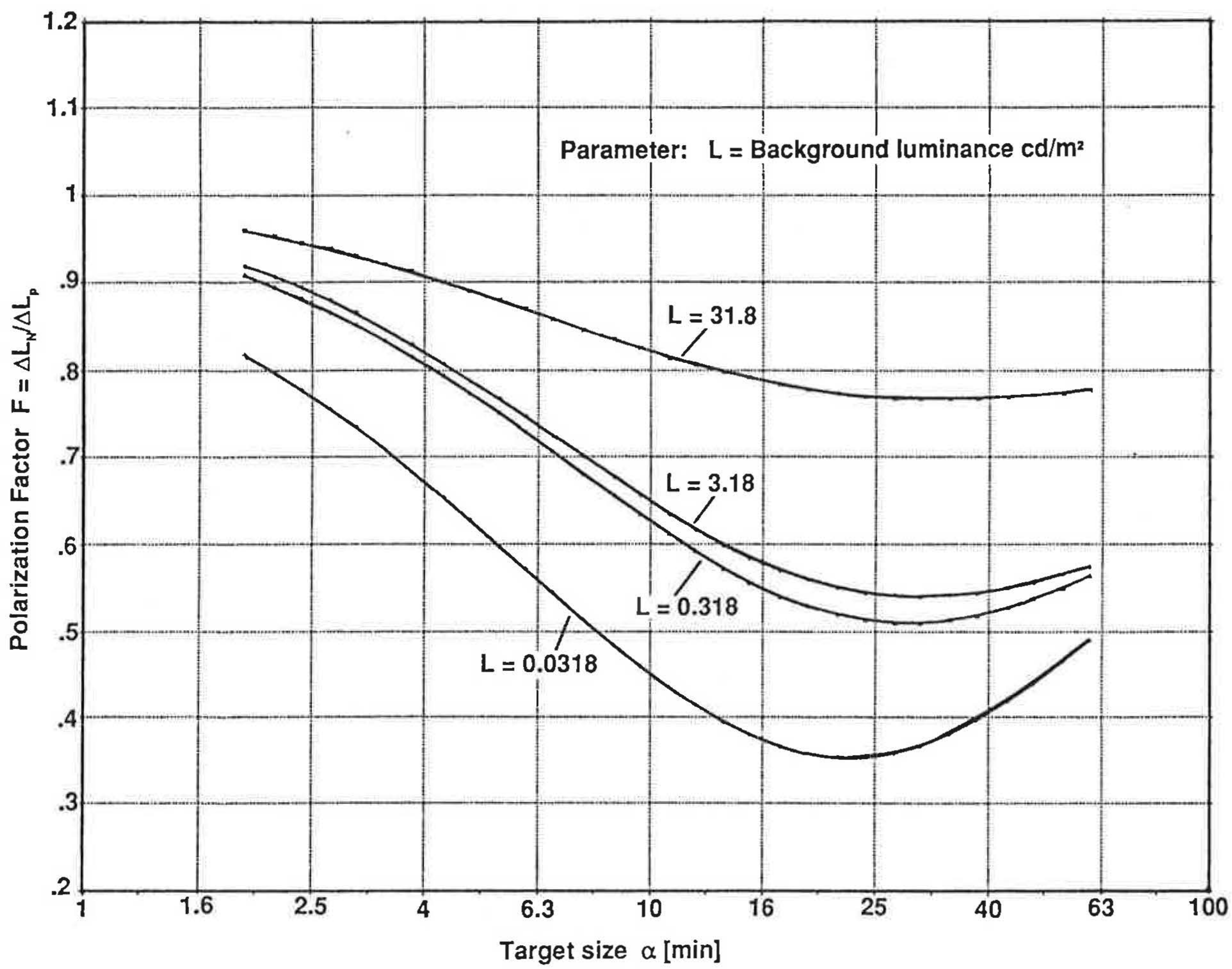


**FIGURE 4 The contrast polarity factor, $F_{CP}$, dependent on target size $\alpha$ and the background luminance. The curves show the relationship between positive and negative target contrast. In negative contrast the threshold of a target of a defined size is always lower than in positive contrast at the same background luminance, so darker targets appear to be better perceived than brighter targets at the same luminance difference.**

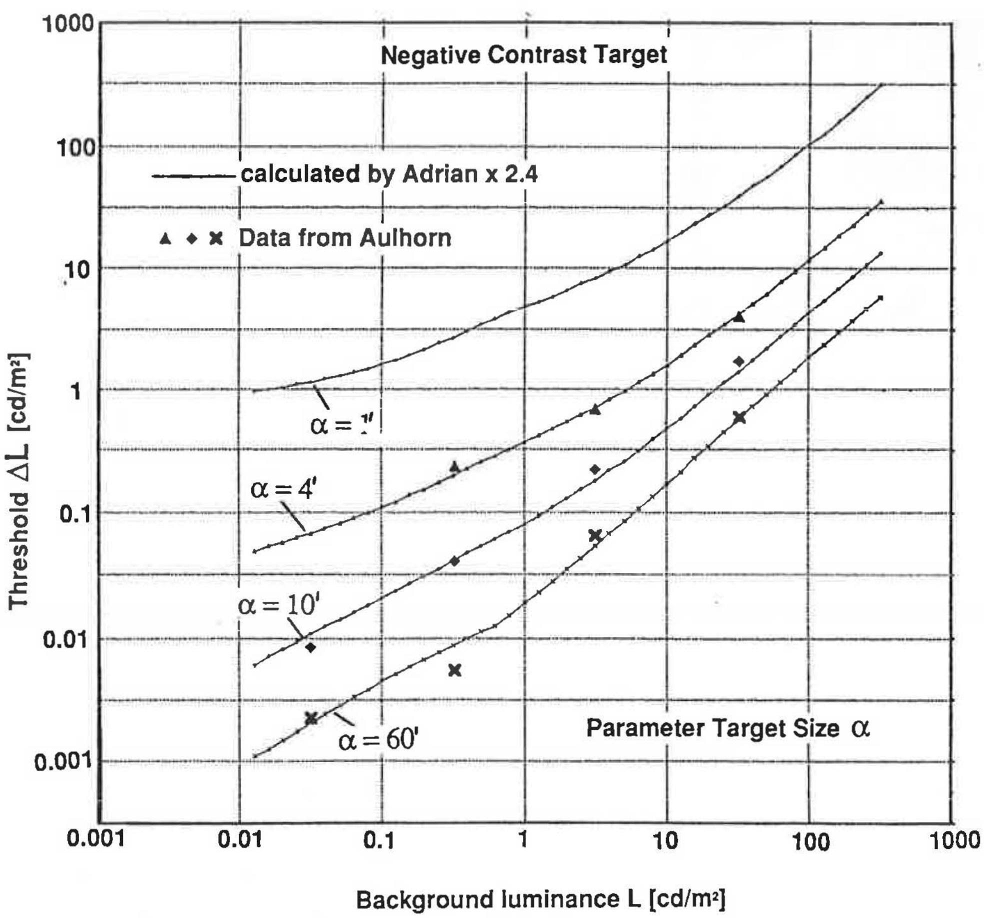


**FIGURE 5 Comparison between Aulhorn's data for negative contrast targets and Adrian's $\Delta L_{pos}$. The data have been multiplied by $F_{CP}$ to convert them to negative contrast. A factor of 2.4 had to be applied to account for Aulhorn's monocular observation conditions and the age difference of her subjects. There are no data for $\alpha = 1'$ measured by Aulhorn in negative contrast.**

To obtain the best fit, the calculated values had to be multiplied by 2.4. This was due to the different observation conditions Aulhorn chose in contrast to those used in Adrian's and Blackwell's experiments. Aulhorn used only three subjects. One of them was 55 years old and requested a higher threshold due to reduced ocular transmittance. Furthermore, Aulhorn used monocular observation rather than binocular viewing, which was used in the other investigations.

Monocular and binocular observation are known to be different by a factor of around 2, although Campbell and Green (*7*) reported a higher $\Delta L$ threshold for monocular observations of 1.64 (see below). The 55-year-old person would demand on average 1.59 times higher $\Delta L$ levels than a 23-year-old subject. The weight with which the readings of the older subject were incorporated in the reported data are not available. However, if the factors of 1.64 for monocular observation and 1.59 for the higher age are considered, the total is 2.6, which explains the shift of 2.4 (keeping in mind that two younger subjects also contributed to the mean data, thus lowering the increase caused by the older one).

## INFLUENCE OF AGE

Mortenson-Blackwell and Blackwell (*8*) and Weale (*9*) have measured ocular transmittance and found that it decreases with age. This results in higher $\Delta L$ thresholds for older people, as shown in Figure 8 (*8*). From those findings, a multiplier can be derived to account for the age-dependent threshold increase. The findings are obtained for positive contrast, and it is not unreasonable to assume that it holds also for negative contrast. The relatively good fit of the data for negative contrast with the calculated curves in Figure 5 justifies this assumption.

The $\Delta L$ for subjects older than 23 years, on which the function assumes unity, can be found in the following way:

$$\Delta L_{Age} = \Delta L_{23} \cdot AF$$

| *For* | *Where Age Factor AF is* |
|---|---|
| $23 < \text{Age} < 64$ | $AF = \dfrac{(\text{Age} - 19)^2}{2{,}160} + 0.99$ |
| $64 < \text{Age} < 75$ | $AF = \dfrac{(\text{Age} - 56.6)^2}{116.3} + 1.43$ |

Due to the parameters influencing the light perception, as described in the previous paragraphs, the visibility of a target expressed by the luminance difference threshold can be calculated according to

$$\Delta L = 2.6 \left(\frac{\sqrt{\Phi}}{\alpha} + \sqrt{L}\right)^2 \cdot F_{CP} \cdot \frac{a(L_b, \alpha) + t}{t} \cdot AF$$

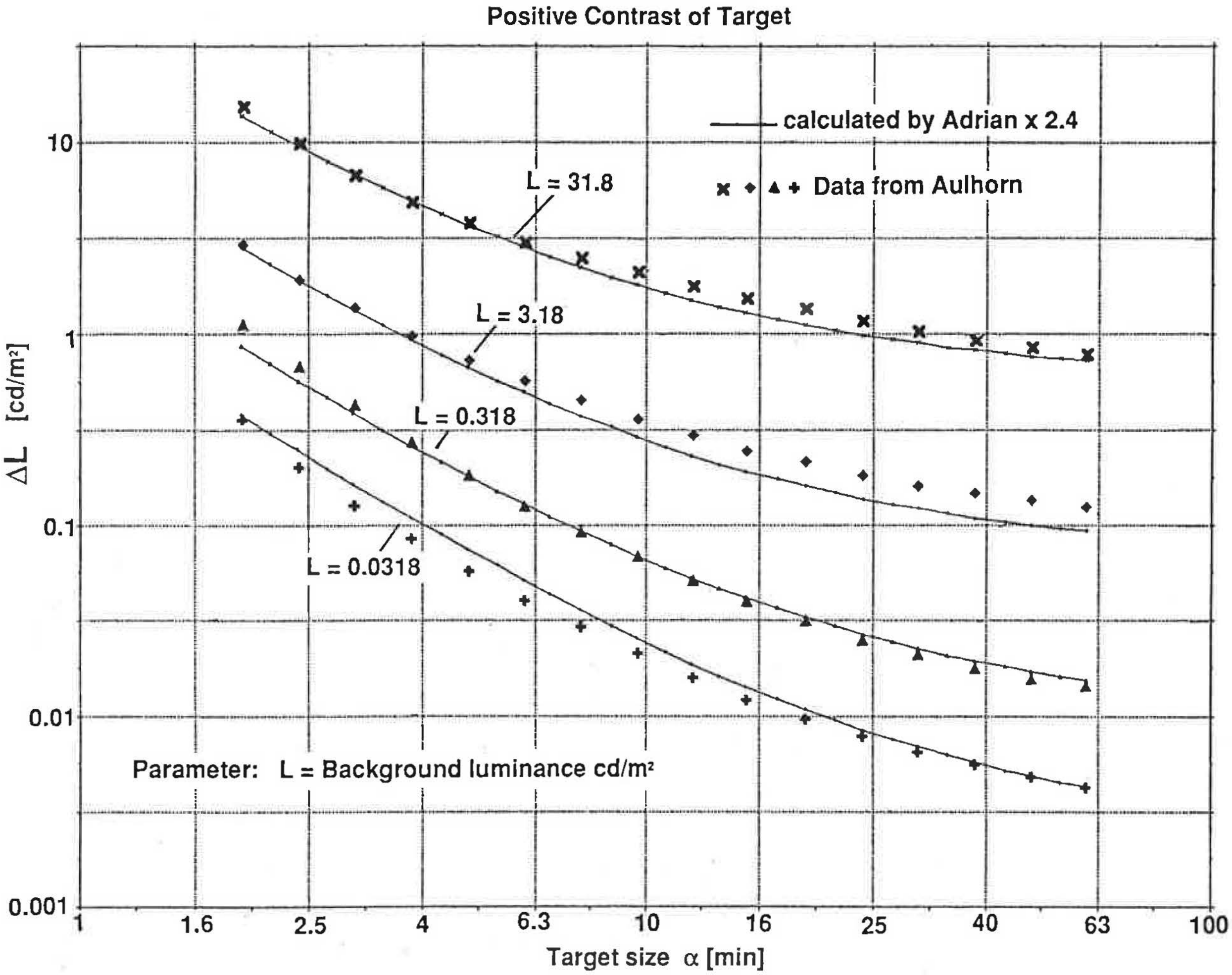


**FIGURE 6 Comparison between calculated curves, as in Figure 5, and direct measurements of thresholds for targets in negative contrast. The calculated curves are obtained by using the positive thresholds of Adrian and Blackwell and applying the contrast polarity function $F_{CP}$.**

where $F_{CP}$ equals 1 for positive contrast and $AF$ equals 1 for a young observer group with an average age of 23 years. $\Delta L$ is practically constant for exposure time less than or equal to 2 sec.

## DISABILITY GLARE

The influence of disability glare can be incorporated in a relatively simple way. Glare sources present in the visual field impair vision and require an increase in $\Delta L$ to keep targets visible. The reason for that phenomenon is well known and lies in stray light produced by the sources of high illuminance in the various eye media, especially in the cornea crystalline lens and in the retinal layers. This stray light superimposes on the retinal image, which results in a reduction of the image layers. This can be expressed as

$$C = \frac{\Delta L}{L_b}$$

With glare,

$$C_{red} = \frac{\Delta L}{L_b + L_{seq}}$$

$L_{seq}$ represents a uniform luminance that adds to the background luminance ($L_b$) and is equivalent to the glare effect on the target visibility. This effect increases with smaller angular distance between the glare source and target and with growing illumination at the eye due to the glare source, according to the following expression:

$$L_{seq} = k \sum_{i=1}^{n} \frac{E_{G1}i}{\Theta_i^2} \text{ cd/m}^2$$

where

$E_{G1}i$ = illumination in lux at the eye from glare source $i$;
$\Theta_i^2$ = glare angle in degrees between the center of the glare source and fixation line valid for $1.5° < \Theta < 30°$; and
$k$ = age-dependent constant (for the 20- to 30-year age group, $K = 9.2$ is obtained).

In the case of glare, the adaptation luminance around the location of the target on the retina is consequently composed of $L_b$ and $L_{seq}$. In the calculation of $\Delta L$, $L_b$ is substituted by $L_b + L_{seq}$.

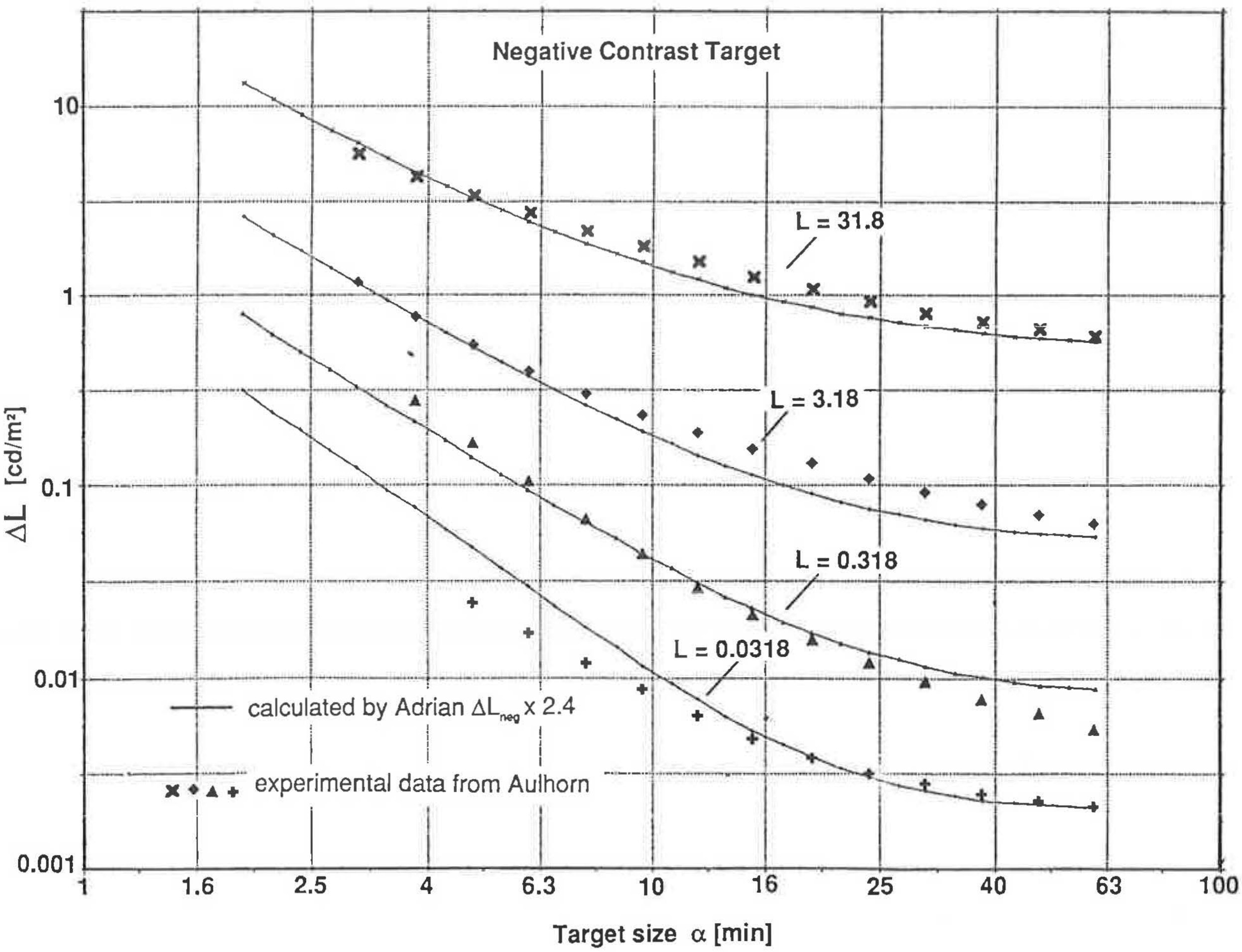


**FIGURE 7 Luminance difference thresholds for ~100 percent probability of perception for targets of various size and brighter than their background. The curves are calculated and reflect Adrian's and Blackwell's measurements. The symbols are data from Aulhorn. Multiplication by 2.4 was necessary to account for different experimental conditions (see text).**

## VISIBILITY LEVEL *LV*

So far, this paper has dealt with the numerical description of the luminance difference threshold $\Delta L$, based on experimental data. $\Delta L$ indicates a value at which a target of defined size becomes perceptible with near 100 percent probability under the observation conditions used in the laboratory experiments, which included free viewing with binocular observation (monocular in Aulhorn's study).

Under practical observation conditions, however, a multiple of $\Delta L$ is needed depending on the visual task demand. In most cases, the luminance difference has to reach a level that allows for form perception or that renders conspicuity to the target. One researcher in the early 1950s termed this the "suprathreshold factor." In an old DIN (Deutsche Industrie Norm) standard on signal lights, the multiple of the threshold was named the "safety factor" since it makes the target more visible. In CIE Report 19.2 (*10*), Blackwell introduced the descriptive term "visibility level (*VL*)," which indicates

$$VL = \frac{\Delta L_{\text{actual}}}{\Delta L_{\text{threshold}}}$$

The visibility level needed to secure safe traffic conditions is a function of the luminance to which the eye is adapted and the degree of form perception or visual acuity that is required. An attempt to determine necessary *VL* levels resulted in values between 10 and 20 for *VL* in the luminance range of street lighting (*11*). It has also been shown that a direct relationship exists between *VL* and the subjective rating of the visibility in street lighting installation (*12*).

The method described in this paper provides this value and allows an estimation regarding whether or not a target can be seen and how much the $\Delta L$ of the target is above the level of threshold perception.

## CONCLUSION

The model presented allows the computation of the threshold luminance difference $\Delta L$ for various sizes of targets as a function of the background luminance $L_b$, seen in positive and negative contrast. $\Delta L$, from which the threshold contrast $C = \Delta L/L_b$ or the contrast sensitivity $CS = L_b/\Delta L$ can be derived, applies for binocular, free viewing observations under laboratory conditions.

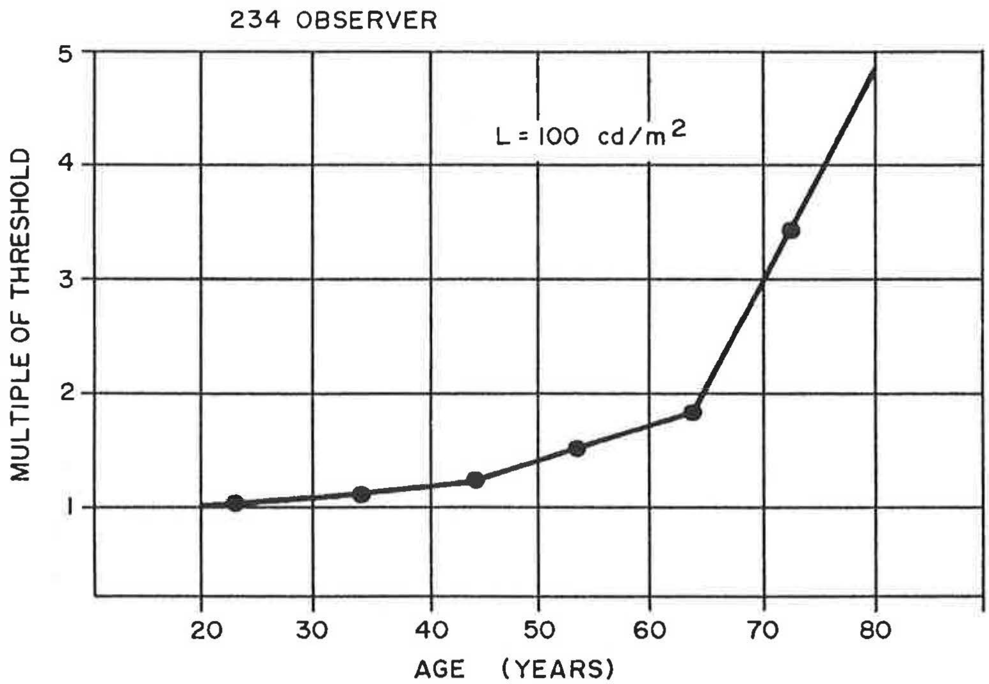


**FIGURE 8 Multiple of the threshold contrast required for observer of higher age in relation to the base group with an average of 23 years [adopted from the work of Mortenson-Blackwell and Blackwell (*8*)].**

The visibility level *LV* indicates how much the $\Delta L$ of a target is above its threshold value and can be used as a measure to evaluate visibility in lighting installations. For example, according to the latest draft of the American IES Committee, the quality of roadway lighting will be based on *VL* and recommendations on required visibility levels for different road categories will be made on this basis.

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# Effects of Headlamp Aim and Aiming Variability on Visual Performance in Night Driving

VIVEK D. BHISE AND CALVIN C. MATLE

**This paper presents results of headlamp aim studies using the DETECT and CHESS models. The influence of horizontal and vertical aim of low beam headlamps and variability of aim on the visual performance of drivers was studied. In the first study, the DETECT model was used to predict sight distances to pedestrian targets for various horizontal and vertical aim conditions of low beams. The results showed that the sight distances are more sensitive to aim changes in the vertical direction than in the horizontal direction. Similar results were obtained in the second study using the CHESS model, which computes such performance measures as the percentage of targets detected, percentage of drivers discomforted, and figure-of-merits. The third study, again using the CHESS model, investigated the effect of variability in headlamp aim on the night visual performance of drivers. In this study, the CHESS model was run under seven different levels of headlamp aiming variability—ranging from the high variability represented by random misaim to the ideal condition of no misaim. The results showed that the performances increased monotonically from the worst case of aim variability to the best case aim.**

During the past 15 years, Ford Motor Company's human factors engineers have conducted extensive research on night visibility. Their primary focus has been to develop computerized tools that can assist in the evaluation of vehicular headlamp systems. This paper presents results obtained from using two computer models, DETECT and CHESS, to evaluate headlamp aiming issues.

The DETECT model computes target-seeing distances (also referred to as visibility or detection distances) to pedestrian targets and pavement delineation lines under headlamp illumination. The model can predict the sight distances both under unopposed (when no oncoming vehicle glare is present) and opposed situations (when an oncoming vehicle glare is experienced by the observer driver in the form of "disability glare" which generally reduces the sight distances). In addition, the model is programmed to compute discomfort glare levels experienced by the two meeting drivers. More detailed information on the validation of the model and its operation details is available elsewhere (*1*, *2*). In general, the sight distances predicted by the model were found to be within about 13 percent of the average field-observed seeing distances (*3*).

The Comprehensive Headlamp Environment Systems Simulation (CHESS) model includes major portions of the DETECT model in its core. The CHESS model evaluates headlight performance by computing measures of driver visual performance in simulated encounters under different night roadway environments. In each encounter, there are sight distance tests and a glare discomfort check. The succession of encounters constitutes a standardized test route. The basic output of CHESS is the figure-of-merit, which is the percentage of the total distance traveled by the simulated drivers, over the standardized test route, where the headlighting satisfies preselected vision performance criterion levels. CHESS will judge the visual environment to be adequate when, in a given simulated encounter (a random event defined by a set of road-environmental conditions and vehicle/driver characteristics), the calculated sight distance to pedestrians and to the road delineation, and the calculated discomfort glare experienced by an oncoming driver all satisfy preselected criterion levels. More detailed descriptions of the performance criteria and CHESS model are available elsewhere (*3*, *4*).

One important variable that influences the effectiveness of headlamps is headlamp aim. This paper presents results of three studies using the DETECT and CHESS models to evaluate the following headlamp aim-related issues:

- Expected variations in low beam performance when headlamps are aimed at the SAE specified ±4 in. at 25 ft limits,
- Effect of horizontal and vertical aim on the overall performance of low beam headlamps, and
- Effect of variability in headlamp aim on the night visual performance of drivers.

## STUDY 1

### Objective

This study estimated the sensitivity of seeing distance and discomfort glare when the low beam headlamps are aimed with different combinations of vertical and horizontal misaim. These misaims are within the range of the aiming tolerance specified in the SAE J599 standard (*5*).

### Method

The DETECT model was used to predict seeing distances to a pedestrian target illuminated by type 2A1 halogen low beams (H4656—small rectangular sealed headlamp) under the following conditions on a straight level two-lane roadway:

Ford Motor Company, P.O. Box 2110, Dearborn, Mich. 48123.

| Aim Description | *Left Headlamp Aim* | | *Right Headlamp Aim* | |
|---|---|---|---|---|
| | *Horizontal* | *Vertical* | *Horizontal* | *Vertical* |
| Both aimed up | 0 in. right | 4 in. up | 0 in. right | 4 in. up |
| Perfect aim | 0 in. right | 0 in. up | 0 in. right | 0 in. up |
| Both aimed down | 0 in. right | 4 in. down | 0 in. right | 4 in. down |
| Right lamp aimed left | 0 in. right | 0 in. up | 4 in. left | 0 in. up |
| Right lamp aimed right | 0 in. right | 0 in. up | 4 in. right | 0 in. up |
| Both aimed right | 4 in. right | 0 in. up | 4 in. right | 0 in. up |
| Both aimed left | 4 in. left | 0 in. up | 4 in. left | 0 in. up |

Note that the aim is measured in inches at 25 ft (1 in. at 25 ft equals 0.19 degree).

The conditions describing the simulations were as follows:

- Pedestrian target: 6 ft high, 7 percent reflectance, located on the right edge of a 12-ft wide lane;
- Pavement reflectance: 6 percent;
- Ambient luminances: 0.001 fL (pavement), 0.005 fL (sky);
- Observer driver: 35 years old, 50th percentile contrast threshold.

The opposed driving evaluations were conducted with an oncoming vehicle equipped with the same headlamps and aim as that of the observer vehicle. This oncoming vehicle was placed at a 400 ft separation distance from the observer car.

## Results

### *Unopposed Situation*

Figure 1 presents sight distances to the pedestrian target for three different vertical aims under an unopposed driving condition. When the low beam headlamps are aimed perfectly (both headlamps at 0 in. right, 0 in. up), the driver can see the 7 percent reflectance pedestrian located on the right edge of the lane at a distance of 279 ft from the observer headlamps. When the headlamps are aimed down at 4 in. at 25 ft (about 0.8 degree down), the sight distance decreases to 195 ft. Conversely, if the headlamps are aimed up 4 in. at 25 ft (about 0.8 degree up), the sight distance increases to 342 ft. Thus, within the ±4 in. at 25 ft SAE aiming tolerance, the sight distance spread is 147 ft.

Figure 2 shows the effects of misaiming left and right while vertical aim is kept perfect (0 in. up at 25 ft). The top bar shows the sight distance of 279 ft with no misaim (as in Figure 1). Aiming only the right headlamp 4 in. to the left (4 in. at 25 ft) the sight distance goes up slightly to 292 ft. The increase in sight distance was due to shifting the hot spot of the low beam (which is about 2 degrees to the right of the headlamp axis) closer to the pedestrian. When the right headlamp is aimed the same amount to the right, the sight distance drops to 261 ft. The next two cases show results when both headlamps are misaimed by 4 in. at 25 ft in the same direction. Thus, as the horizontal aim of the headlamps is varied within the SAE limits of ±4 in. at 25 ft, the spread of sight distance is 41 ft. This is substantially lower than the 147 ft spread obtained over the vertical aim limits shown in Figure 1. These data clearly indicate that sight distance performance in an unopposed situation is more sensitive to changes in vertical misaim than to changes in horizontal misaim.

### *Opposed Situation*

Figure 3 presents sight distances to the pedestrian targets under both the unopposed and opposed driving situations for the three vertical aims shown in Figure 1. The sight distance to a pedestrian target under perfect aim decreases from 279

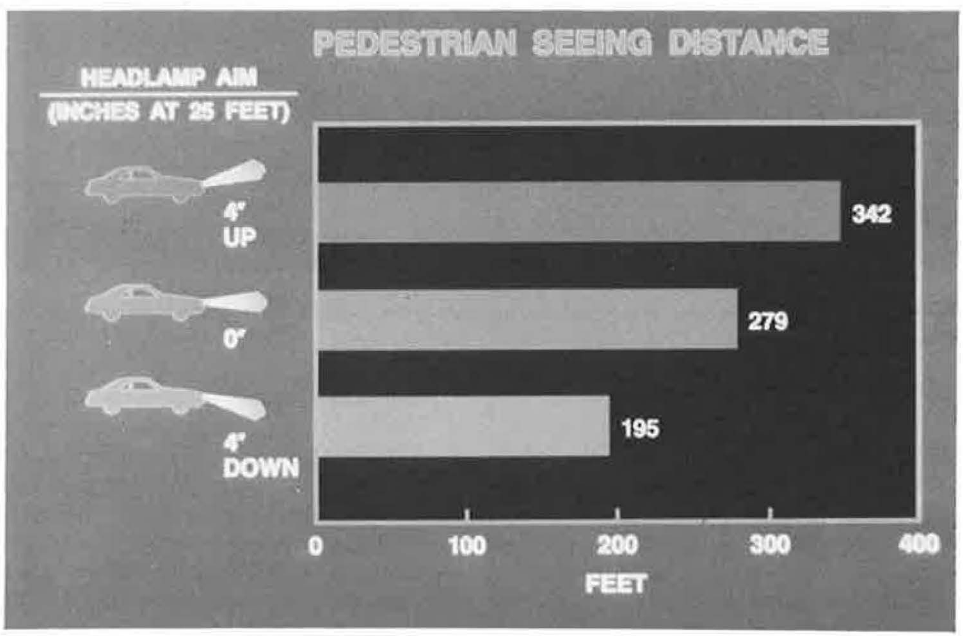


**FIGURE 1 Effect of changes in vertical aim on pedestrian sight distances under unopposed driving situation.**

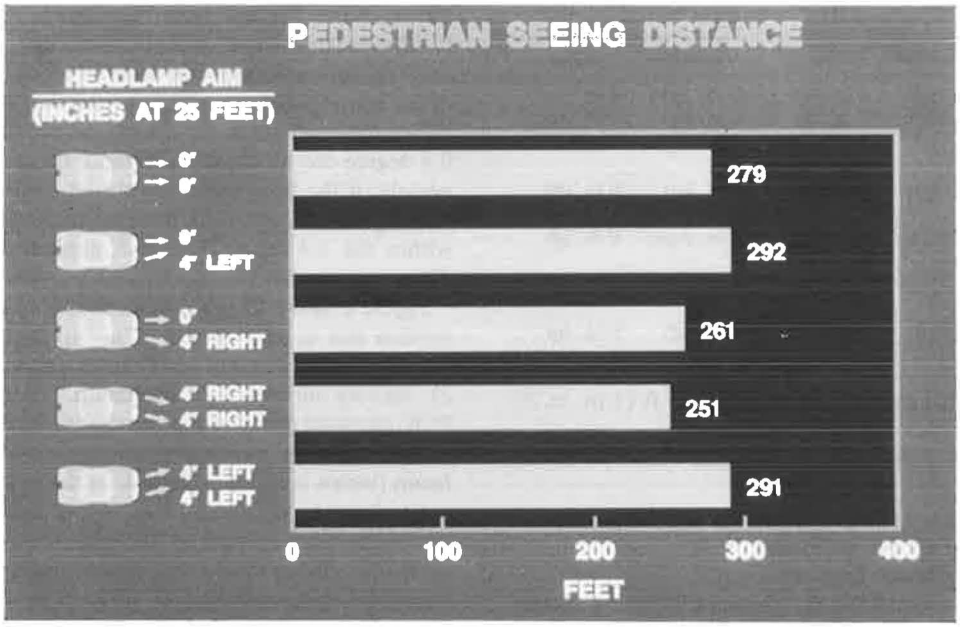


**FIGURE 2 Effect of changes in horizontal aim on pedestrian sight distance under unopposed driving situation.**

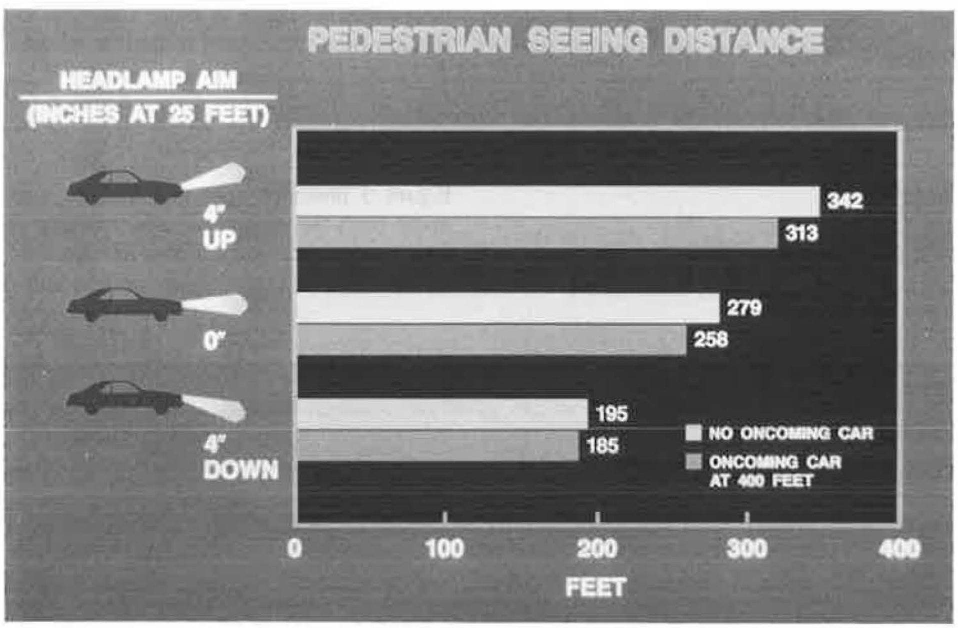


**FIGURE 3 Effect of changes in vertical aim on pedestrian sight distance under opposed driving situation.**

ft in an unopposed situation to 258 ft in an opposed situation (when an oncoming car with similar equipment and aimed headlamps is located at 400 ft). The reduction is due to the "disability" glare effect (modeled by using Fry's veiling glare expression (*1*)).

The DETECT model also computed the discomfort experienced by the driver in the oncoming vehicle. The discomfort glare was measured by computing the value of discomfort index based on a 9-point discomfort scale defined by DeBoer (*1, 2*). Figure 4 presents the discomfort glare levels experienced by the oncoming driver for the three vertical misaim levels. The oncoming driver's eye was assumed to be at an adaptation level of 0.1 fL. The figure shows that with perfect aim, the computed value of the DeBoer discomfort index is about 4 units, which can be classified as "slightly discomforting." With the low beam headlamps aimed upwards 4 in.

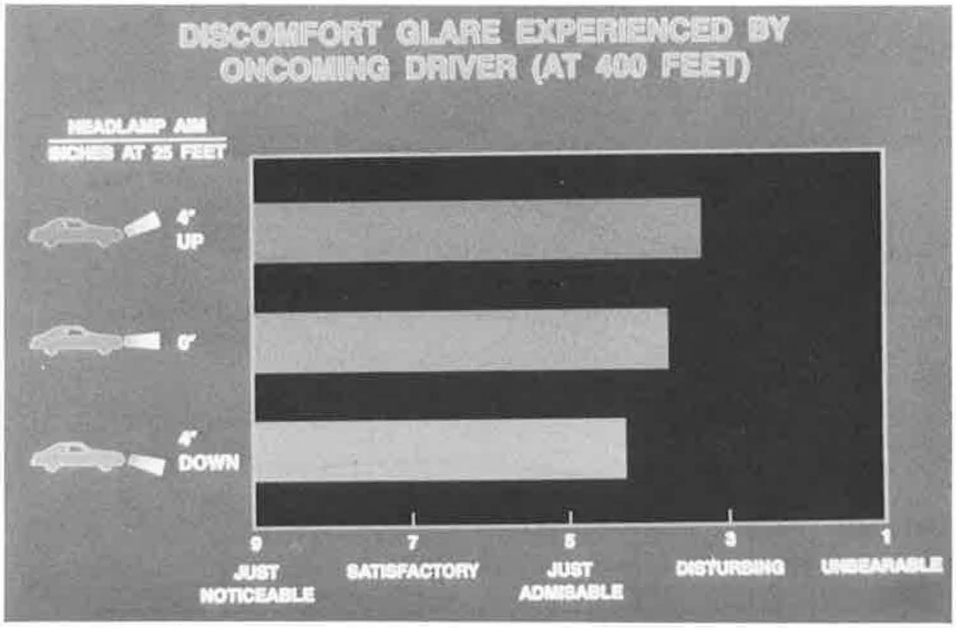


**FIGURE 4 Effect of changes in vertical aim on discomfort glare experienced by the oncoming driver.**

at 25 ft, the discomfort level increased to the point of being "disturbing." Conversely, aiming headlamps down reduced the discomfort level.

## STUDY 2

### Objective

This study was conducted to determine the effect of horizontal and vertical aim on the performance of low beam headlamps using the CHESS model.

### Method

A series of 35 CHESS runs was made. In each, both headlamps of the observer vehicle were aimed in a preselected combination of horizontal and vertical positions; the 35 runs involved combinations of the following:

- Seven horizontal levels (measured in inches at 25 ft): 12 in. left, 8 in. left, 4 in. left, 0 in., 4 in. right, 8 in. right. 12 in. right.
- Five vertical aim levels (measured in inches at 25 ft): 8 in. down, 4 in. down, 0 in., 4 in. up, 8 in. up.

In all the runs, the headlamps of the opposing vehicle were perfectly aimed.

### Results

Figures 5 through 10 present results obtained from these runs. Figure 5 presents the figures-of-merit (FOMs) for the 35 aim combinations of the observer vehicle headlamps. In this figure, FOMs obtained for each vertical aim level are joined by a curve. Thus, each curve predicts the effect of changes in horizontal aim for a given level of vertical aim. The curves, in general, are relatively constant (or flat) for horizontal aim between 4 in. left to 12 in. left. This indicates that overall performance of the low beam system would not be substantially influenced by changes in horizontal aim. The relative closeness of the curves for 0 in. up, 4 in. up, and 8 in. up indicates that vertical aim between 0 in. and 8 in. up should not affect the overall performance of the low beam system.

However, the large separations between the 0 in. up, 4 in. down, and 8 in. down curves show that if the headlamps are aimed downward, the overall performance should drop considerably.

As a general rule in interpreting the above results, two FOMs must differ by at least 2.0 points to be considered significantly different on a statistical basis (at the 90 percent confidence level).

Figures 6 through 10 illustrate how the three components of the FOM, the percentage of delineations and pedestrians detected and the percentage of discomforted drivers, vary with changes in horizontal and vertical aim. The relatively constant nature of the curves in Figures 6 through 9 indicates that visibility of delineation and pedestrians under both unopposed and opposed situations is less affected by changes in horizontal aim as compared to changes in vertical aim. Figure 10, however, predicts that the percentage of discomforted drivers should increase as the horizontal aim is moved left (toward the oncoming drivers) or as the vertical aim is moved up.

### Conclusions

On the basis of data presented in Figures 5 through 10, it appears that, for the H4656 low beam pattern used in this

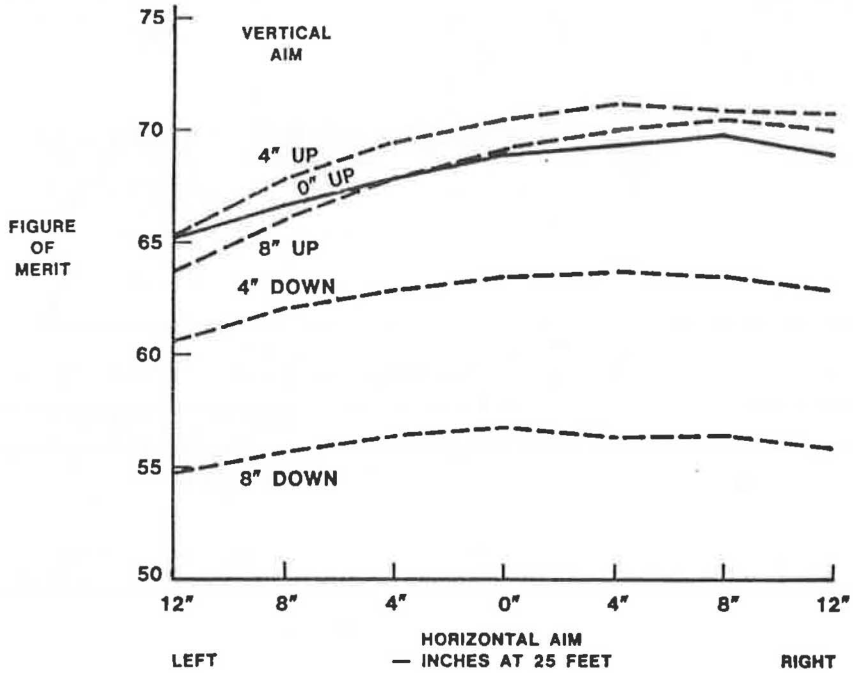


**FIGURE 5** Figure-of-merit of H4656 low beam as a function of aim.

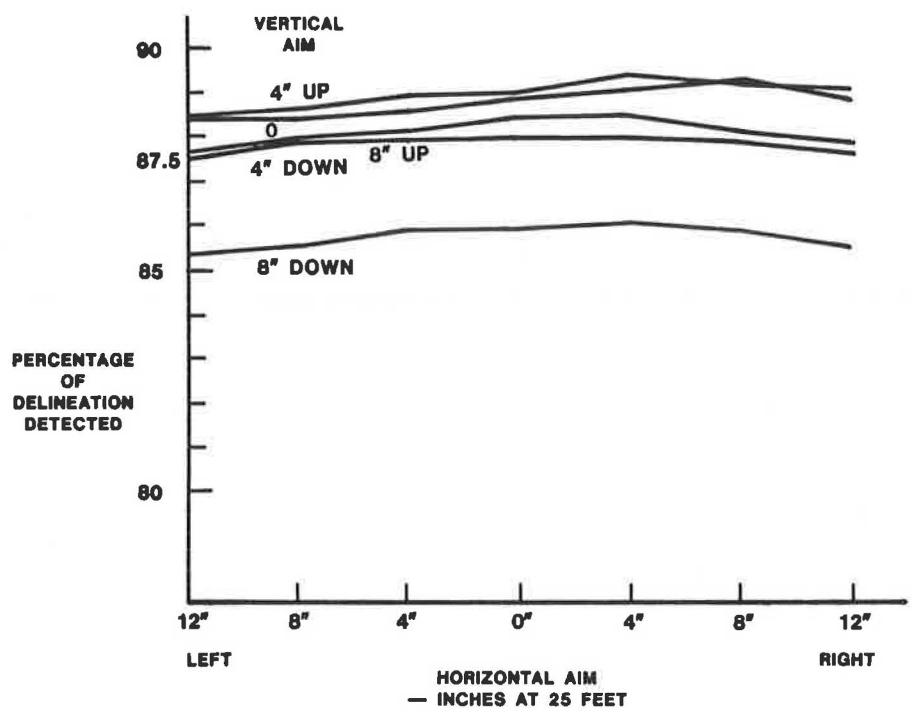


**FIGURE 6** Percentage of delineation detected as a function of aim (unopposed).

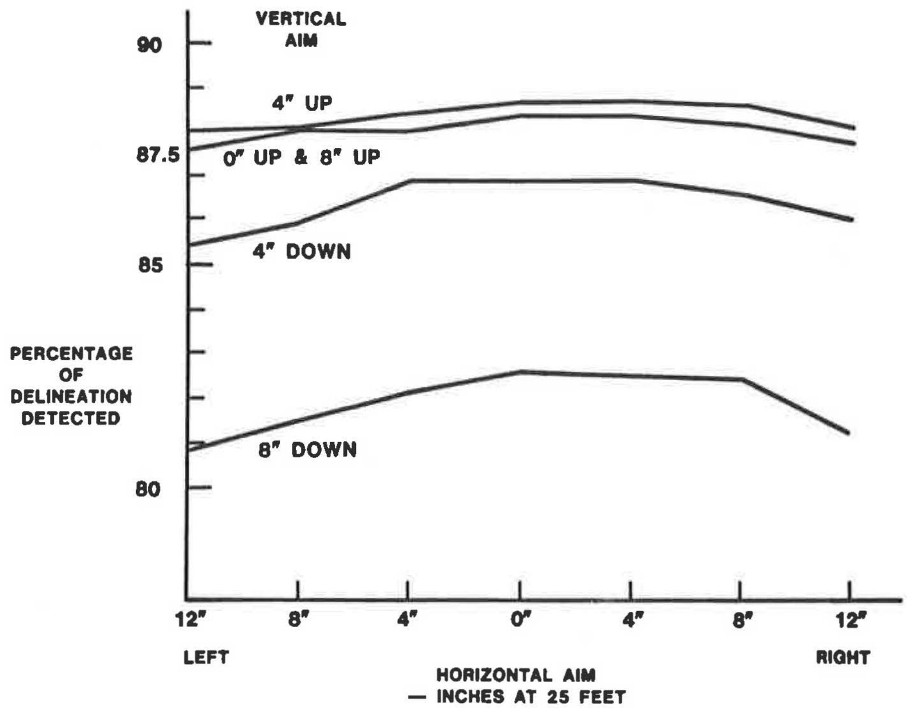


FIGURE 7 Percentage of delineation detected as a function of aim (opposed).

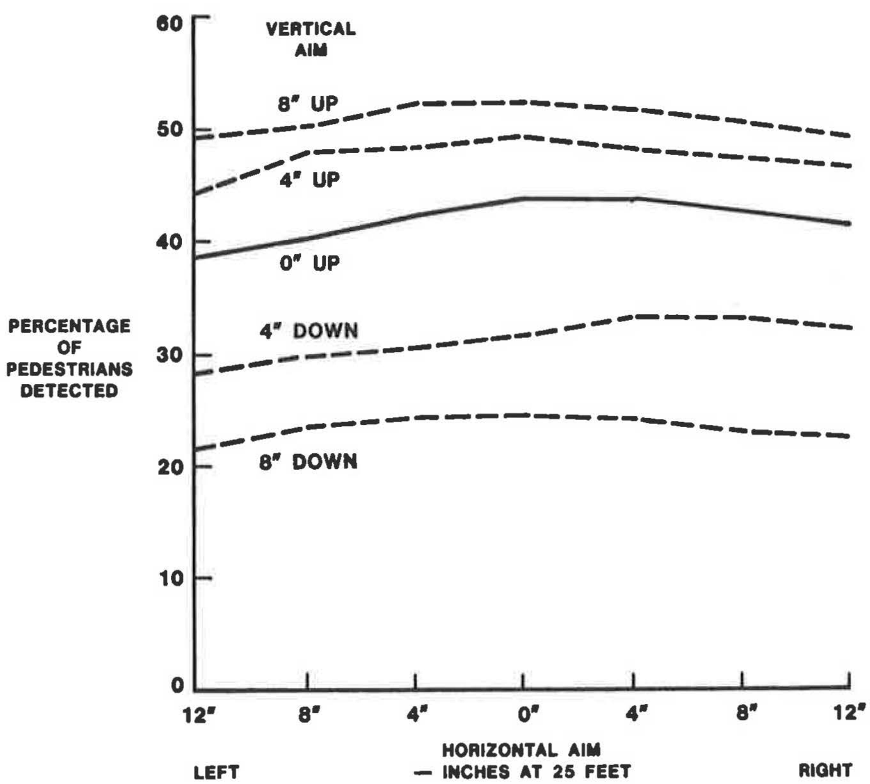


FIGURE 8 Percentage of pedestrians detected as a function of aim (unopposed).

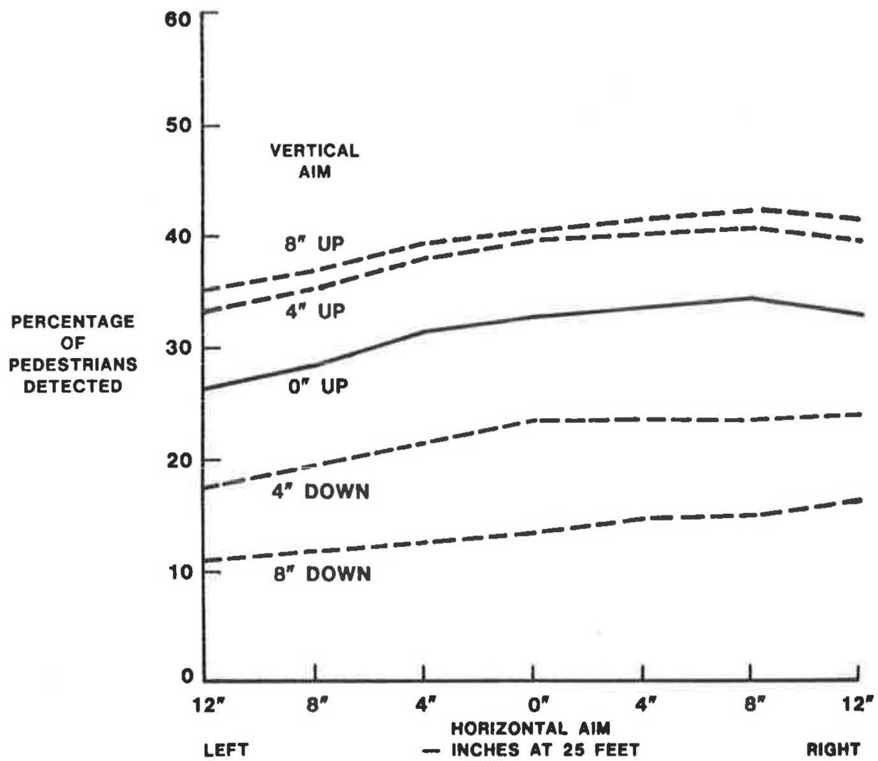


**FIGURE 9** Percentage of pedestrians detected as a function of aim (opposed).

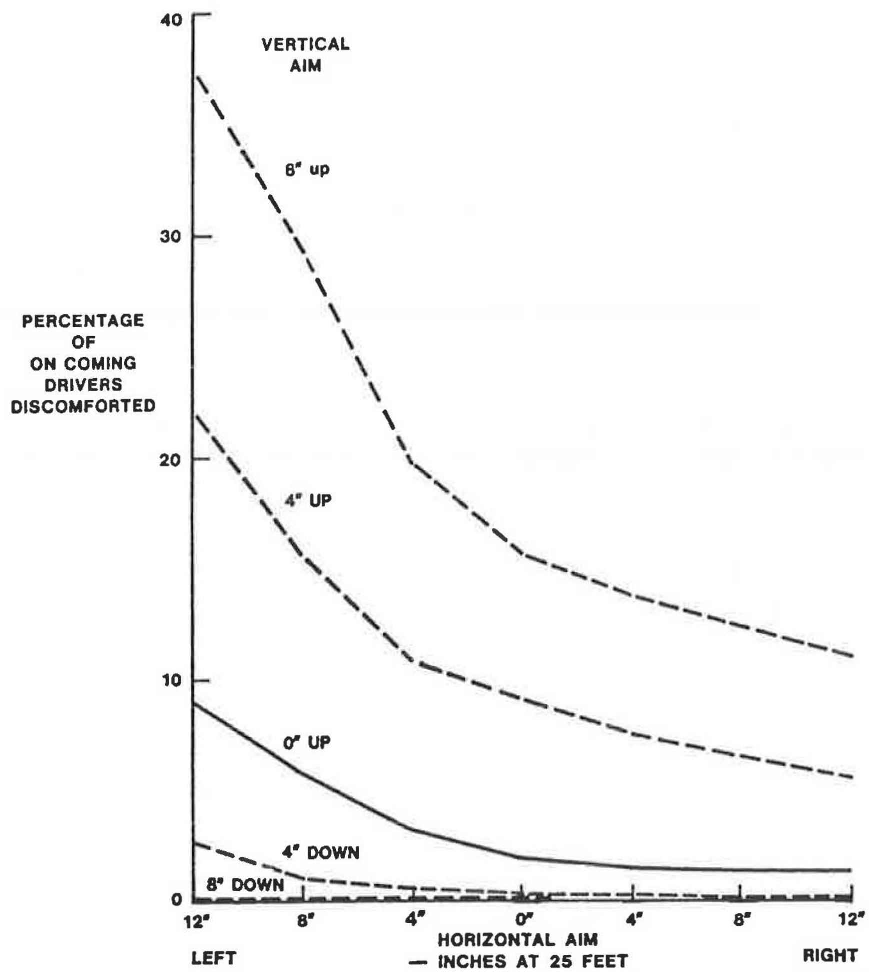


**FIGURE 10** Percentage of oncoming drivers discomforted as a function of aim.

exercise, the headlamp performance is less sensitive to changes in horizontal misaim between 4 in. left and 12 in. right. This suggests that even if some small changes in beam patterns occur in the future due to production or assembly tolerances, the horizontal aiming capability may not be needed. On the other hand, any refinements in the vertical aiming capability of headlamps would be useful in improving headlamp performance.

## STUDY 3

### Objective

This study was conducted to determine the effect of stringency in the control of aim (the aiming tolerance) on low beam performance.

### Method

A set of seven CHESS model runs, using H4656 low beams, was conducted. The seven aiming conditions, from least stringent to most stringent aim tolerance, are presented below.

- Random Aim—This condition assumed the headlamps to be randomly misaimed to the extent determined by Olson in his road study (*6*). This aim had a mean of 0 degree horizontally and 0.25 degree down in the vertical direction. The standard deviations were 0.78 degree horizontal and 1.00 degree vertical.
- SAE Horizontal Only—This case assumed that the horizontal aim of the headlamp can be held within the current SAE specifications (SAE J599, May 1981 specifies a range of misaim of ±4 in. at 25 ft (±0.76 degree) for inspection purposes). The vertical aim, however, was allowed to drift as in the current random misaim. The mean location of the headlamp was assumed to be 0 degree horizontal and 0 degree vertical. The standard deviations of the aim were assumed to be 0.253 degree horizontal and 1.00 degree vertical (*6*). The value of 0.253 degree for the horizontal standard deviation was based on the assumption that the SAE aim limit of 4 in. at 25 ft (equal to 0.76 degree) encompasses three units of standard deviation.
- UMTRI Measured New Car Aim—This case was based on Olson's survey for NHTSA (*6*). In this survey, Olson found that current year model cars at the time of the study (1984) had a mean headlamp aim at 0 degree horizontal and 0 degree vertical, and standard deviations of 0.53 degree horizontal and 0.77 degree vertical.
- SAE Vertical Only Aim—This case assumed that headlamps were aimed within SAE limits in the vertical direction, but the horizontal misaim was maintained at a current random aim level. For this situation, the mean position of the headlamps was maintained at 0 degree horizontally and 0 degree vertically. The standard deviations were 0.78 degree horizontally (*6*) and 0.253 degree vertically. The 0.253 degree vertical standard deviation was developed based on the assumption that three standard deviation limits can be contained within the present 4 in. limit at 25 ft SAE specification.
- SAE Aim Specifications—This case assumed that the headlamps were aimed with a mean of 0 degree horizontally and 0 degree vertically and with standard deviations of 0.253 degree (1.33 in. at 25 ft) horizontally and 0.253 degree (1.33 in. at 25 ft) vertically. The present SAE tolerances (*5*) of ±4 in. at 25 ft in both horizontal and vertical directions were assumed to be equal to ±3 standard deviations.
- NHTSA Proposed Requirements—This case assumed the same tolerances proposed in Docket 85-15, Notice 5, Section 7.7.5 (*7*). The mean headlamp aim location was assumed to be 0 degree, 0 degree with standard deviations of 0.12 degree (0.67 in. at 25 ft) horizontally and 0.06 degree (0.33 in. at 25 ft) vertically. The standard deviations were obtained by assuming that the NHTSA proposed tolerance bands (±2 in. at 25 ft horizontal and ±1 in. at 25 ft vertical) equal three standard deviations in each direction.
- Perfect Aim—This condition assumed that each headlamp was aimed perfectly, (along the H-V axis with 0 degree horizontal and 0 degree vertical mean) and with zero standard deviation in horizontal and vertical directions, 0 degree, 0 degree.

The seven aim conditions are graphically displayed in Figure 11.

### Results

Table 1 defines the seven aiming conditions and presents the CHESS results. The table describes each aiming condition, the aiming tolerances, and the parameters used to represent the aiming conditions as inputs to the CHESS model. The last two columns provide FOM values obtained from the CHESS runs and percent changes relative to the figure of merit for Condition 1 (also see Figure 12).

Comparing the improvements in FOMs gained by reducing the aiming variability, a measure called percent change in

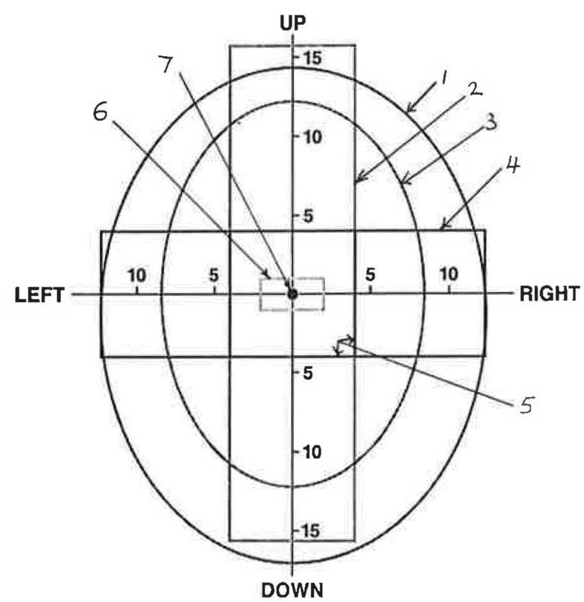


**FIGURE 11 Tolerance envelopes for seven cases. Note: 1 = Random aim; 2 = SAE horizontal only aim; 3 = UMTRI measured new car aim; 4 = SAE vertical only aim; 5 = SAE aim specifications; 6 = NHTSA proposed; and 7 = Perfect aim.**

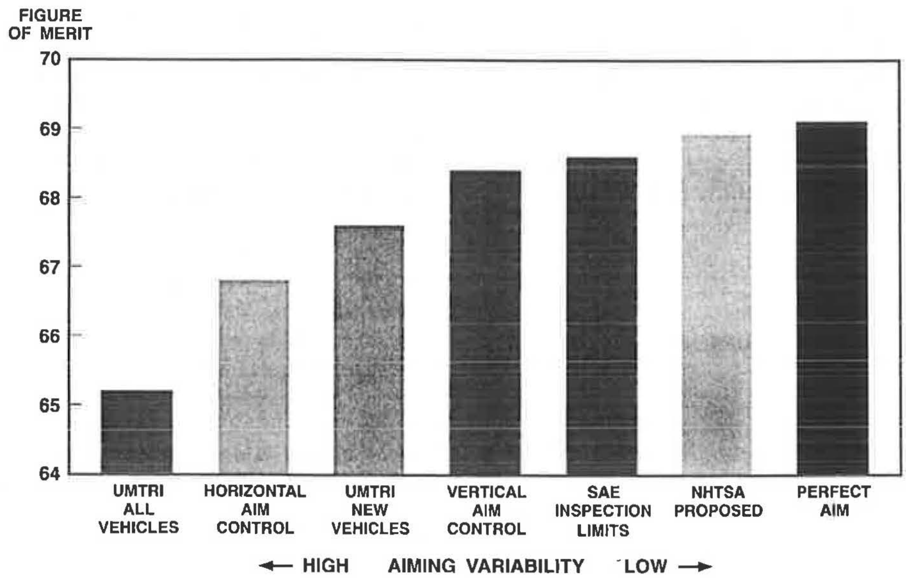


**FIGURE 12 Figure-of-merit for the seven aim conditions.**

TABLE 1 SUMMARY OF AIMING CONDITIONS AND CHESS MODEL RESULTS

| | | | Aiming Parameters for CHESS Runs | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Aiming Tolerance (in. at 25 ft) | | Mean (deg.) | | Standard Deviation (deg.) | | | Percent Change in Figure of Merit |
| Aiming Condition | Horizontal | Vertical | Horizontal | Vertical | Horizontal | Vertical | Figure of Merit | (69.1–65.2%) |
| Random aim (from 1984 UMTRI Survey; includes all vehicles) | ±12 | ±16 | 0.0 | −0.25 | 0.78 | 1.00 | 65.2 | 0.0 |
| SAE horizontal only (horizontal aim within ±4 in. at 25 ft) | ±4 | ±16 | 0.0 | 0.0 | 0.25 | 1.00 | 66.8 | 41.0 |
| UMTRI new vehicle aim (from 1984 survey) | ±8 | ±12 | 0.0 | 0.0 | 0.53 | 0.77 | 67.6 | 61.5 |
| SAE vertical only (vertical aim within ±4 in. at 25 ft) | ±12 | ±4 | 0.0 | 0.0 | 0.78 | 0.25 | 68.4 | 82.1 |
| SAE specs (both horizontal and vertical within ±4 in. at 25 ft) | ±4 | ±4 | 0.0 | 0.0 | 0.25 | 0.25 | 68.6 | 87.2 |
| NHTSA proposal (Doc. 85-15, N5) | ±2 | ±1 | 0.0 | 0.0 | 0.12 | 0.06 | 68.9 | 94.9 |
| Perfect aim | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 69.1 | 100.0 |

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FOMs was computed. Values of this measure are presented in the last column of Table 1. This percentage change is computed by assuming that the random aim condition represents the low anchor point of 0 percent, and the perfect aim condition represents the high anchor point of 100 percent. This measure helps in understanding the relative improvement in FOM that can be obtained by using these points. Thus, the table shows that 87.2 percent of the maximum improvement in the FOM can be obtained if all headlamps are aimed and maintained within the SAE specification, and 94.5 percent of the improvement can be obtained by holding aim to the NHTSA proposed aim requirements.

Figure 13 presents a bar chart showing the percent change in FOM obtained for the seven conditions. By observing the relative heights of the columns, it is clear that as the aim variability is decreased (in the successive columns to the right) the heights of the bars increase, but at a decreasing rate. This is a very important finding. Thus, in determining future aiming tolerances, it must be realized that very stringent aiming tolerances will not provide substantially greater benefits as compared to those achieved by conforming to the existing SAE specifications.

## CONCLUSIONS

The major conclusions from the three studies presented are as follows:

- Vertical misaim is much more important than horizontal misaim.
- FOMs are very insensitive to horizontal misaim in the range of 4 in. left and right. This indicates the possibility of fixing horizontal aim and eliminating provisions for horizontal aim adjustment.

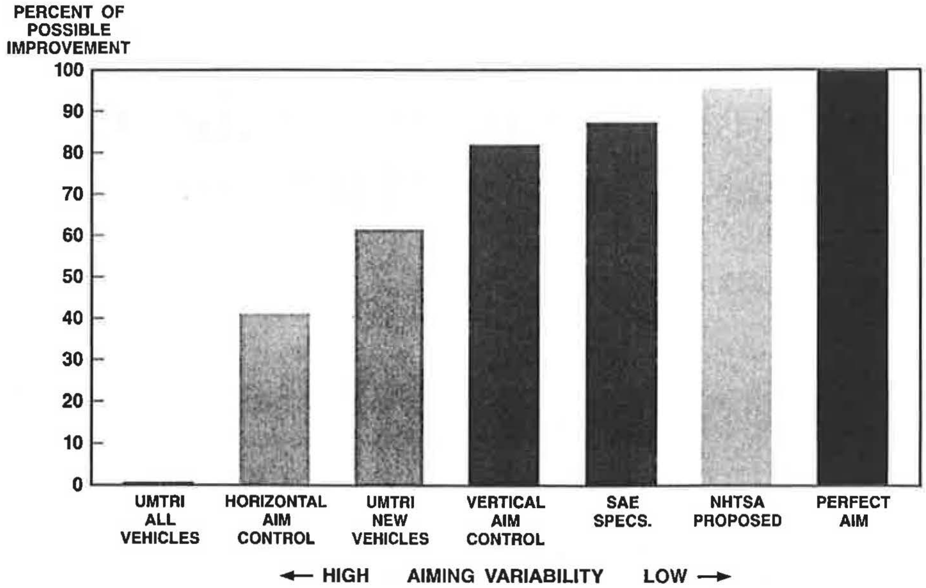


**FIGURE 13 Percent change (or possible improvement) in figure-of-merit as aiming variability is decreased from UMTRI measured aim to perfect aim.**

- Reductions in the allowable range of misaim beyond that referenced in the SAE standards (±4 in.) will produce only slight increases in performance. Thus, the present range of ±4 in. for inspection (specified in SAE J599) is adequate and should not be reduced.

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# Minimum Photometric Properties of Retroreflective Signing Materials

PAUL L. OLSON

**Laboratory and field studies were conducted to assess the minimum luminance levels of signs that ensures that they will be detected and identified at adequate distances under nighttime driving conditions. Thirty subjects participated in the field study, driving a car on public roads and reporting when they could identify the test signs that were positioned at random points along the side of the road. Surround complexity, subject age, retroreflective efficiency, and sign color were considered. A study was also carried out to measure the effect of subject expectancy. All of the independent variables, including color, were found to have an effect on sign conspicuity. For example, sign retroreflectivity had to be increased by a factor of about 10 to achieve equivalent conspicuity when going from areas of low to high complexity and by a factor of about 3 to compensate for the effect of subject age. The colors red, orange, green, and blue had substantially greater conspicuity than did yellow with equivalent retroreflectivity. Possible reasons for the latter finding are discussed. Minimum retroreflectivity recommendations and the rationale for their development are presented for stop signs, construction area warning signs, warning signs, and overhead guide signs.**

The purpose of this research was to develop information that would aid in recommending minimum candlepower values for various types of retroreflective signs in cluttered urban, suburban, and dark rural environments. The work was carried out in four stages:

1. The first stage was a laboratory study, which provided information on relationships such as sign size and the effects of borders and legends. Details about the laboratory study are contained in the project final report (*1*).
2. Stage two was a field study, which measured the distances at which subjects could identify test sign panels and their color in real-world environments.
3. Stage three was a study designed to develop a correction for the expectancy level of the subjects in the field study. Details about this investigation are contained in the project report (*1*).
4. In stage four, recommendations for minimum reflective material specifications were developed for different types of signs in three levels of environmental complexity.

## FIELD STUDY OF SIGN CONSPICUITY

The field study was the primary data-gathering effort in the sign conspicuity program. Its purpose was to develop information on the relative nighttime conspicuity of signs in a real-world setting. The test was run on public roads; the subject drove. Measures were made of the distances at which subjects could distinguish and identify the color of test sign panels having different levels of retroreflective efficiency in environments of varying complexity.

### Method

#### *Independent Variables*

The independent variables in the study were the retroreflective properties of the sign, sign color, surround complexity, and subject age.

Five levels of retroreflective efficiency were available in one color (yellow). These ranged from SIA 750 to SIA 16. Three of these were used in each level of surround complexity.

Yellow was the primary sign color used in the study. Some data were also taken on orange, red, green, blue, and white signs. However, these colors did not appear at all levels of surround complexity.

Three levels of surround complexity were used. These will be referred to as high-, medium-, and low-complexity areas.

Subjects were classified into two age groups: young and old. The young subjects ranged in age from 20 to 46 years, the old subjects from 58 to 75 years. There were 15 subjects in each age group, for a total of 30. All were licensed drivers and drove regularly at night.

#### *Dependent Variable*

The dependent variable was the distance at which the subject could identify the test sign and its color.

#### *Equipment*

A number of blank signs were fabricated for use in this project. Each was 30 $in^2$. They were faced with retroreflective material in various grades and colors.

The SIA values of the test panels were measured using an Advanced Retro Technology Model 920 Field Retroreflectometer. A minimum of five measurements were taken on each panel. Four of these were at a point about 6 in. in from each corner, and the last was approximately in the center. The value assigned to each panel was the average of the individual measurements.

Five yellow signs, with SIA values of 750, 250, 77, 40, and 16, were the basic set on which most of the data were based.

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Each subject was exposed to each of the yellow signs three times in each complexity area.

In addition, in each complexity area, subjects were exposed once to each of three other signs having colors other than yellow. It was intended to use all colors at least once and one color (green) in all three areas. Otherwise, the choice of signs in colors other than yellow in the different complexity areas was governed by the opportunity to investigate color differences with minimum differences in SIA. Where such comparisons were made, the signs appeared at the same location within a given area. Table 1 is a listing of signs assigned to the different complexity areas.

The test vehicle driven by the subjects was a 1981 full-sized station wagon. It was equipped with a distance measuring system that worked off the left front wheel, producing four counts (1.74 ft or 0.53 m per count) per revolution. The test vehicle was also provided with a precision voltage control system that kept the lamps operating at 12.8 volts throughout the test. The headlamps were number 6052 (large rectangular sealed beams, meeting FMVSS 108 requirements), mounted with their centers 30 in. above the pavement. They were aimed with calibrated mechanical aimers.

### *Test Areas*

Three test areas represented what the investigators judged to be high, medium, and low levels of complexity. Figures 1, 2, and 3 are photographs that show representative sections of the high-, medium-, and low-complexity test areas, respectively.

In each complexity area, several sites were selected for displaying the signs. The following criteria were used:

- A minimum 1,000-ft approach of straight and flat roadway,
- A safe place to park the sign handler's car so that it would be out of the subject's sight, and
- A representative sign surround.

A number of sites were selected in each complexity area. Because no site was identical to any other, there was the

TABLE 1 LISTING OF SIGNS BY COMPLEXITY AREA

| High Complexity | | Medium Complexity | | Low Complexity | |
|---|---|---|---|---|---|
| Color | SIA | Color | SIA | Color | SIA |
| Yellow | 750 | Yellow | 250 | Yellow | 77 |
| Yellow | 250 | Yellow | 77 | Yellow | 40 |
| Yellow | 77 | Yellow | 40 | Yellow | 16 |
| White | 115 | Red | 41 | Blue | 11 |
| Red | 64 | Orange | 38 | Orange | 38 |
| Green | 64 | Green | 64 | Green | 15 |

Note: All sign panels were 30 inches square.


**FIGURE 1 High-complexity area.**

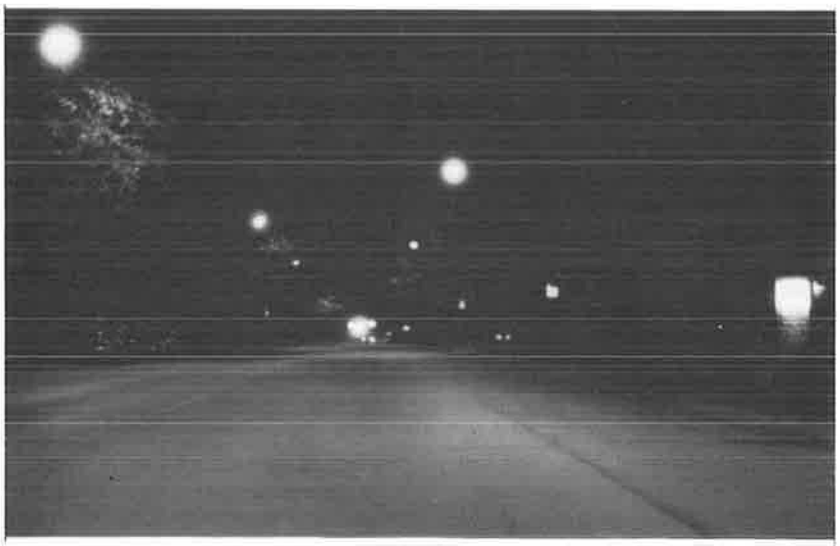

FIGURE 2 Medium-complexity area.

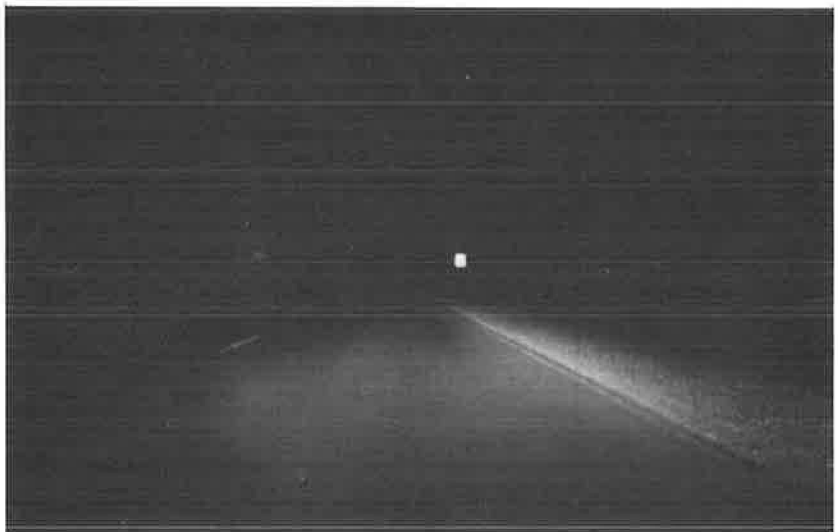

FIGURE 3 Low-complexity area.

possibility of differences between signs being confounded by differences between sites. There was no way of completely avoiding this problem. However, the following steps were taken to minimize it:

- In the preparation stage, all sites were viewed under test conditions to make sure there were no obvious problems. Some sites were eliminated in this process. Adjustments to the sign position were made at others.
- The three presentations of each sign were made at different sites, minimizing the influence of any one site on a particular sign.
- Signs that had different SIAs were presented at the same site, thus allowing an unbiased estimate of the effect of SIA. However, the extent to which this could be done was limited because the subject had to be uncertain about where signs would appear.

A comparison of mean identification distances for the same sign at different sites showed that task difficulty did vary from site to site within a given complexity area. In some cases, the differences were fairly large. Clearly, the results that will be obtained in an investigation such as this depend in part on the specific sites which the experimenter chooses. Thus, the resulting conclusions are only generally indicative of performance in different types of surroundings.

*Procedure*

Subjects were run individually. Each was seated in the test vehicle and told to arrange the seat and mirrors in the best position. The instructions were then read. As part of the orientation process, the subjects had the opportunity to see the six different colors of signs side by side about 300 ft away, using the illumination from the test vehicle's headlamps. The colors were named by the experimenter at that time.

When the instructions had been read and all questions answered, the subject was instructed to drive to the starting point for the first area, following specific roads. Along the way, two yellow signs were presented. This was to ensure that the subjects understood the instructions, to allow them to become familiar with how the signs looked in the field, and to encourage them to be on the lookout for signs. No data were taken on these two presentations.

The signs were positioned by two experimental assistants, each responsible for half of the test route. The assistants drove from site to site, parked their car, selected the proper test sign, positioned themselves next to the road, and watched for the test vehicle (which was distinctively marked with two yellow lights across the roof). When the test vehicle was identified they held up the sign at head height until it passed. They then returned to their car, stored the sign, and drove to the next site.

The subjects made six passes through each area. Signs were encountered at random points on each pass and normally not at the same points on the following pass.

When the subjects detected a sign, they were required to call out, "sign." The experimenter in the back seat then started a distance counter. When the subject could identify the color of the sign, he or she called out the color. The experimenter started a second counter if the identification was correct. If not, the counter was started when the subject made the appropriate correction, and the error was noted. Both counters were stopped as the sign was passed, and the experimenter wrote down the values and reset the counters.

### *Interpretation of Recorded Distances*

In the following analysis paradigm, five steps were assumed necessary for drivers in interacting with highway signs (*2*). These were detection, identification or recognition, decision, response, and maneuver. The subjects in this study were required to detect the test signs, identify them as test signs, and then call out, "sign." The experimenter then pressed a button to start the distance counter. With the exception of the reaction time of the experimenter in starting the counter, the values recorded in this study were assumed to correspond to identification distance, or response distance for signs leaving no choice of response to the driver (e.g., a stop sign).

A follow-up study was concerned with the development of a correction for the expectancy levels of the field study subjects. That study was conducted in such a way that it compensated for experimenter response time as well. Hence, no attempt will be made to apply such a correction to the results presented in the next section.

## Results

### *Sign Identification Distance*

A summary of the sign identification distance results is given in Table 2. The values shown in this table are mean identification distances for all 30 subjects for each color and SIA level in each complexity area. For the yellow signs only, mean identification distance varied directly with SIA and inversely with area complexity. For colors other than yellow (with the

TABLE 2 MEAN SIGN IDENTIFICATION DISTANCES FOR ALL SUBJECTS AS A FUNCTION OF SIGN COLOR AND AREA COMPLEXITY

| Sign | | Area Complexity | | |
|---|---|---|---|---|
| Color | SIA | High | Medium | Low |
| Y | 750 | 965 | | |
| Y | 250 | 735 | 845 | |
| Y | 77 | 617 | 701 | 1070 |
| Y | 40 | | 600 | 817 |
| Y | 16 | | | 675 |
| W | 115 | 457 | | |
| R | 64 | 911 | | |
| R | 40 | | 811 | |
| O | 40 | | 824 | 1062 |
| G | 64 | 889 | 844 | |
| G | 15 | | | 1039 |
| B | 11 | | | 1196 |

exception of white), the mean identification distances were substantially greater than for the yellow sign having the most comparable SIA. This point will be raised again later. The presentation of results begins with data obtained from the yellow signs.

Normal probability distributions of identification distances for all 30 subjects are shown in Figures 4, 5, and 6. There is one figure for each complexity area. These figures show the percentile associated with each identification distance for each sign SIA. For example, the 85th-percentile distance in the high-complexity area for the SIA 750 sign was about 500 ft. It was about 400 ft for the 250 SIA sign and about 275 ft for the 77 SIA sign.

It is evident from Figures 4 through 6, as it was in Table 2, that sign identification distance varies as a function of both SIA and surround complexity. Figure 7 shows the relationship between identification distance and surround complexity for the SIA 77 yellow sign, the only one to appear in all three complexity areas. The differences are substantial. For example, the 85th-percentile identification distances are about 275, 400, and 600 ft in the high-, medium-, and low-complexity areas, respectively.

The discussion so far has concerned data from all subjects involved in the study. This can be misleading, because performance differences between the young and older subjects were fairly large. Figure 8 illustrates this point, providing a comparison between the two age groups for the SIA 77 sign in the high- and low-complexity areas. At the 85th-percentile level, the difference in identification distance between the groups was 150 to 200 ft. To achieve performance equivalent

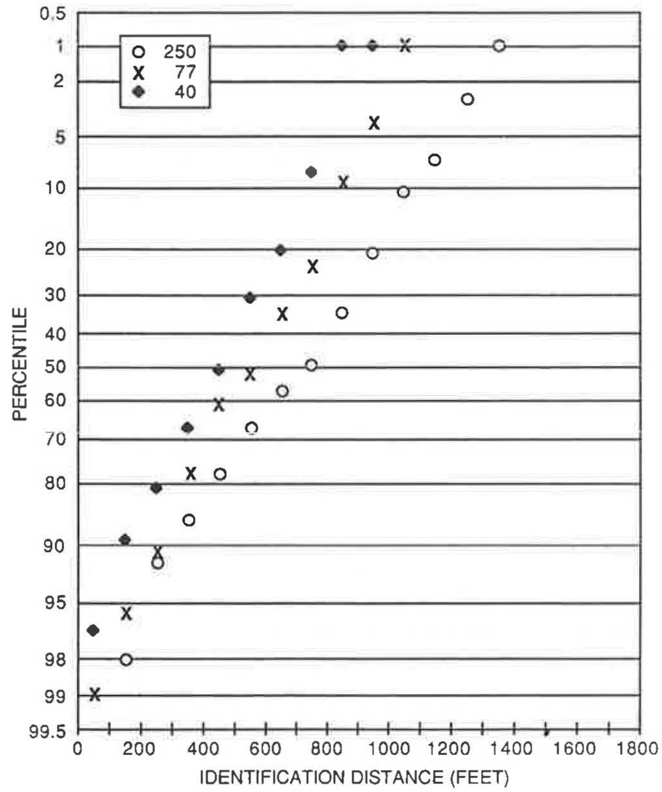


**FIGURE 5 Normal probability distribution of sign identification distances in the medium-complexity area.**

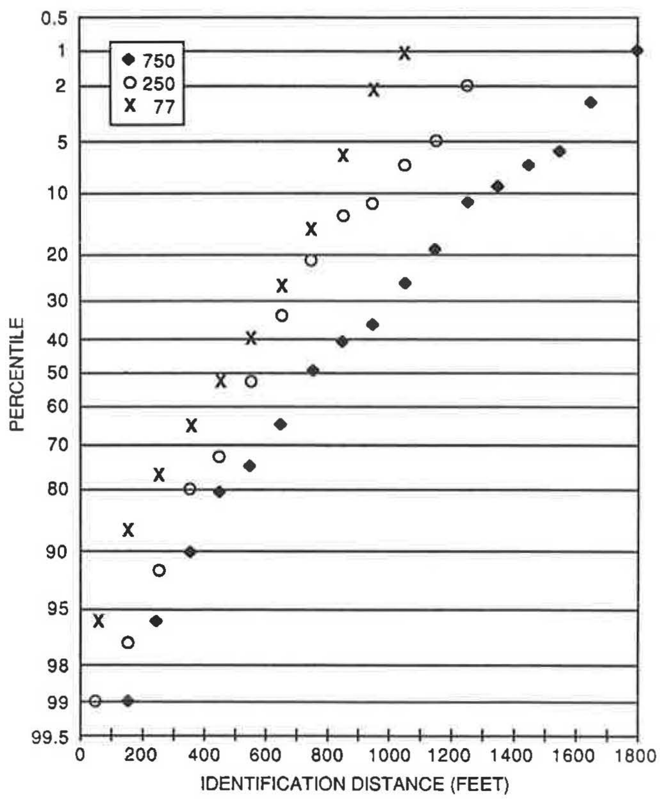


**FIGURE 4 Normal probability distribution of sign identification distances in the high-complexity area.**

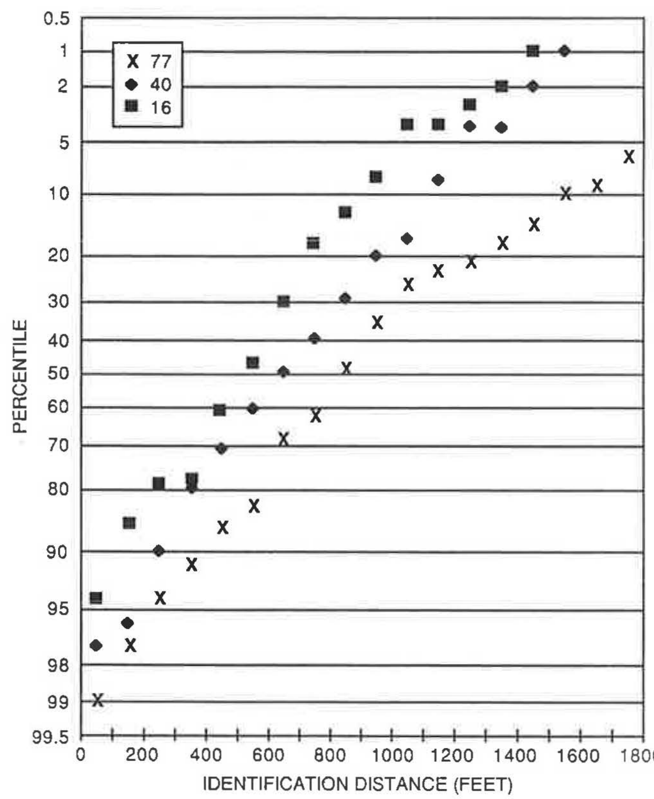


**FIGURE 6 Normal probability distribution of sign identification distances in the low-complexity area.**

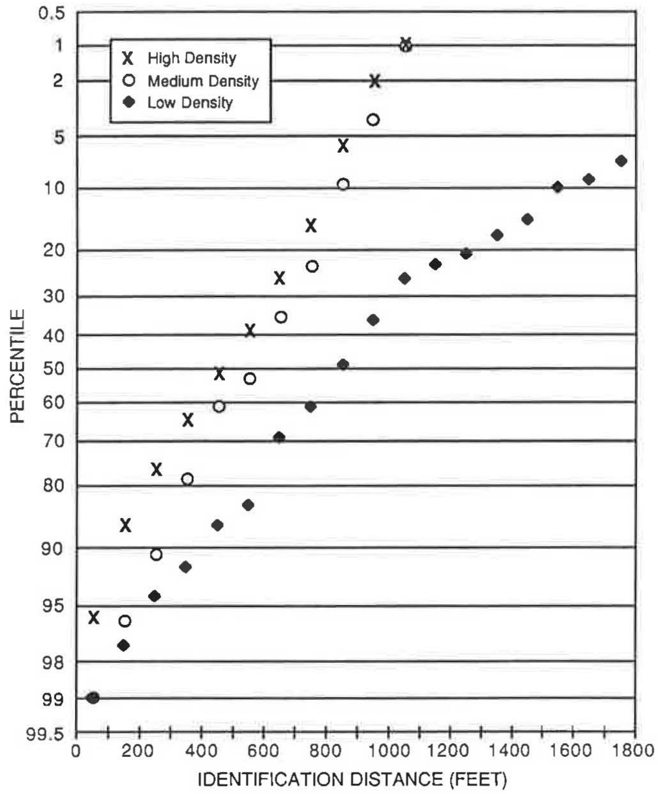


**FIGURE 7 Normal probability distribution of sign identification distances for the yellow SIA 77 sign as a function of area complexity.**

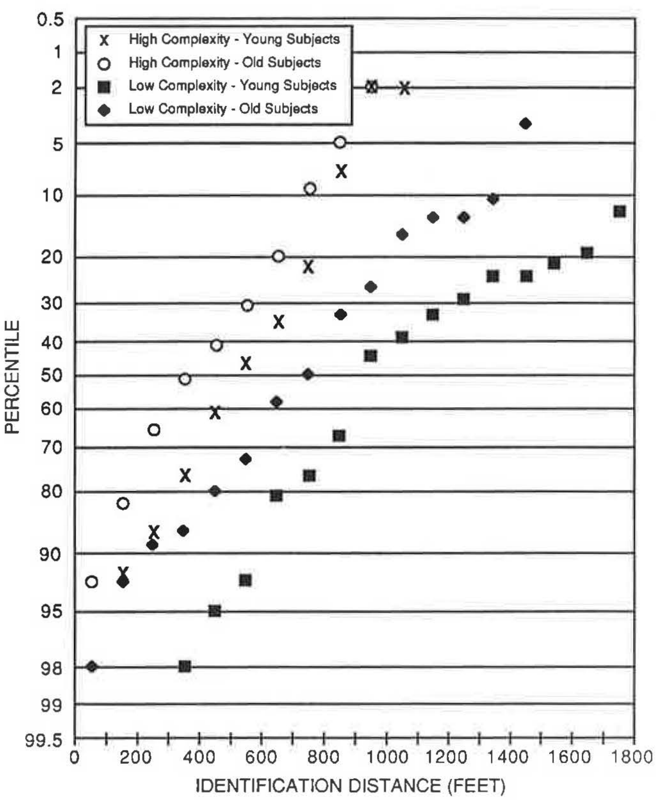


**FIGURE 8 Normal probability distribution of sign identification distances for the SIA 77 sign by the young and older subjects at two levels of area complexity.**

to the young subjects, the data from this study indicate that the older subjects required signs having about three times greater SIA.

*Color Identification*

Color identification errors were fairly common, particularly with certain signs. However, the subjects usually corrected themselves before passing the sign. Table 3 lists the percent of trials on which the subjects initially correctly identified the color as a function of the sign color, SIA, and area complexity. These data are for all 30 subjects. The yellow signs were identified correctly about 90 percent of the time by most subjects. (The yellow signs may have had an advantage in that the subjects knew that yellow would be the color most frequently used.) There is some evidence that errors were inversely related to sign brightness.

Color identification errors of the other signs were much more variable. In particular, the SIA 40 red (usual error: orange), orange (yellow), and blue (green) signs were associated with large numbers of errors. In many cases, errors involving the orange and blue signs were not corrected by the subject.

**Color as a Factor in Sign Identification Distance**

It was pointed out earlier that colors other than yellow were identified at substantially greater distances than were yellow signs having about the same SIA (see Table 2). An exception to this was the white sign. In the case of the white sign, it was felt that the site at which it appeared included a great deal of white in the surround, which may have affected its conspicuity. Hence, the identification distance associated with the white sign may not be representative.

A number of avenues were reviewed in trying to find some explanation for the apparent differences in conspicuity associated with color. One promising possibility is that the differences may be attributable to the same phenomenon that causes the judgments of brightness made by human observers to be influenced by hue.

There have been a number of investigations of what is usually referred to as heterochromatic brightness matching [see the work of Wyszecki (*3*)]. A typical approach to research in this subject area requires subjects to adjust the luminance of a white surface until it appears to be the same brightness as an adjacent colored surface. When the match has been made to the satisfaction of the subject, the two surfaces are photometered. If the luminance of the reference surface (white in this case) is denoted by $R$ and the luminance of the colored test surface by $T$, the ratio $R/T$ is generally greater than 1 when the subject judges the surfaces to be equally bright. The ratio increases with increasing saturation of the test surface. Interestingly, yellow is a color often cited as an exception to this rule. Experimental data show that the value of $R/T$ typically stays close to 1 even as the saturation of a yellow surface approaches maximum.

In an effort to determine whether the phenomenon just described might account for the color results found in the field study, a laboratory color brightness investigation was conducted. This work is described in the project report. Briefly,

TABLE 3 PERCENT OF TRIALS ON WHICH THERE WERE NO COLOR IDENTIFICATION ERRORS—ALL SUBJECTS

| Sign | | Area Complexity | | |
|---|---|---|---|---|
| Color | SIA | High | Medium | Low |
| Y | 750 | 98 | | |
| Y | 250 | 86 | 91 | |
| Y | 77 | 82 | 89 | 88 |
| Y | 40 | | 90 | 89 |
| Y | 16 | | | 81 |
| W | 115 | 97 | | |
| R | 64 | 100 | | |
| R | 40 | | 56 | |
| O | 40 | | 47 | 57 |
| G | 64 | 96 | 89 | |
| G | 15 | | | 86 |
| B | 11 | | | 31 |

the results are in accord with those from heterochromatic brightness matching studies. However, although colors such as red, green, and blue were judged brighter than would be indicated on the basis of their photometric performance, they were not judged brighter than white or yellow from the same family of materials.

The work on brightness judgments as a function of color is suggestive and may afford a complete explanation of the results of the study. However, experimental work to date has been concerned solely with the perception of brightness. The data from the field study conducted as part of this program indicate that colors such as red, orange, green, and blue also have inherently greater conspicuity per unit SIA than does yellow (and perhaps white) in the context of road signs.

The fact that conspicuity depends to a significant degree on sign color complicates the recommendations with which this program is ultimately concerned. Unfortunately, the study was not designed to systematically evaluate color, since major effects were not anticipated. Signs having colors other than yellow were generally matched at a particular site within a given complexity area with a yellow sign having approximately the same SIA. Where these comparisons are available, it is clear that the other colored signs (with the exception of white) were identified at a much greater distance than the yellow sign. The red, blue, green, and orange signs in a given complexity area typically performed about as well as the brightest yellow sign tested, although the latter had anywhere from 2 to 10 times greater SIA.

Lacking more definitive information on the effect of color, recommendations were based on the assumption that orange, red, green, and blue have conspicuity equal to that provided by yellow in the same family of materials. This is strongly supported by the data that were collected, and, if anything, is conservative. Further work on color effects should be carried out to better define the relationship.

## RECOMMENDATIONS

### Background

This section presents recommendations for minimum sign SIA values based on the results of the two field studies just described. Certain assumptions were required to arrive at these recommendations. These are described as well.

In formulating these recommendations, an 85th-percentile performance level was used. There are two reasons for this. First, the 85th percentile is a common performance limit in traffic engineering. Second, the 85th percentile can be estimated with some accuracy from these data. A much higher level (e.g., 95th or 99th) is more difficult because of the limited number of measurements (maximum of 90) per condition.

A separate investigation was carried out to develop a correction for the expectancy levels of the subjects in the field study. The results suggest that the identification distances recorded in the field study must be reduced by about 40 percent to approximate normal expectancy levels.

### *Sign SIA, Surround Complexity, and Driver Expectancy*

Figure 9 illustrates the relationship between SIA and 85th-percentile identification distance for the three levels of surround complexity and includes a correction for driver expectancy. The recommendations for minimum SIA levels for most

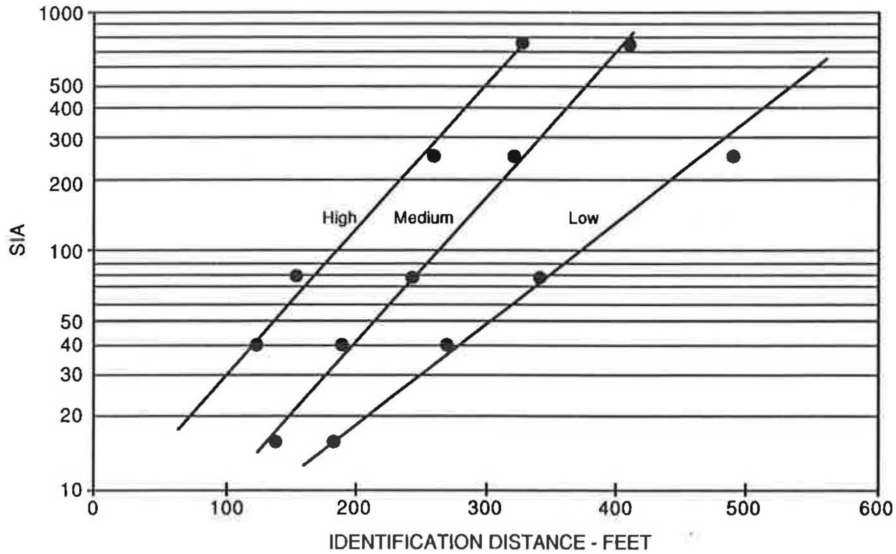


**FIGURE 9 Eighty-fifth percentile yellow warning sign identification distances for three levels of area complexity, corrected for driver expectancy.**

applications to be considered in this paper can be traced back to this figure.

The figure was prepared by estimating the 85th-percentile sign identification distance from the appropriate plots presented earlier (see Figure 10). The resultant values were multiplied by 0.6 to correct for driver expectancy.

Only three levels of SIA were tested in each complexity area. Estimates were made of the performance of the SIA 40 level in the high-complexity area, the SIA 750 and 16 levels in the medium-complexity area, and the SIA 250 level in the low-complexity area. This was done by comparing the performance of each of these signs with other signs in areas where they were used. For example, the identification distance of the SIA 40 sign at the 85th percentile was 75 percent and 76 percent of that of the SIA 77 sign in the medium- and low-complexity areas, respectively. Hence it was given an estimated 85th-percentile identification distance of 75 percent of that of the SIA 77 sign (122 ft) in the high-complexity area.

In the case of the high- and medium-complexity areas shown in Figure 9, the fit of these estimates to the empirical data is good, and the extrapolations are included in the visual best-fit line shown. In the case of the low-complexity area, the estimate of the 250 SIA is not as close as the others, and it was given no weight in positioning the best-fit line.

### *Driver Age*

The large differences between the two age groups included in the study raised a question of how to weight the results for

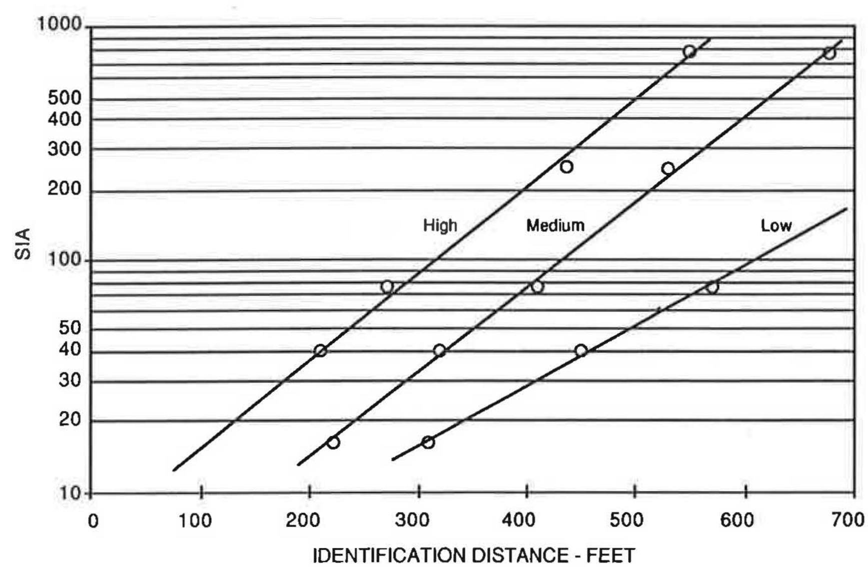


**FIGURE 10 Eighty-fifth percentile yellow warning sign identification distances for three levels of area complexity, without correction for driver expectancy.**

purposes of recommendations. For example, Awadallah (*4*) argues that the weighting should consider the percentage of nighttime miles driven by older individuals.

Although some information is available concerning the visual characteristics of older people, it is not clear that this includes those characteristics that determine the ability to detect and identify highway signs as night. Even if it were certain that this information was available, it seems reasonable that older persons who drive very much at night would tend to be those with better night vision. Thus there is no way at present to accurately estimate the low-luminance vision characteristics of the population of persons who drive at night. It must be remembered, too, that the age composition of the population is changing. The percentage of people 55 and over is increasing. In addition, these people are enjoying better health and have more disposable income than in the past, so they are likely to travel more. As a result of these known trends, setting standards based on current population characteristics could cause them to be outdated in the near future. It does seem clear that it would be unfair to use only the data from one of the age groups. For purposes of this paper, the recommendations were based on the combined data from the two groups.

### *Sign Background Color*

The effect of sign color on identification distance was much greater than expected. Because of this, estimates of the effective SIA of various colors could not be made to a high level of accuracy using these data. For the purposes of this paper, it was assumed that all colors within a given family of retroreflective materials are equally effective.

In making recommendations on the basis of Figure 9, adjustments were based on relative SIAs within the family of materials. For example, the SIA of a screened red was assumed to be 21 percent of that of yellow. If Figure 9 indicates that the minimum SIA of a yellow sign for a given application should be $X$, then the minimum for a red sign would be $0.21(X)$.

### *Sign Size, Borders, and Legends*

The baseline data from the field study were based on signs that are 30 in. square. Adjustments appropriate for signs that are greatly different in size (e.g., guide signs) were made as indicated by the results of the laboratory study carried out as part of this program (*1*).

Yellow, orange, and white signs use black borders and legends, which would be expected to reduce their conspicuity by reducing their apparent brightness. This effect would be most significant at longer distances, where the sign approximates a point source. The effect should be proportional to the percent of the surface area that is black. No precise data are available, but the portion of the faces of yellow, orange, and white signs that is black was estimated to range from 10 percent to 30 percent. A 15 percent figure was taken as representative. The replacement SIA value of such signs was adjusted by 15 percent to allow for this effect.

Red, green, and blue signs have white borders and legends. Nominally, these borders should prove helpful, because they increase the effective SIA for the whole sign. However, when the use of borders and legends was barred from a family of materials having higher overall SIA, the field data indicated that the benefits of the colored background outweighed the contribution of the white areas. Hence no adjustments were made to the recommendations for minimum values of red, green, and blue signs due to the effects of borders and legends.

### *Headlamps*

The recommendations were based on the assumption of a single vehicle in the right-hand lane, using low-beam headlamps (of the type specified in FMVSS 108) in correct aim and driven at 12.8 volts. All glass was assumed to be clean and clear.

### *Spatial Location*

Where a sign is located (to the right, left, or overhead) and how far it is from the path of travel affects the amount of illumination reaching it from an approaching vehicle's headlamps. To generalize the data from the field study to locations other than the right edge of the road, a computer model was written to calculate sign luminance. The field data could then be used to estimate minimum SIA values. The accuracy of the model was verified by a number of field photometric measurements of sign panels in various positions and at various distances.

### *Classes of Signs*

Recommendations were based on a structure first defined by Perchonok and Pollack (*2*). These authors classified signs into four categories, based on what the driver must accomplish prior to reaching them. These categories are as follows.

- *Class I.* The driver must accomplish all critical steps (i.e., detection, recognition, decision, response, and maneuver) before reaching the sign. A stop sign is an example of a class I sign.
- *Class II.* The driver must accomplish all but the maneuver stage before reaching the sign. There are few signs in this category. Perchonok and Pollack cite the "TURN OFF 2-WAY RADIOS" sign (W22-2) as the only example in the MUTCD.
- *Class III.* The driver must detect and recognize the sign and reach a decision before reaching the sign. Response and maneuver, if any are necessary, can occur after the sign is passed. Most warning and guide signs fall into Class III.
- *Class IV.* The driver must only detect and recognize a Class IV sign. Mileposts and general service signs are examples of this category.

## Recommendations for Stop Signs

Stop signs are Class I signs (i.e., the required maneuver must be completed by the time the sign is reached). In preparing these recommendations, it was assumed (a) that the distances given in Figure 9 are equivalent to response distance in the case of a stop sign, and (b) that the driver decelerates at a mean of 0.25 g. Table 4 gives the minimum SIA recommended for stop signs not accompanied by an advance warning sign or other supplemental device, for various traffic speeds and areas of different complexity.

The values in Table 4 were derived as follows. First, red was assumed to be equal in conspicuity to yellow in the same family of materials. Then, for each stopping distance shown, Figure 9 was accessed to find the appropriate SIA for each level of area complexity. For example, for 121 ft in the high-complexity area, Figure 9 indicates an SIA of about 40. This value was multiplied by 0.21 to obtain the equivalent SIA for a screened red material, yielding an estimated minimum SIA of 8.

SIA values above 40 are not generally attainable with Type III materials in red at present. At any point in the table where the minimum recommendations cannot be met, some form of supplemental warning device (e.g., flasher or advance warning sign) should be employed.

A recent report on the conspicuity of stop signs by Morales (*5*) offers an opportunity for comparison. Morales used 10 stop signs having different retroreflective properties in a field test involving 20 subjects of various ages. The test was run on a dark, private road. The signs always appeared at the same location.

Morales's recommendations are based on what he calls "overall SIA," a measure that takes into account both the red and white areas of the sign. Using this index, a new Type II stop sign that had SIAs of 120 and 16 in the white and red areas, respectively, would have an overall SIA of 41.

Morales's recommended minimum SIA values are generally much lower than those given in Table 4 for the low-complexity area. However, if the correction for expectancy is removed from the values given in Figure 9, the values are much closer. To illustrate this point, Table 5 has been prepared. In this table, the recommended minimum SIA values given in Table

TABLE 4 RECOMMENDED MINIMUM SIA VALUES FOR A STOP SIGN

| Speed (mph) | Stopping Distance @ 0.25 g (feet) | Area Complexity | | |
|---|---|---|---|---|
| | | High | Medium | Low |
| 65 | 569 | * | * | 150 |
| 60 | 484 | * | * | 71 |
| 55 | 407 | * | 155 | 30 |
| 50 | 337 | 170 | 63 | 14 |
| 45 | 272 | 70 | 25 | 8 |
| 40 | 215 | 30 | 11 | 4 |
| 35 | 164 | 16 | 5 | 3 |
| 30 | 121 | 8 | 3 | 2 |

*Supplemental warning required.

TABLE 5 COMPARISON OF RECOMMENDED MINIMUM SIA VALUES FOR STOP SIGNS FROM TWO STUDIES

| Speed (mph) | Stopping Distance @ 0.25 g (feet) | Minimum Overall SIA | |
|---|---|---|---|
| | | Current Study* | Morales |
| 65 | 569 | 46 | 40 |
| 60 | 484 | 29 | 40 |
| 55 | 407 | 17 | 40 |
| 50 | 337 | 11 | 18 |
| 45 | 272 | 8 | 10 |
| 40 | 215 | 6 | 6 |

*Calculated from data for low complexity area in Table 4 after removing correction for expectancy. Assumes red SIA is 13% of white SIA.

4 for the low-complexity area were recomputed without the correction for expectancy and converted to overall SIA (assuming red to be 13 percent of white). Table 5 shows the recommended minimum values for 40 and 45 mph to be very close. From 50 to 60 mph, Morales's recommended minimums are actually somewhat higher. (Note that Morales found no benefit for signs having an overall SIA greater than 40.)

Given that the two studies were conducted in different ways, the similarity shown in Table 5 is encouraging. However, it does seem clear that raw experimental data in a study such as this require an appropriate adjustment for the test subjects' expectancy level.

## Recommendations for Construction Area Signs

Orange-series construction zone signs are mostly warning signs. However, some fall into Class I, in that a maneuver must be completed by the time the sign is reached. An example is a lane closure sign that is placed at the end of the available lane.

Table 6 gives the minimum recommended SIAs for such a sign as a function of area complexity and traffic volume. The latter variable assumes that it takes 8 sec to check for traffic and make the lane change maneuver in light to medium traffic, and 9.8 sec in medium to heavy traffic. These values are recommended by Perchonok and Pollack (*2*), based on a review of the literature.

The values in Table 6 were derived as follows. First, it was assumed that orange and yellow from the same family of materials have equal conspicuity. Then, for each required distance in the table, Figure 9 was used to determine the appropriate SIA for a yellow sign. For example, for 293 ft in the low-complexity area, Figure 9 indicates an SIA of 45. This value was multiplied by 0.55 to obtain the equivalent orange SIA, and the result was multiplied by 1.15 to correct for the effect of borders and legends.

An examination of Table 6 makes it clear that there are relatively few cases where a single sign will serve. These occur largely at low speeds and in areas of low complexity.

## Recommendations for Warning Signs

Warning signs are Class III devices, meaning that detection, identification, and some level of decision are required before reaching the sign. Response and maneuver, if any, can take place after the sign is passed.

In developing recommendations for warning signs, a consideration was the complexity of the decision that must be made by the driver. Perchonok and Pollack (*2*) distinguish three levels of decision complexity (low, medium, and high), assigning time values of 0.5, 2.5, and 4.5 sec, respectively. Table 7, derived from Perchonok and Pollack's Table 19, shows the assignment of decision complexity (hence decision time) as a function of the area complexity and number of choices created for the driver by the warning sign.

Table 8 lists recommended minimum SIA values for yellow (warning) signs as a function of area complexity and the number of options available to the driver. The values in this table were derived as follows. First, the speed in feet per second was multiplied by the appropriate decision time to obtain a decision distance. Figure 9 was then accessed to obtain an SIA. As a final step, this value was multiplied by 1.15 to correct for the effect of borders and legends.

For orange-series signs that fall under Class III, an approximation of their minimum values can be obtained by multiplying the values in Table 8 by 0.55.

The lowest SIA listed in Table 8 is 15. This is primarily because extrapolations below 15 in Figure 9 are difficult. However, an SIA of 15 represents about 30 percent of the new minimum value of a yellow sign. By the time it reaches this level, a sign would typically present a poor appearance night and day and be a candidate for replacement in any event.

Guidelines for warning signs have been prepared by Mace et al. (*6*). They suggest that Type II yellow sheeting degraded to 36 percent of federal specifications (i.e., an SIA of about 18) would be adequate for low-complexity sites. This compares well with the values given in Table 8, except for speeds of 55 or higher in situations that present the driver with three or more choices.

At medium-complexity sites, Mace et al. suggest that an SIA of 36 may be the appropriate minimum. For many appli-

TABLE 6 RECOMMENDED MINIMUM SIA VALUES FOR A CONSTRUCTION SIGN (ORANGE) REQUIRING A LANE CHANGE

| Speed (mph) | Traffic Volume | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Light to Medium | | | | Medium to Heavy | | | |
| | Required Distance (feet) | Area Complexity | | | Required Distance (feet) | Area Complexity | | |
| | | High | Medium | Low | | High | Medium | Low |
| ≥ 45 | | * | * | * | | * | * | * |
| 40 | 469 | * | * | 170 | 575 | * | * | * |
| 35 | 411 | * | 425 | 95 | 503 | * | * | 240 |
| 30 | 352 | * | 230 | 51 | 431 | * | * | 114 |
| 25 | 293 | 280 | 98 | 28 | 359 | * | 250 | 57 |

*Advance warning sign required.

TABLE 7 DECISION COMPLEXITY AS A FUNCTION OF NUMBER OF POSSIBLE CHOICES AND AREA COMPLEXITY

| Area Complexity | Number of Choices | | |
|---|---|---|---|
| | 0–1 | 2–3 | ≥ 3 |
| Low | Low | Low | Medium |
| Medium | Low | Medium | High |
| High | Medium | High | High |

Adapted from Perchonok and Pollack, 1981.

TABLE 8 RECOMMENDED MINIMUM SIA VALUES FOR WARNING SIGNS (YELLOW) AS A FUNCTION OF AREA COMPLEXITY AND DECISION REQUIRED OF THE DRIVER

| Speed (mph) | Area Complexity | | | | | | |
|---|---|---|---|---|---|---|---|
| | Low | | Medium | | | High | |
| | Number of Choices | | Number of Choices | | | Number of Choices | |
| | 0–3 | 3 or more | 0–1 | 2–3 | 3 or more | 0–1 | 2 or more |
| 65 | 15 | 31 | 15 | 86 | 630 | 230 | * |
| 60 | 15 | 25 | 15 | 63 | 414 | 173 | 1115 |
| 55 | 15 | 21 | 15 | 52 | 276 | 144 | 750 |
| 50 | 15 | 17 | 15 | 38 | 180 | 110 | 520 |
| 45 | 15 | 15 | 15 | 29 | 126 | 80 | 345 |
| 40 | 15 | 15 | 15 | 23 | 80 | 63 | 230 |
| 35 | 15 | 15 | 15 | 17 | 52 | 52 | 150 |
| 30 | 15 | 15 | 15 | 15 | 35 | 38 | 100 |

*Supplementary devices required.

cations, the recommendations in Table 8 are about half that value. For more complex choice situations, their recommendation would be adequate for speeds of 50 mph or less, based on Table 8.

Mace et al. feel that Type III sheeting (SIA of about 170) may be required in high-complexity areas. This compares well with the recommendations given in Table 8 for higher speeds, when the driver has a limited number of choices to make.

### Recommendations for Overhead Guide Signs

Developing recommendations for guide signs is a more complex process than for the other types of signs considered up to this point. A number of assumptions must be made. These are

- Green is equal in conspicuity to yellow in the same family of materials.
- The effect of the white border and legend on conspicuity is minimal.
- The correction for driver expectancy does not apply. It will be assumed that drivers are searching for guide signs and their expectancy is approximated by that of the subjects in this study. Figure 10 has been prepared to estimate the SIAs without the correction for expectancy incorporated into Figure 9.
- Guide signs are typically much larger than the signs used in the field study, and their larger size aids conspicuity. An estimate of this effect can be obtained from the laboratory study (*1*). Those data indicate that a multiplier of 2.4 would be appropriate.
- Because of the distributional characteristics of low-beam headlamps, the level of illumination reaching an overhead guide sign will be a great deal less than the illumination reaching the test signs at the same distances. As noted earlier, a computer model was used to estimate the illumination levels appropriate for overhead signs.
- Because of the position of overhead and many ground-mount guide signs, they are difficult to see when the car gets close to them. In addition, their luminance level begins to drop off rapidly as the car gets to within 200 to 300 ft. Therefore, it was assumed that the driver had to complete the reading task before passing 100 ft in front of the sign.
- Reading time for a guide sign depends on the number of words contained on the sign. Mitchell and Forbes (*7*) have

TABLE 9 RECOMMENDED MINIMUM SIA VALUES FOR THE GREEN BACKGROUND AREAS OF AN OVERHEAD GUIDE SIGN

| Speed (mph) | Area Complexity | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Low | | | Medium | | | High | | |
| | Words on Sign | | | Words on Sign | | | Words on Sign | | |
| | 3 | 6 | 9 | 3 | 6 | 9 | 3 | 6 | 9 |
| 70 | 8 | 15 | 27 | 13 | 31 | 70 | 35 | 82 | 200 |
| 60 | 8 | 13 | 22 | 12 | 25 | 54 | 32 | 70 | 150 |
| 50 | 7 | 11 | 17 | 11 | 20 | 37 | 28 | 54 | 100 |
| 40 | 7 | 9 | 13 | 10 | 15 | 25 | 25 | 40 | 68 |
| 30 | 6 | 8 | 10 | 8 | 12 | 17 | 22 | 33 | 46 |

Sign is assumed to be 20 feet high and centered over a roadway 24 feet wide.

estimated this time at 3 words/sec. Thus, the tables that present minimum recommended SIAs contain headings for 3, 6, and 9 words, representing 1, 2, and 3 sec of travel time, respectively.

The recommended minimum SIAs for an overhead guide sign are presented in Table 9. These values were derived as follows. First, the illumination reaching the overhead position was calculated. This was typically found to be about 10 percent of that reaching the test signs in the field study at the same distance. Thus, to achieve the same luminance level, the material on the overhead sign would have to have 10 times the SIA. However, it was assumed that green has the same conspicuity characteristics as yellow in the same family of materials. Because green has about 23 percent of the reflectivity of yellow, the SIA value must be increased only by 2.3. The correction for size was 2.4, which nearly canceled out the correction for relative reflectivity. Thus, the values given in Figure 10 are a good estimate of the minimum SIAs for overhead signs and were used directly in making up Table 9.

An examination of Table 9 indicates that Type II materials would be appropriate on overhead guide signs only in areas of low complexity and with three or fewer words on the sign. More highly reflective materials and/or multiple signs are appropriate in most cases.

## DISCUSSION OF RESULTS

This paper has described an experimental program designed to determine the minimum luminance characteristics required of reflectorized highway signs to ensure adequate conspicuity. It has also provided some example specifications based on those data.

It should be clear that this is a complex area, and one study cannot resolve all relevant questions. A comparison of these recommendations with those offered by other investigators, in particular Mace et al. and Morales, does show reasonable agreement and suggests that a time may be approaching when minimum SIA levels can be set with some confidence.

However, a number of significant questions remain. Among those that should be addressed are the effects of sign color, size, and location on conspicuity. Hopefully, significant work on these issues can be undertaken in the near future.

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# Mobile System for Measuring the Retroreflectance of Traffic Signs

JOHN J. LUMIA

**A practical system is needed to evaluate the nighttime visibility of existing signs and provide data for making decisions about sign replacement or refurbishment. Laboratory methods and portable instruments are available for measuring the retroreflectance of traffic signs, but easy-to-use mobile systems are not. Research is currently under way to develop a system that can measure the average retroreflectance of sign legend and background, irrespective of color, size, and placement, and that can be operated during daylight from a moving vehicle. Based on the use of a charge-coupled device video camera to acquire sign images, a xenon flash as a source of light, and a portable personal computer to analyze the images, experiments and analyses indicate that such a system is feasible, is well suited for making measurements from a moving vehicle, and can be built from commercially available components.**

This paper discusses a device used for measuring traffic sign retroreflectance from a moving vehicle during daylight hours. Average values of both legend and background retroreflectance, in units of candelas per footcandle per square foot (commonly defined as $R'$), are sought. Accurate measurements depend on the angle between the source and detector, and this is generally not fixed for realistic situations. Signs may be of differing colors, shapes, sizes, and placement. The finished system should be simple and not pose a danger to the operator or other motorists.

The basic concept for the measurement of average legend and background retroreflection is the use of a video camera to record the sign, with an electronic flash source providing a short burst of light bright enough to overcome the sign luminance caused by ambient daylight illumination. The video camera signal is then converted to a digitally sampled representation of the sign. Using the power of computer image processing, histograms of the retroreflected intensity distribution can be used to yield average legend and background values. In a moving system, a laser range finder provides an accurate means of monitoring the distance from the vehicle to the sign.

## BACKGROUND

A number of sources describe systems for single-spot measurement of signs in situ (*1–3*). The systems described for measurement during daylight hours generally define phase-lock detection techniques, which are not readily applied to the large number of point measurements required to distinguish legend from background averages, particularly in a moving environment (*2,3*). Other references describe the effects of source and detector sizes on measurement accuracy (*4*), as well as the photometric properties of retroreflective sign materials as a function of lighting geometry (*5*). Additional sources contain reports of average luminance measurements of sign materials during daylight hours, along with typical average sky luminance readings (*6*). Certain standards and methods were also included in this study and consulted regularly to ensure that the design concept was consistent with conventional methods (Federal Test Method Standard 370 (*7*), ASTM E808-81, ASTM E809-81, ASTM E810-81, ASTM E811-81, FP-85 (*8*), and AASHTO M268-84).

A retroreflector is a device that turns light back toward its source, generally over a wide range of input angles. Signs are typically comprised of either retroreflective sheeting or glass beads mounted directly on the face of the sign. The design of this system has been based on retroreflective sheeting. Three types are commonly used for highway signs: enclosed glass beads, encapsulated glass beads, and cube-corner prismatic elements (see Figure 1). Each of these materials has different retroreflective properties, which will be demonstrated later.

This design requires the measurement of the coefficient of retroreflection ($R'$) with the desired units in candelas per footcandle per square foot. This can be expressed as

$$R' = \frac{I}{E_n A} \qquad (1)$$

where $E_n$ is the normal illumination incident on the retroreflector, $A$ is the area of the surface to be measured, and $I$ is the reflected intensity (*9*). With manipulation of these parameters, the retroreflectance can be regarded as the absolute brightness of the retroreflective target for a given amount of incident illumination on the target. Arithmetically, this can be expressed as

$$R' = \frac{L}{E_n} \qquad (2)$$

where $L$ is the luminance of the reflected light. Figure 2 shows the commonly accepted geometry and definitions as prescribed by ASTM E808-81 for evaluating retroreflective materials.

The incident illumination is generally measured using an illuminance meter located at the target and facing the direction of light. A more realistic approach for a mobile system is to use the inverse-square law to infer the illumination from the source intensity, or

$$E = I/d^2$$

EKTRON Applied Imaging, 23 Crosby Drive, Bedford, Mass. 01730.

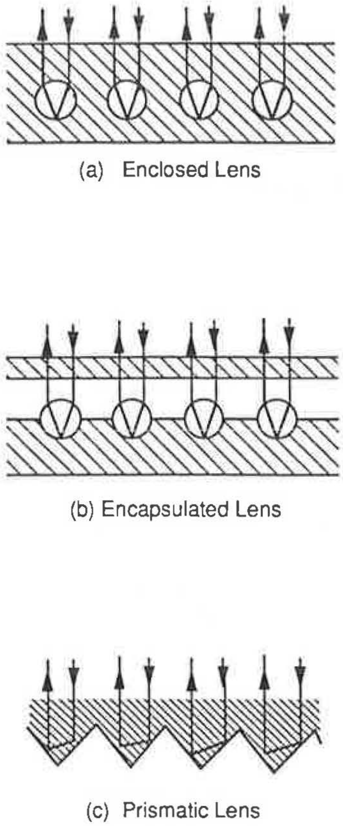


**FIGURE 1 Common retroreflective materials.**

where $I$ is the intensity and $d$ is the distance from the source to the detector (assuming that the source behaves as if it were a point). The intensity can be calibrated from laboratory measurements, while the distance can be measured using an appropriate laser ranging device. The reflected luminance can be measured with a luminance meter, which is similar to an illuminance meter except that the field of view (FOV) of the detector must be limited to a sufficiently small angle. The use of a video camera effectively divides the FOV defined by the system magnification into smaller FOVs, thereby creating individual luminance meters at each sensing element site. Video is a practical way of obtaining a large number of samples suitable for measuring average legend and background retroreflectances.

The video system takes advantage of the contrast that typically exists between legend and background, anticipating a "bimodal histogram." That is, the contrast difference allows the use of hardware or simple software algorithms to group areas of similar intensity, which usually correspond to legend and background. When the system is properly calibrated, the average value of each group corresponds to the average luminance. If the illumination is known, the retroreflectance can be readily obtained.

This is illustrated in the histogram plots of video imagery from an actual sign (shown in Figure 3). This sign image was digitized under outdoor conditions and illuminated directly using a slide projector. The histogram of the sign area is shown in Figure 4, plotted as relative number of image points versus reflected light intensity. The double peaks in the histogram correspond to the legend and background intensities.

## RESEARCH APPROACH

In this phase of the program, the critical factors involved in each of the key technology areas identified in the research proposal were studied:

- The use of a video camera to acquire a large number of sign samples,
- An electronic flash to provide sufficient amounts of light to overcome ambient sign luminance,
- Range measurement using a laser range finder to obtain distance to the sign, and
- Image analysis to evaluate the video image for average legend and background retroreflectance.

These concepts are summarized in Figure 5, in which a proposed system configuration is presented. A number of analytical studies were conducted in conjunction with labo-

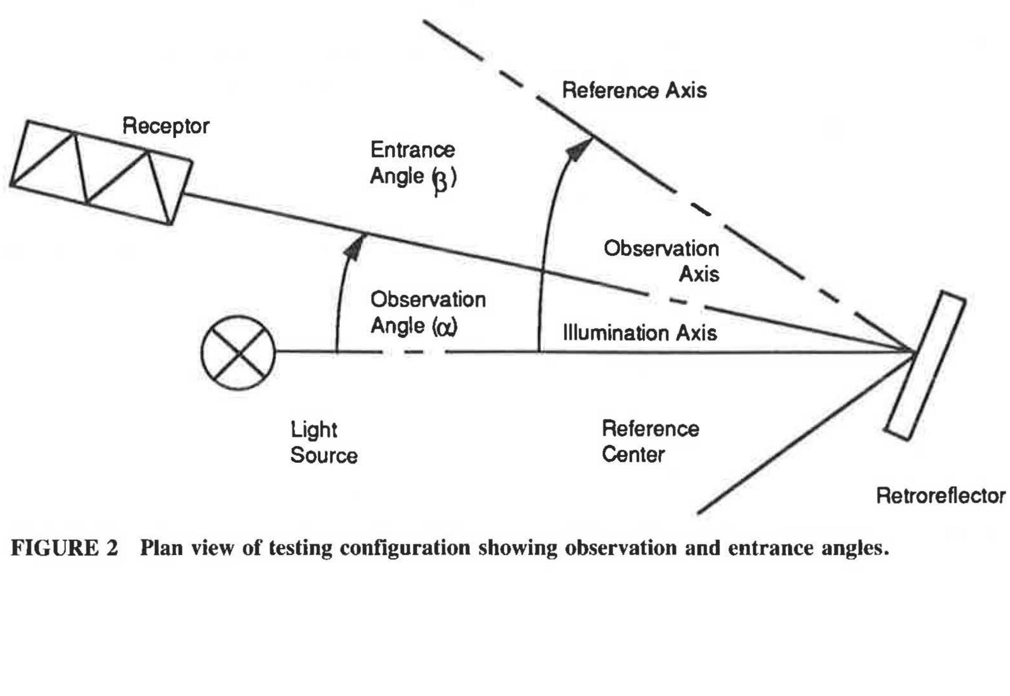


**FIGURE 2 Plan view of testing configuration showing observation and entrance angles.**


**FIGURE 3 Image of typical traffic sign with black legend on white background.**

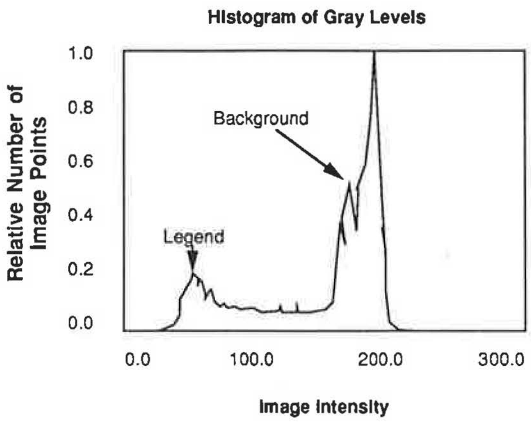


**FIGURE 4 Related histogram of image in Figure 3.**

ratory and field experiments. The results of these studies were then used to determine the required performance of each of the system components for use in the breadboard system.

The universal research tool for the laboratory and field studies was an IBM-compatible Compaq portable personal computer. Software was compiled to digitize video camera images and generate histograms of all or part of the resulting data.

### Ambient Illumination Effects

Since daylight measurements were required, it was necessary to either eliminate the effect of ambient illumination or reduce the effect to a point where it became tolerable with the desired accuracy of the measuring system. Retroreflective effectiveness is relevant over small observation angles, and published measurements typically give data to about 2°. However, retroreflective materials exhibit a small but appreciable coefficient of retroreflection at large observation angles. For instance, the $R'$ for enclosed-lens white materials is typically 100 to 120 at a 0.2° observation angle ($-4°$ entrance angle) but generally levels off to a value of approximately 0.3 at angles beyond 20°. Ambient illumination levels can be quite high, approaching 10,000 fc for combined sun and clear sky, effectively offsetting the low $R'$ value at large angles.

To determine the effect of ambient illumination on sign luminance, samples of white enclosed, encapsulated, and cube-corner materials were measured at various sun elevation angles. Measurements of sample luminance were taken with the plane of the material oriented vertically, but always in a direction facing the sun. The results are plotted in Figure 6. The data indicate that, at any given angle, the enclosed-lens white material has the maximum luminance, followed by the cube-corner and encapsulated materials. Also, the graph indicates that the sample luminance decreases with increasing solar elevation angle and exhibits a minimum as the sun approaches maximum elevation. Below 20°, the rate of change increases more rapidly. This should be expected since the sun is creating a smaller observation angle with respect to the detector. To minimize illumination requirements, it may be necessary to limit the measurement window to times when the sun is above a minimum elevation. Using a value of 20°, the ambient sign luminance is 2,500 cd/ft$^2$ for enclosed materials, 2,100 cd/ft$^2$ for encapsulated materials, and 2,300 cd/ft$^2$ for cube-corner (white) materials.

Additional data taken on an overcast day indicated a maximum sign luminance of 170, 140, and 204 cd/ft$^2$ for enclosed, encapsulated, and cube-corner materials, respectively. These values are much lower than the range of values recorded for full sunlight. Additionally, maximum sky luminance values of 825 cd/ft$^2$ for an overcast sky and 1,600 cd/ft$^2$ for a clear sky (near the horizon) were recorded. These are also lower than the sign luminance values for clear conditions. Thus, worst-case illumination requirements can be based on the clear sky data presented above.

### Measurement Geometry

Geometry is an important factor to consider when designing a system for measuring sign retroreflectivity under moving conditions. The geometries of concern are observation angle, entrance angle, and source/detector aperture size. In a system designed for in situ measurements, achieving a specific measurement geometry is straightforward. In a moving system, the geometric relationship between source, sign, and detector is constantly changing. This is important because all retroreflective devices do not behave the same as the geometry is changed.

A number of sources give the typical behavior of enclosed, encapsulated, and cube-corner retroreflective materials as a function of observation angle (*4,5*). Figure 7 shows the results of one study (*4*). These materials are highly directional upon retroreflection, with cube-corner materials the most highly directional, followed by encapsulated and enclosed materials. More important, from a measurement standpoint, the rates of change of these materials are significantly different, with cube-corner having the highest rate of change in the vicinity of a 0.2° observation angle, followed by encapsulated and enclosed-lens materials.

Assuming a fixed source-detector separation, the observation angle increases with decreasing distance to the sign. Realistically, the material of the sign will probably not be known, so, unless the angle is kept constant for all situations, it will be nearly impossible to relate the measured value to a commonly measured observation angle (such as 0.2°). To maintain sufficient accuracy, there is a "distance window" in

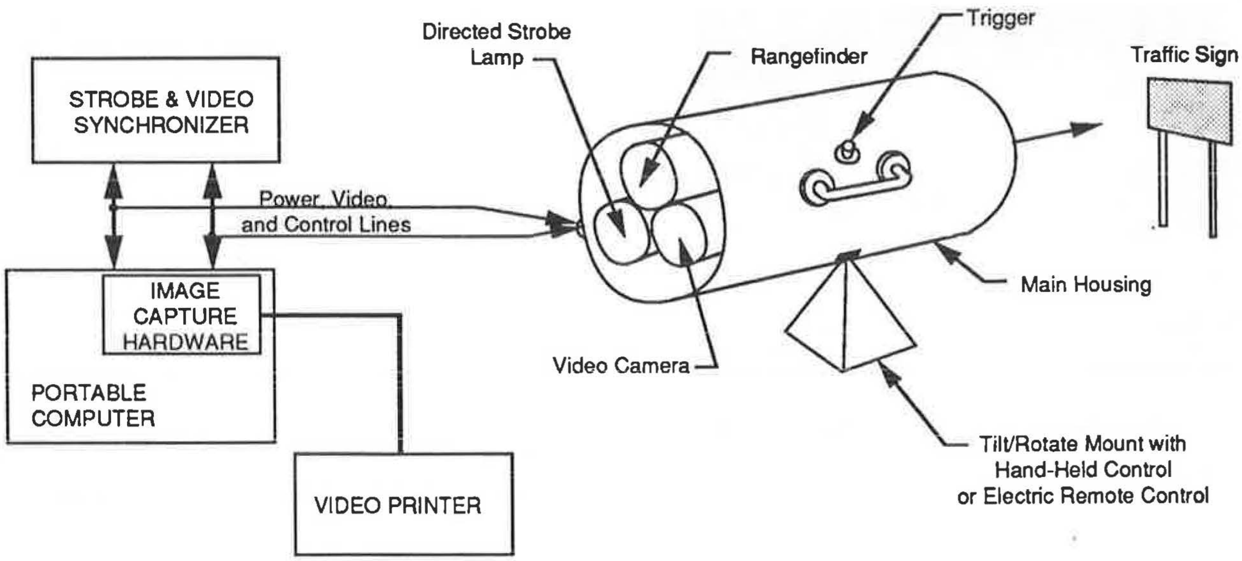


**FIGURE 5 Conceptual illustration of the basic components of the proposed MSMRTS system.**

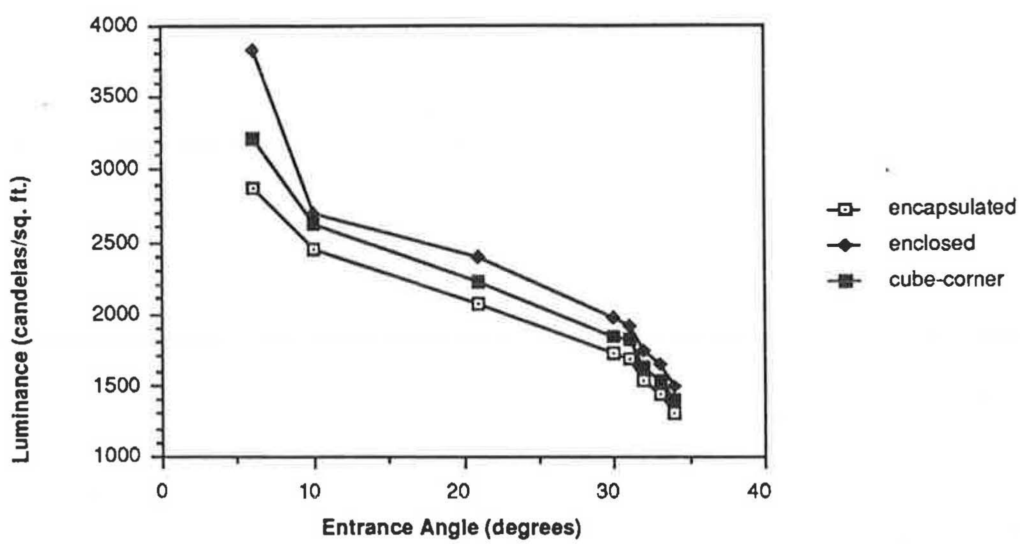


**FIGURE 6 Sign luminance versus solar elevation for enclosed, encapsulated, and cube-corner materials (white).**

which the measurements need to be taken, assuming a fixed source-detector separation. The size of this window may be influenced by the degree of collimation of the illumination system. If the illumination system is highly collimated, then the incident illumination at the sign will remain nearly constant with changes in distance, possibly requiring a relatively short distance window. For a completely uncollimated beam (point source), the illumination will vary inversely as the square of the distance. This will tend to compensate for the effect of the observation angle, resulting in the reflected sign luminance remaining constant over a longer distance.

The results of another study indicate that the effect of entrance angle is far less severe (*5*). In Figure 8, the reflected intensity falls by a worst-case approximation of 1 percent per degree to about 20° for cube-corner materials. In moving situations, it would be very difficult to measure this angle. It has been suggested that the video image be used to examine the perspective distortion of the sign image so an estimate of the entrance angle can be obtained, but this function would most likely require operator intervention and seriously limit data collection. However, the entrance angle of most signs at appreciable distances will be small, minimizing this effect. Since this angle will be the same for a measurement as for the driver, it will not be considered in the measurement system.

### Range Finder Accuracy

The use of a laser range finder is proposed to obtain sign distance information. The particular system under consideration uses a time-of-flight (TOF) method where short pulses of laser light, supplied by a laser diode, are sent out to the

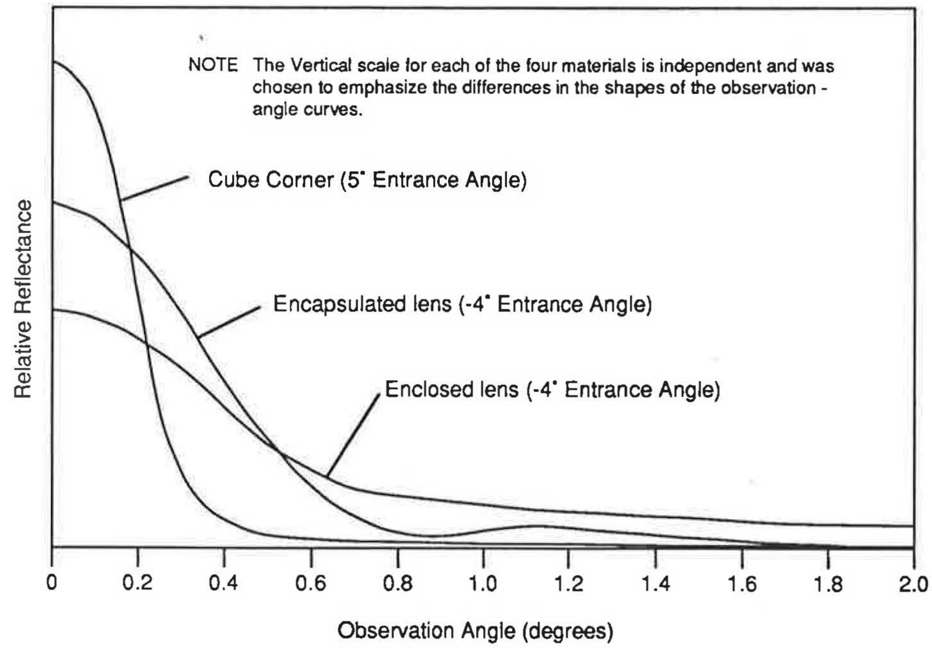


**FIGURE 7 Relative retroreflectance versus observation angle (*4*).**

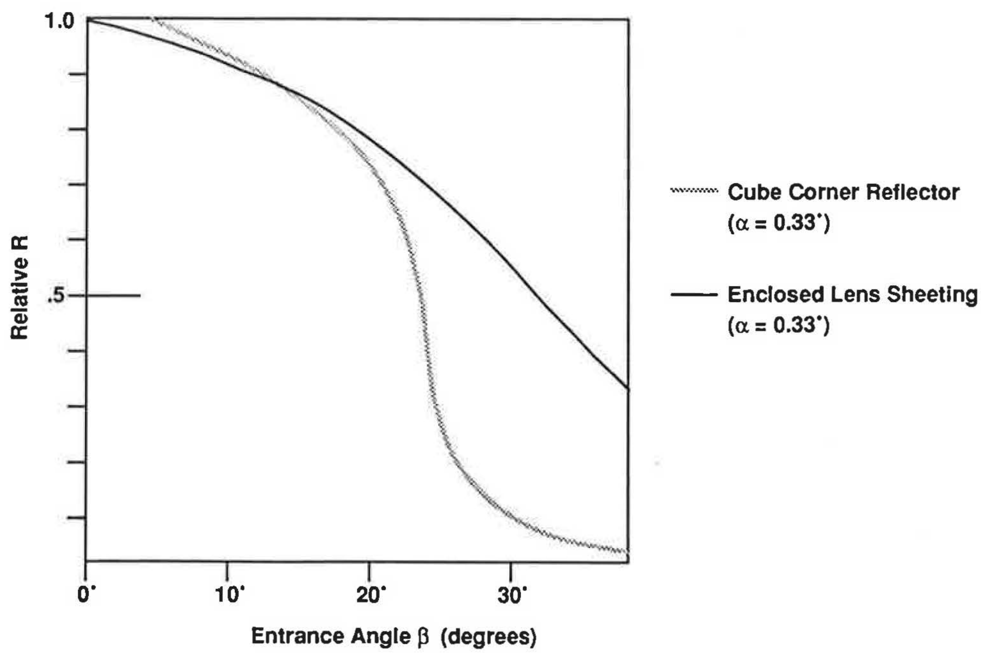


**FIGURE 8 Relative retroreflectance versus entrance angle (*5*).**

target. By measuring the time it takes to receive the returned pulse, and knowing the speed of light, the total round-trip distance can be calculated. This value is divided by two to obtain the actual distance to the target. One commercially available device has a sampling rate of 2,000 samples/sec. The unit can average a number of samples to obtain an accurate distance reading. The number of samples per reading is called the repetition rate. The data rate of the interface used to transfer the distance information limits the effective data transfer to approximately 133 readings/sec, or 15 samples/reading, with a net estimated accuracy of ±0.27 ft under stationary conditions.

Under moving conditions, the distance at which a reading is obtained represents an average value of the measured distance samples taken during the reading interval. This results in a systematic error of approximately half the distance traveled during this time. At a constant speed of 55 mph (81 ft/sec), and at 133 readings/sec, the resulting distance resolution is 0.60 ft/reading, with a systematic error of 0.30 ft. Coupled with the stationary sampling accuracy of the unit, the net distance accuracy would be 0.30 ft, ±0.27 ft. This results in a worst-case error of 0.3 percent at a 200-ft range and 0.6 percent at a 100-ft range. This should have a minimal effect on the resulting calculation of sign illumination from light source intensity.

## Intensity Requirements

For a uniform retroreflective target possessing a given luminance due to ambient illumination, the light source must provide an adequate amount of additional exposure above the ambient signal so that the retroreflection caused by the illumination system can be detected and isolated. This additional exposure factor can be denoted by a constant $K$. The value of $K$ determines the capability of the system to reject the sign luminance caused by ambient illumination. For example, a value of 20 implies a 20:1 ratio of artificial to ambient signal; hence, the measured data will have a 5 percent maximum error due to the presence of an ambient signal. The value of $K$ could be as high as the signal-to-noise ratio of the camera, typically 200:1 for charge-coupled device (CCD) cameras, but the additional demands required of the illumination system may not be realistic.

For electronic flash sources, the intensity is not constant over the duration of the flash. For this reason, it is customary to specify flash intensity in terms of an integrated value, denoted by $(It_f)$. The "intensity exposure" required to produce the necessary detection can be expressed as

$$(It_f) = \frac{K\, L_{amb}\, t_{cam}\, d^2}{R'} \qquad (\text{for } t_f < t_{cam}) \qquad (3)$$

where

$L_{amb}$ = maximum ambient sign luminance for a given material,
$t_{cam}$ = camera exposure time,
$t_f$ = flash lamp duration,
$d$ = distance to sign, and
$R'$ = coefficient of retroreflection for a given material.

The units for $(It_f)$ are in candela-seconds (cd-sec). To operate effectively with all materials, $(It_f)$ should be based on the retroreflective material (generally enclosed, encapsulated, or cube-corner sheeting) that produces the worst case, or largest value, of $(It_f)$. Equation 3 shows that $(It_f)$ is greatest when $L_{amb}$ is large and $R'$ is small. This occurs with the enclosed-lens material. $L_{amb}$ was chosen to be 2,500 cd/ft$^2$, based on the white enclosed-lens material (see Figure 6). Furthermore, to obtain accuracy over a reasonable range of retroreflection, the value of $R'$ was chosen to be the minimum recommended value corresponding to the enclosed white material, or 70 cd/fc/ft$^2$. Figure 9 shows the required exposure plotted against $K$ and $t_{cam}$, based on a 200-ft target distance. Assuming a $K$ value of 20 and a camera exposure time of 1 msec, the required value of flash exposure is 28,500 cd-sec, as long as the flash duration is less than the camera exposure time. From Equation 3, flash exposure is directly proportional to $K$, indicating that system accuracy will be sacrificed if the required quantity of light is not available.

## Electronic Flash

The advantage of the electronic flash is that large quantities of light are produced over short periods of time. Figure 10 shows an intensity profile for a typical flashlamp. For maximum efficiency, the flash duration should be less than or equal to the exposure time of the camera. For camera applications, flash duration is commonly defined as the time between the two points on the intensity-time curve that are at 10 percent of the peak intensity.

As Equation 3 indicates, exposure requirements are minimized when $t_{cam}$ is reduced. However, the flash exposure $(t_f)$ must be reduced as well. It would, therefore, seem desirable

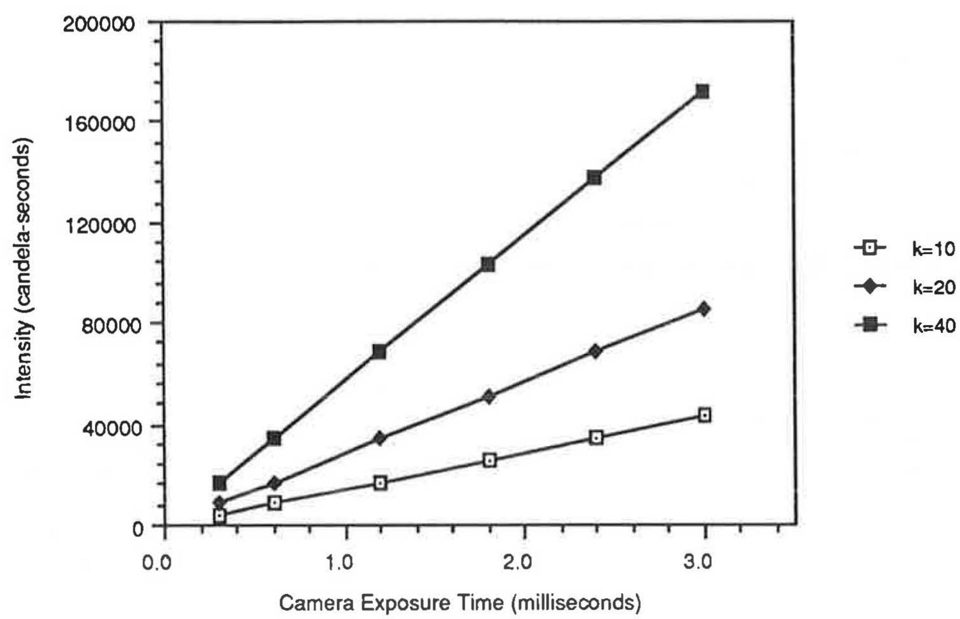


FIGURE 9 Exposure versus $K$ and $t_{cam}$.

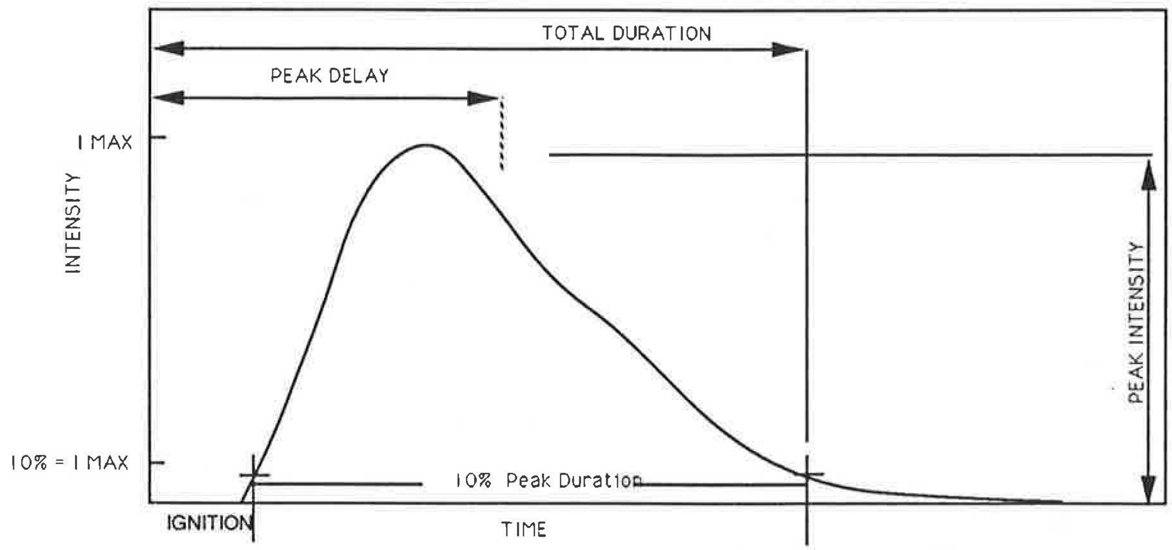


**FIGURE 10 Typical intensity-time profile of an electronic flash lamp.**

to reduce $t_{cam}$ as much as possible, but there is an optimum flash duration in which light output efficiency is maximized for a given flashtube design. The necessity for an appreciable quantity of light for this application will require long flash durations (estimated to be from 0.1 to 1 msec) but, in moving situations, the duration needs to be short enough to "freeze" the effects of image motion due to vibration. Actual exposure time requirements to compensate for vibration are not yet known. This may depend on the characteristics of the vehicle in which the camera is mounted. If the 1-msec time described above is not adequate to freeze the motion, the electronic flash can be optimized to operate at shorter durations. The distance covered during the 1-msec flash duration is calculated to be 1 in. at 55 mph and is expected to have little effect on the image.

One major manufacturer of electronic flash systems offers a commercially available unit for use as an obstruction warning light on tall towers and smokestacks. This system has a duration of approximately 1 msec in the high intensity mode and produces 40,000 cd-sec, nearly 40 percent greater than the 28,500 value described above. The spectral quality of electronic flash units is categorized in the daylight region of the spectrum, with typical color temperatures ranging from 5,000°K to 7,500°K, depending primarily on fill gas, pressure, and energy loading. The spectral power distribution of the typical xenon flashlamp ("high energy linear xenon") is shown in Figure 11. The output is nominally continuous, with a few spikes that may adversely affect color measurement accuracy. The unit uses a long linear flashtube in a trough-type reflector having a parabolic cross section and yielding a long, but nar-

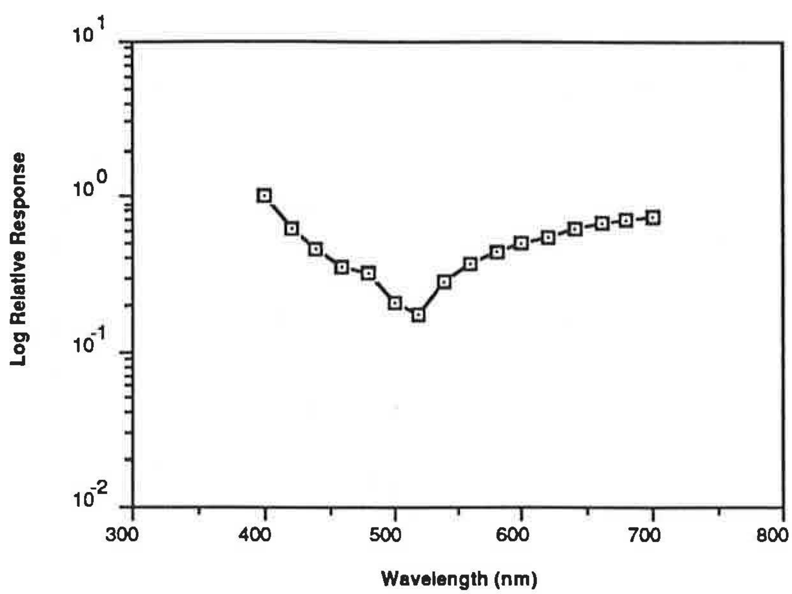


**FIGURE 11 Spectral distribution of xenon flash.**

row, beam profile (see Figure 12). In the more critical vertical direction, the total beam spread defined at the 90 percent points is approximately 2°.

## COMPONENT SELECTION

Based on the operational requirements presented above, a preliminary selection of components was made. These are categorized as follows:

- Digital frame capture,
- Directed strobe,
- Range measurement, and
- Digital conversion/image analysis.

### Digital Frame Capture

To satisfy the exposure requirements of this system, the use of a shuttered camera is recommended. An electronically shuttered camera having a 1/1,000 sec duration is commercially available. The camera uses a CCD area array measuring 8.8 mm × 6.6 mm (an aspect ratio of 1.33:1) with 491(H) × 384(V) pixels, a signal-to-noise ratio of 46 db (200:1), a sensitivity of 40 fc incident on a diffuse white target using a lens aperture of f/4.0, and a source color temperature of 3,200°K (with infrared cutoff filter). The camera has an automatic gain control (AGC) that can be disabled, which is desirable for this application. Additionally, the camera is RS-170 compatible, outputting two interlaced video fields (termed odd and even) in 1/60 sec, for a total frame time of 1/30 sec. The camera measures 5.5 in. × 2.5 in. × 3 in.

To facilitate synchronization of the camera to the flash unit, the camera has an output that indicates the vertical blanking signal. Also, the camera has an output port for a video CRT viewfinder. A color conversion filter to correct the spectral distribution of the flash to 2,856°K, and a filter to correct the camera response to a photopic behavior, will be attached to the front of the lens.

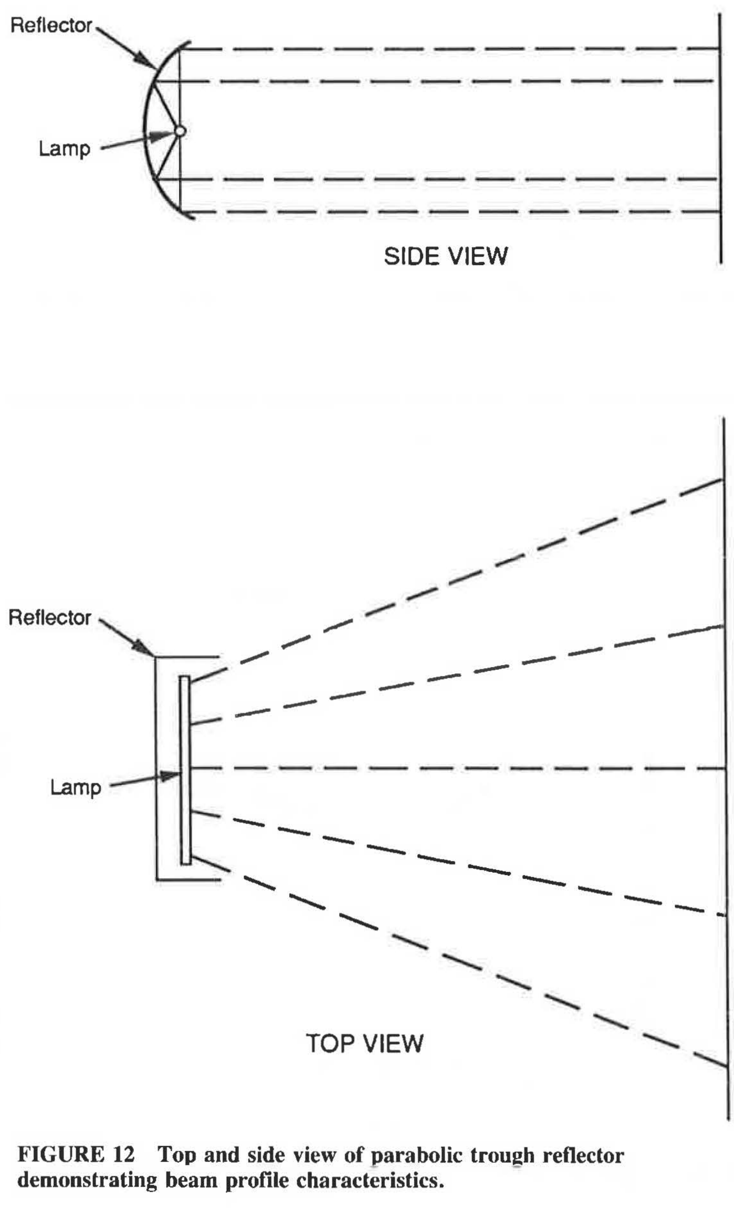


**FIGURE 12 Top and side view of parabolic trough reflector demonstrating beam profile characteristics.**

**Directed Strobe**

As discussed previously, a commercially available strobe unit is proposed. The reflector, lamp, and trigger transformer will be isolated from the power supply and fitted into a separate enclosure. The input to the supply is 120 VAC and draws 500 watts. Flash-to-flash variability is estimated to be within 5 percent. Production designs could include a flash monitor to mitigate this effect, if warranted.

**Range Measurement**

The proposed laser range finder is reported to be eye-safe and is expected to meet FDA approval. The device measures approximately 8 in. × 5 in. × 4 in. and weighs approximately 2 lb. Also included is an RS-232 port to trigger the device and transmit range data.

**Digital Conversion/Image Analysis**

A personal computer will be the essential link between the video camera, strobe, and range finder units. The computer used in this phase of the program will be one of a number of portable systems available commercially. This system will have a standard RS-232 port, which will be used to communicate to the range finder, a parallel port for a printer, and two floppy disk drives. A frame-grabber card will be installed to sample the analog signal from the camera, convert the signal to digital values, and store the data in memory on the board. This creates a digitized image of the desired video frame. Additionally, an output port is available to facilitate storage of the image on a video tape recorder.

Vertical blanking pulses are constantly sent by the camera so that a strobe triggered directly from this signal would flash constantly. A means of generating the strobe trigger only for the desired frame is required. To accomplish this, a strobe-video synchronizer circuit will be custom-built to monitor the status of the vertical blanking signal on the frame grabber (which is synchronous with the camera) immediately after the operator depresses a switch, and then fire the flash. A computer keyboard switch will be used for these experiments, and a trigger signal for the strobe will be issued at the computer's parallel port.

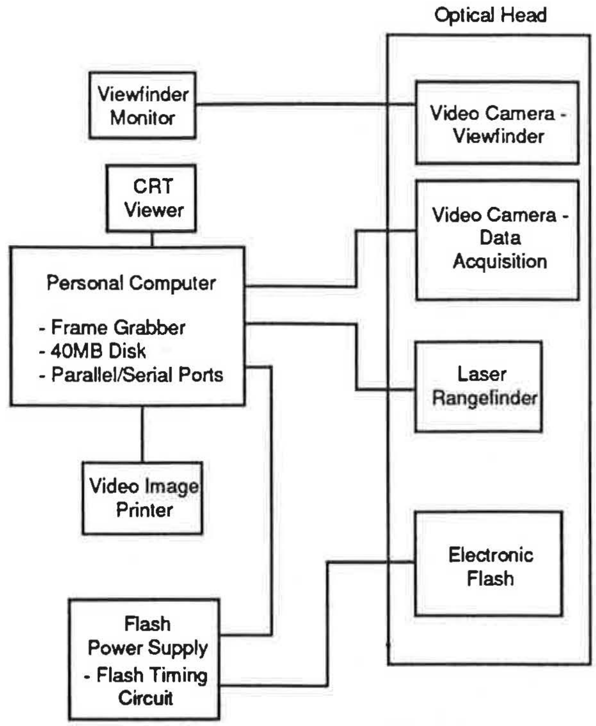


**FIGURE 13 Diagram of proposed MSMRTS breadboard.**

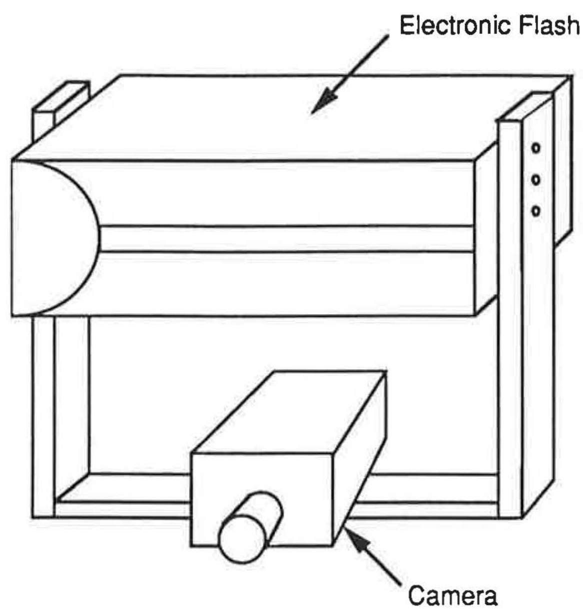


**FIGURE 14 Optical head concept for MSMRTS breadboard.**

## SYSTEM CONFIGURATION

The proposed breadboard components will be integrated as shown in Figure 13. This block diagram shows the location of the camera, electronic flash, range finder, and personal computer. Figure 14 shows a conceptual drawing of the optical head. The flash module, consisting of lamp and reflector, will be mounted above the camera and can be positioned at the height needed to obtain the correct observation angle for a given distance. For a 0.2° observation angle at 100 ft, the required separation from the camera centerline to the center of the reflector is 4 in. A bracket will secure both the camera and flash head as a unit. The power supply for the flash unit will be remotely located.

## SYSTEM ACCURACY

The results of this investigation generally indicate worst-case errors for the variables identified. These are summarized as follows:

| *Variable* | *Error (%)* |
|---|---|
| Measurement geometry | |
| Observation angle | 1–2 |
| Entrance angle | Up to 10 |

| *Variable* | *Error (%)* |
|---|---|
| Camera resolution | 5 |
| Ambient signal | 5 |
| Electronic flash | |
| Output variability | ±2.5 |
| Illumination uniformity | 0 |

Because these are worst-case errors, the average error will be much less than their sum. A more realistic assessment of measurement errors will be available by using the breadboard system to measure a large number of signs, then comparing that data with measurements made using traditional methods.

## CONCLUSIONS

The research and analysis presented in this paper indicate that an accurate mobile system for measuring the average retroreflectance of traffic signs during daylight hours is feasible. The conceptual design of the system is well suited for making measurements from a moving vehicle. The suggested components for this application are commercially available, minimizing the need for an extensive engineering effort.

The highest value of sign luminance due to ambient daylight conditions occurs with enclosed-lens sheeting. Under direct sunlight, the sign luminance is lowest when the sun elevation is highest and increases as the sun approaches the axis of the camera. If measurements are made when the sun is above an elevation angle of 20°, a realistic balance between required artificial source illumination and operational limitations can be achieved.

Under moving conditions, the angular geometry between the source, sign, and detector is constantly changing. The behavior of sign retroreflectance is highly sensitive to the angle between the source and detector (observation angle), and this behavior is markedly different among the types of materials currently available. If accurate measurements are to be made with respect to a given angular geometry, a fixed measurement distance is required.

The entrance angle (the angle between the illumination axis and the normal to the sign) has a minimal effect on measurement accuracy if this angle is small. This is expected to be the case if a sufficiently long measurement distance is used. Therefore, the entrance angle will not be measured.

Accurate distance measurements are required to determine the observation angle and infer the illumination at the sign with as little error as possible. Investigation into the use of a laser range finder indicates that a maximum distance measurement error of 0.3 percent at 200 ft and 0.6 percent at 100 ft is possible at a speed of 55 mph.

The intensity requirements of the electronic flash system are based on the amount of exposure needed to adequately exceed ambient sign luminance. For a maximum error of 5 percent, a flash intensity of 28,500 cd-sec is required for a camera exposure time of 1 msec. This maximum error is calculated for enclosed-lens materials that have deteriorated to minimum recommended values of retroreflectance. A commercially made electronic flash unit is available that produces 40,000 cd-sec for a duration of 1 msec and has a life expectancy of 100,000,000 flashes.

A system of components for creating a breadboard system is proposed. The components selected for the system are commercially available, thereby minimizing engineering costs. The breadboard consists of a compact camera, flash head unit, and range finder connected to a personal computer. The flash power supply will be remotely located. Additionally, a CRT viewfinder will be used to monitor and aim the system.

## ACKNOWLEDGMENT

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# Streetlighting Research Needs of U.S. Utilities

RICHARD E. STARK

**This paper describes the results of a survey to determine the streetlighting research needs of U.S. utilities. The survey involved 163 utilities belonging to the Edison Electric Institute and the American Public Power Association. The results of the survey were divided into three areas, covering theoretical research, equipment/product development, and information and technology transfer. Analysis of the responses indicated a substantial need for theoretical research in the areas of glare, driver visual requirements, and night accidents versus lighting studies to establish a firm basis for design standards. Equipment needs were many, beginning with operation of the high pressure sodium lighting system and covering a multiplicity of equipment problems. The area of information and technology transfer covered training and maintenance procedures as well as a variety of legal and other complaints regarding streetlighting. A great need for information transfer between companies is evident.**

In September 1986, the Lighting Research Institute (LRI) completed a study for the Electric Power Research Institute (EPRI) to determine the streetlighting research needs of U.S. utilities. LRI used a questionnaire approach to gain insight into the utilities' research needs. The questionnaire highlighted known problem areas and directed questions at specific needs as well as general concepts. One hundred sixty-three utilities belonging to the Edison Electric Institute (EEI) and the American Public Power Association (APPA) responded to the questionnaire. These responses produced a substantial amount of material regarding research needs. While there were some differences of approach between the two associations, the general trend was similar. This paper presents the totals of the associations' responses. An individual breakdown of the results can be obtained by contacting EPRI for a copy of the entire study (*1*).

The questionnaire covered four basic areas relating to utility research needs. It included internal concerns, external or outside influences, equipment, and certain specialty areas. Some questions addressed the technical depth of utility design techniques to determine if development of new techniques might be appropriate. Others were directed toward the research needed for product improvement.

Some overall conclusions can be drawn from this study that are not related to the detailed questions but are significant in terms of the utilities' needs. One of the greatest needs is better communication among the utilities. Many of the comments indicated a concern over problems that have already been solved by other companies or agencies in the streetlighting field. For example, some would like a simple computer program for design. These are available and are being used by various agencies. An interutility letter covering these and other questions would be a viable means of communicating those needs and solutions. A second area involves the inability to obtain quality equipment. Many utilities have similar operating problems, and a combined approach would strongly encourage the lighting industry to rectify these equipment problems. A third area is the almost total lack of research being conducted by utilities in the streetlighting field.

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## ANALYSIS OF QUESTION RESPONSES

### Internal

The internal area related to the utilities' administrative handling of streetlighting. It covered organization, training, maintenance, and design standards.

#### *Organization*

Figure 1 indicates that distribution engineers and district (or area) engineers handle the majority of utility streetlighting design. Marketing personnel (21 percent) are a significant factor, especially in EEI companies.

Approximately 30 percent of the utilities employ lighting specialists for streetlighting design. In 25 percent of those utility companies, the specialists set company-wide standards.

#### *Training*

The need for roadway lighting training is evident despite the fact that 26 percent of the utilities believe they have adequate programs. A need for better programs was expressed by 69 percent of the respondents. Of these, the preferred teaching methods were video cassettes (29 percent), text and visuals (28 percent), and a course conducted by lighting consultants (23 percent). Some suggested organizing low-cost seminars, both with and without manufacturer assistance.

#### *Maintenance*

Maintenance needs involve equipment as well as internal practices. Utilities generally want to know quickly when field equipment has failed. Figure 2a indicates that immediate or same-day knowledge of luminaire failure would be desired by over 40 percent of the utilities responding. It is evident (see

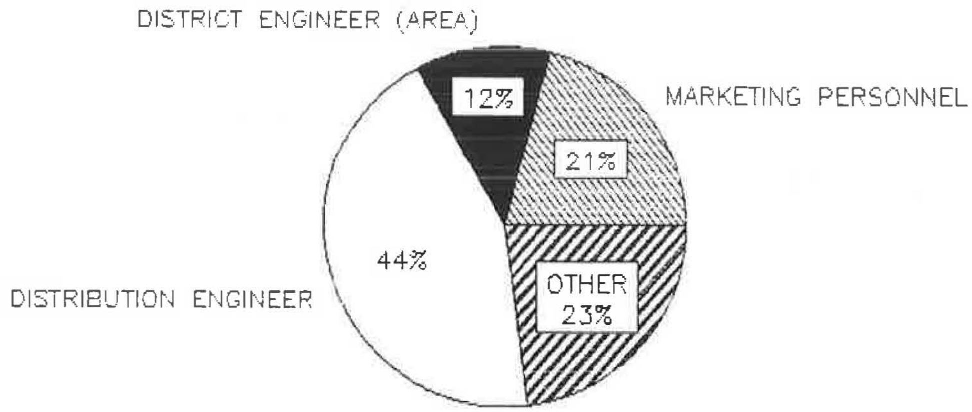



**FIGURE 1** Personnel involved in streetlighting design.

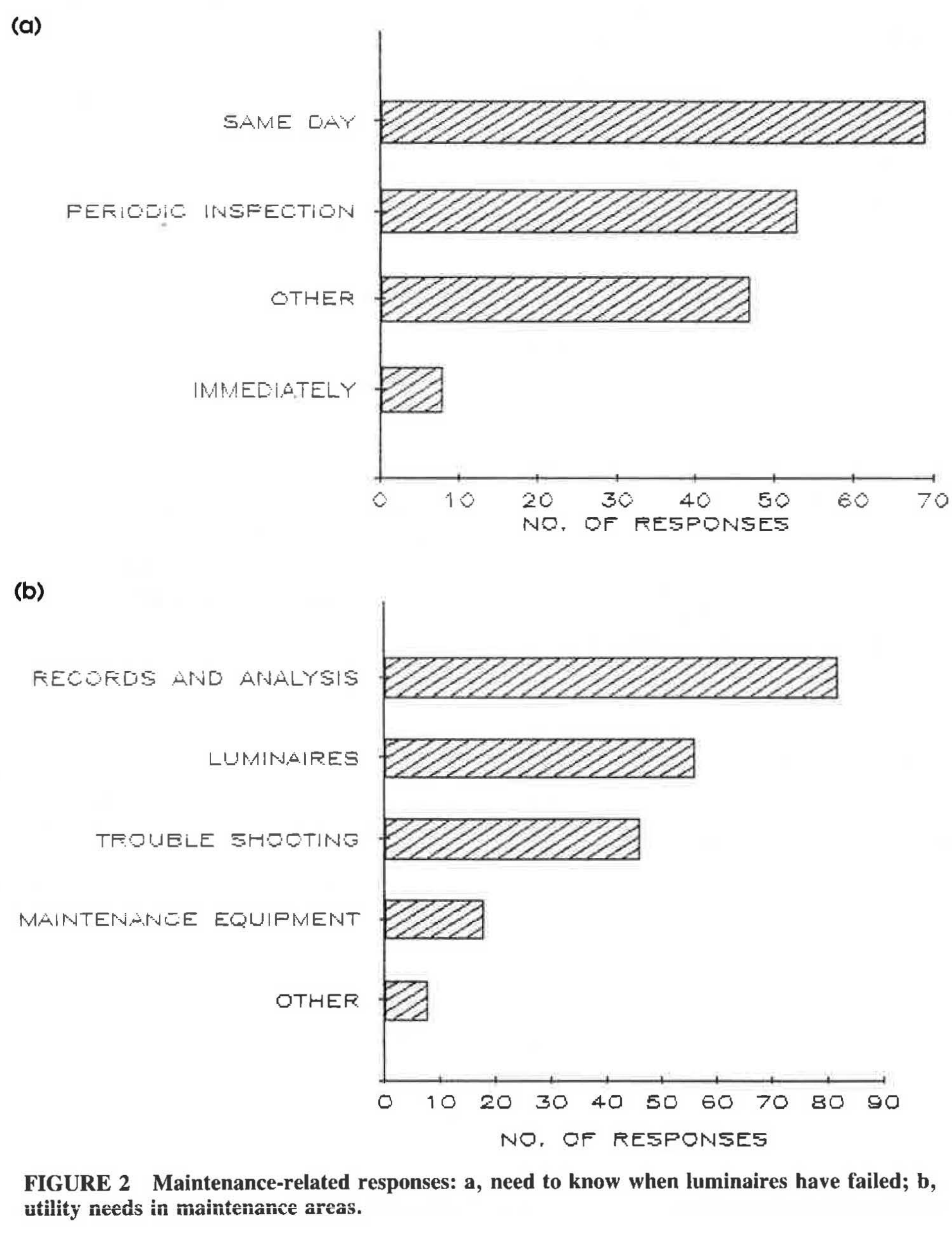



**FIGURE 2** Maintenance-related responses: a, need to know when luminaires have failed; b, utility needs in maintenance areas.

Figure 2b) that a great need exists in maintenance of records and their analysis.

### *Design*

Utility streetlighting designers use a variety of standards (see Figure 3). Use of the utility's own standard predominates, followed by government requirements. The American National Standards Institute (ANSI) usage is shown in Figure 4.

Utilities generally feel that no research is needed to support their own standards. However, if a simplified standard could be devised that was applicable at a majority of installations and had a firm research base, the utilities would likely be anxious to use it.

### External—Astronomical Interference

The utilities were questioned about their research needs from the standpoint of external influences. One problem, which affects some utilities quite severely, is that of astronomical interference. This is the difficulty that arises when uplight from streetlights causes sky glow and degrades the ability of astronomers to perform their space observations.

Thirty-seven percent of the utilities responding have observatories in their service areas, and 23 percent have received complaints of astronomical interference. The majority of complaints have been resolved by installing cut-off luminaires, physically shielding the luminaires, installing low pressure sodium luminaires, turning off or removing luminaires, and filtering.

Suggestions by utilities for research into astronomical interference could be grouped into the following categories:

- Study of the relative contribution of streetlighting, especially high pressure sodium, to astronomical interference;
- Study of the impact of reflected light in relation to direct uplight;
- Research regarding better optical systems;
- Study of sky glow; and
- Comprehensive study of the financial impact of providing systems with little or no uplight, the possible compromises or negotiable resolutions of this problem, existing research, and adequate roadway lighting levels that would reduce astronomical interference.

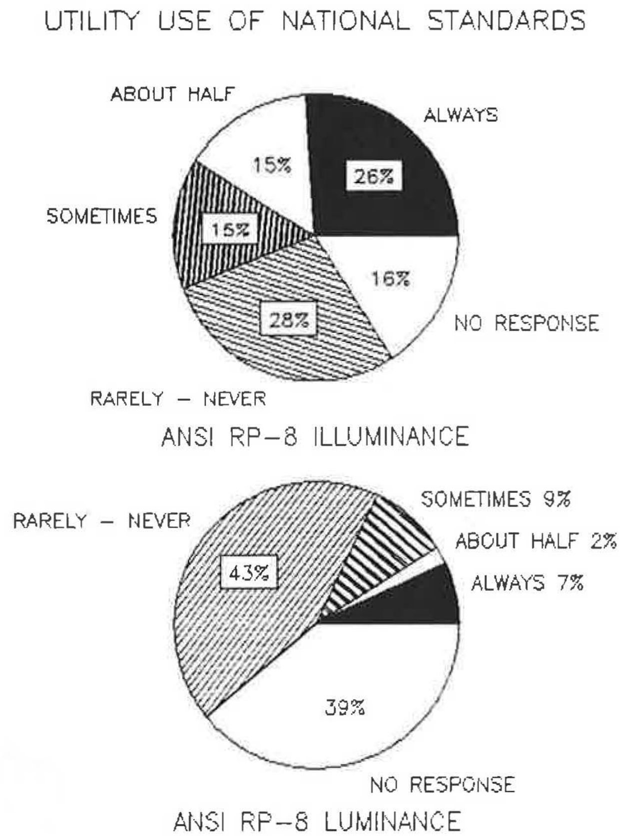



**FIGURE 4 Frequency of use of national standards.**

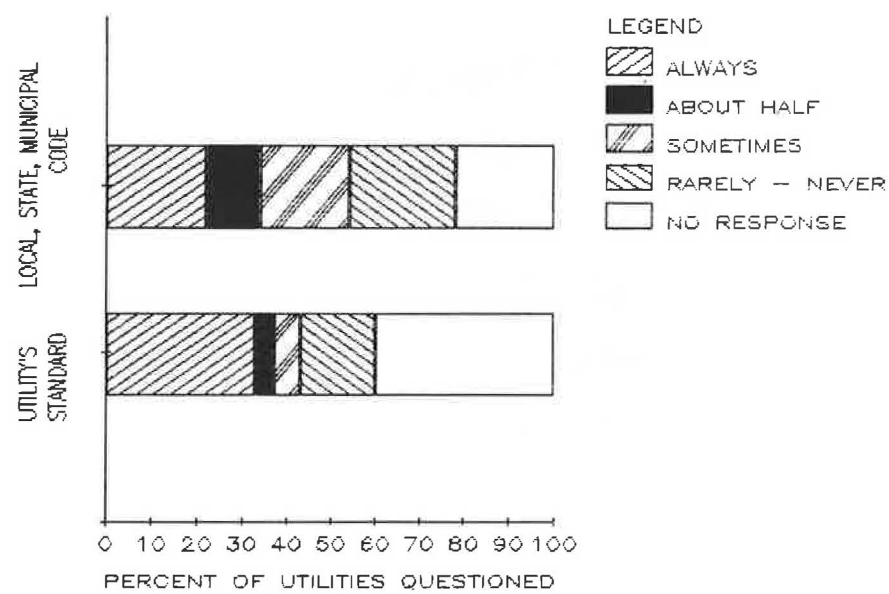



**FIGURE 3 Frequency of usage—two most-used standards.**

A number of other utilities are aware of this interference through various agencies; however, only 8 percent feel that astronomical interference is a problem and, in general, they give it a low priority for research.

## Equipment

### *Photo Controls*

The questionnaire investigated the concerns of utilities regarding the operation and reliability of lighting equipment and where they felt research was needed. One area explored was the need for research into photo controls. The utilities were asked whether there was a need for a more sophisticated control (one that could respond to visibility levels) or simply for improvement of the existing product. Interest in improving the existing control was substantially higher than concern for relating turn-on time to visibility or devising other methods of control. Figures 5a and 5b indicate the importance placed on the various control functions.

### *High Pressure Sodium Lighting*

One of the most significant concerns involved the use of high pressure sodium lighting. Fifty-three percent of the utilities found difficulty with this equipment. A breakdown of the responses by component is shown in Figures 6a and 6b. Starters and lamps obviously require the greatest research effort.

### *Low Pressure Sodium Lighting*

Only the APPA companies were questioned regarding the use of low pressure sodium lighting equipment. Forty-four percent of these companies have tested this equipment, and 26 percent have acquired it. Their evaluation of the factors influencing the use of low pressure sodium indicates that color is the most objectionable feature, followed by maintenance cost, expected life, and availability.

### *New Lamps*

The survey asked about the need for new light sources. The response did not indicate the need for a new type of lamp, but over 60 percent of the respondents desired field data on lamps as well as the current laboratory information. Seventy percent of the respondents felt that color was important.

Research suggestions on lamps were aimed at improving existing lamps in terms of life, color, starting, lumen maintenance, and so forth. There were some suggestions regarding

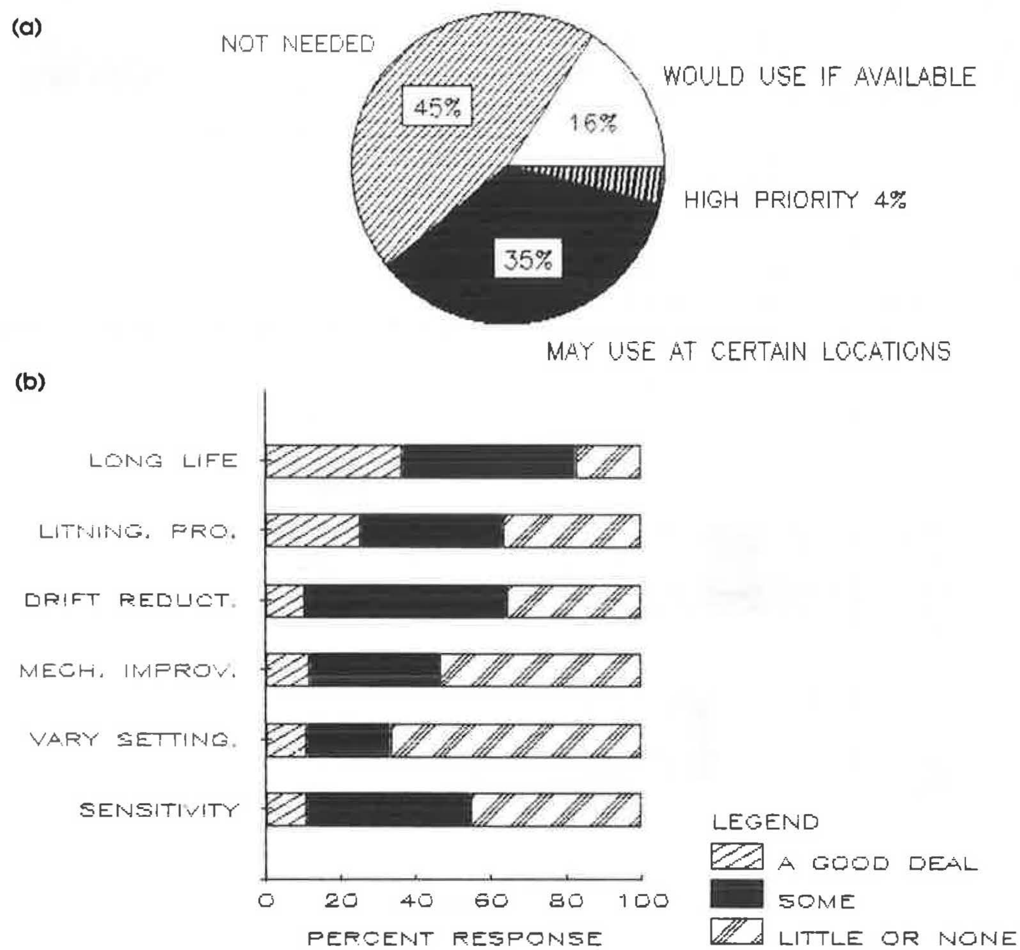



**FIGURE 5 Photo control needs: a, need for exact turn-on turn-off; b, amount of improvement needed for each function.**

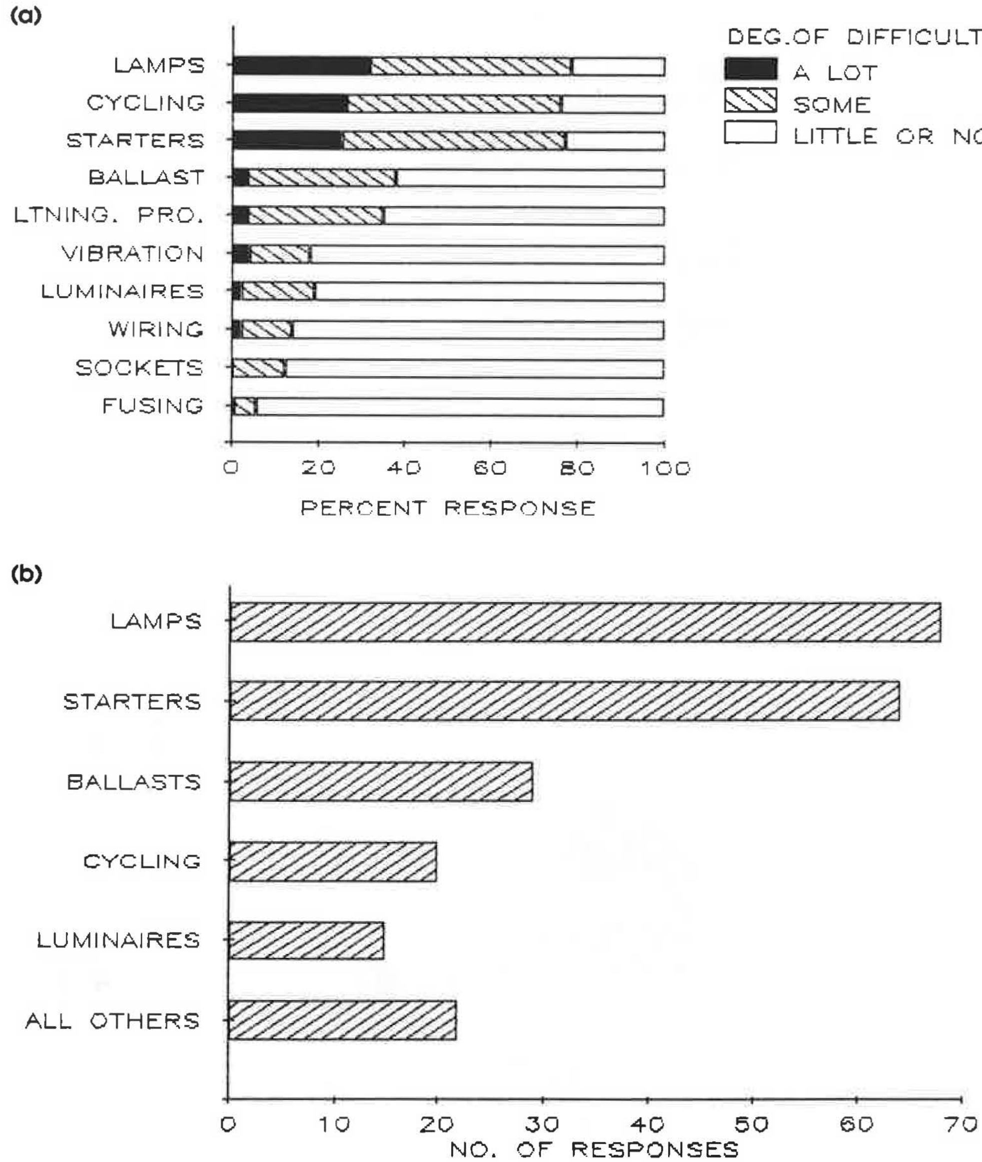



**FIGURE 6 High pressure sodium lighting: a, amount of difficulty for each component; b, components requiring greatest research effort.**

development of different wattages, such as a 600-watt or 750-watt high pressure sodium lamp to replace the 1,000-watt lamp.

### *Intersection, Residential, and Arterial Lighting*

Utility companies are substantially involved in the lighting of rural and suburban intersections as well as urban streets. Figure 7 shows that customer requirements are the most common method for determining design layout, although a variety of methods are utilized. As there are few computer programs available for this application, utilities have indicated a substantial need in this area.

Results for residential and arterial streetlighting were similar. Two factors weigh almost equally in the application of streetlighting to these areas: (a) the requirement of the residents (customers), and (b) the types of equipment available.

Figure 8 indicates the underlying reasons for the installation of streetlighting. These categories reflect the customers' needs in bringing their requests to the companies.

### *Light Trespass*

An area of growing concern for all street or roadway lighting agencies is that of light trespass (unwanted stray light). The number of complaints received by utility companies over a 5-year period are indicated in Figure 9. One company reported over 100 complaints during this time.

Not all of the complaints were due to streetlight equipment. Equipment represents only 20 percent of the cause of stray

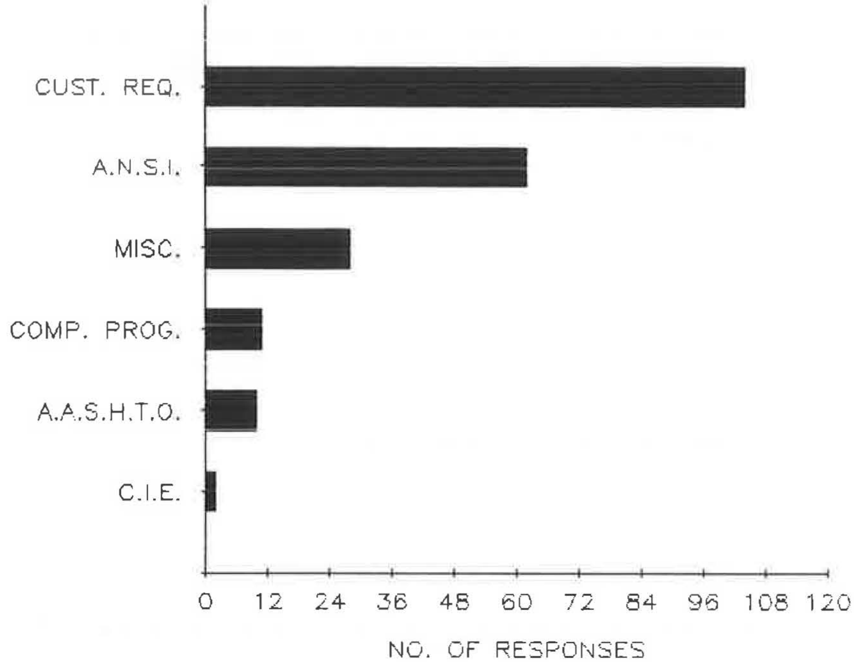



**FIGURE 7 Techniques currently used for intersection lighting design.**

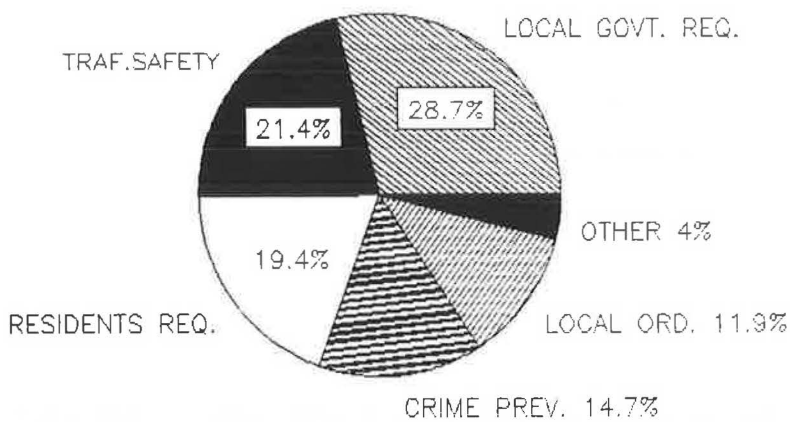



**FIGURE 8 Items influencing the installation of streetlighting.**

light problems but is involved in about 50 percent of all complaints.

The utilities have been diligent in responding with positive action in more than 90 percent of the light trespass complaints. The types of corrective actions are indicated in Figure 10.

### *Vandalism*

While light trespass concerns required the utilities to respond to public complaints, the problem of vandalism requires the utilities to respond to irresponsible public damage. For some utilities, vandalism is severe; for others, it is relatively minor. Figure 11 indicates that there are three peak areas in the percentage of system vandalized. The largest number of companies have between 0 percent and 2 percent vandalism, the second highest group between 4 percent and 6 percent, and the third between 8 percent and 13 percent.

Several methods were proposed to deal with this problem. While a number of suggestions involved new or different products, improved material, and a more sophisticated psychological approach, it is important to note that many felt the problem of vandalism is unsolvable. Some offered excellent suggestions; others asked for help. This indicates a strong need for interchange on the part of the utilities.

### *Legal Involvements*

Legal involvements have become increasingly significant over the past several years. Of the utilities that responded, 35 percent to 43 percent experienced streetlighting legal prob-

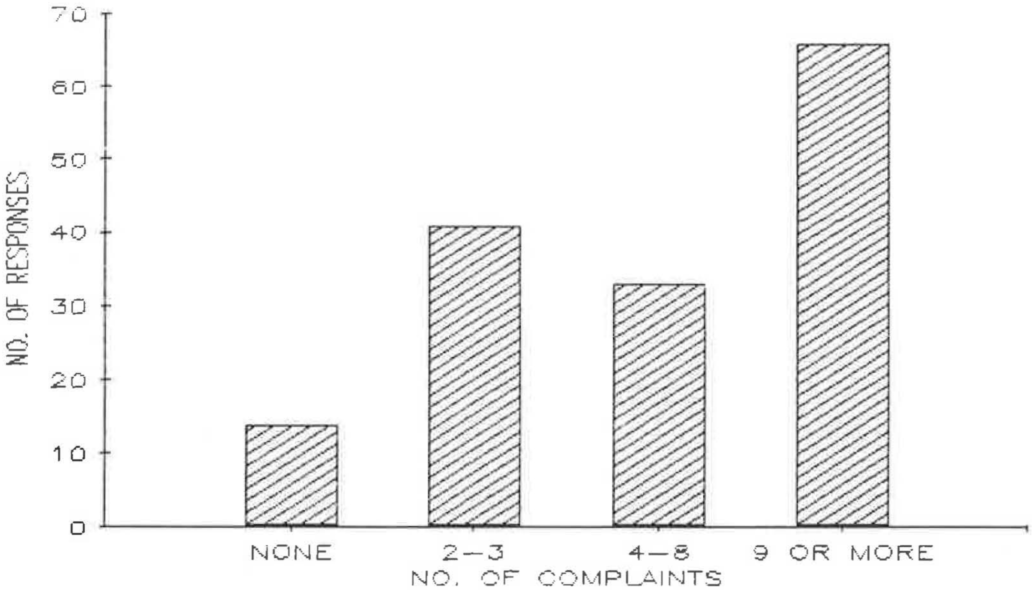



**FIGURE 9 Light trespass complaints over past 5 years.**

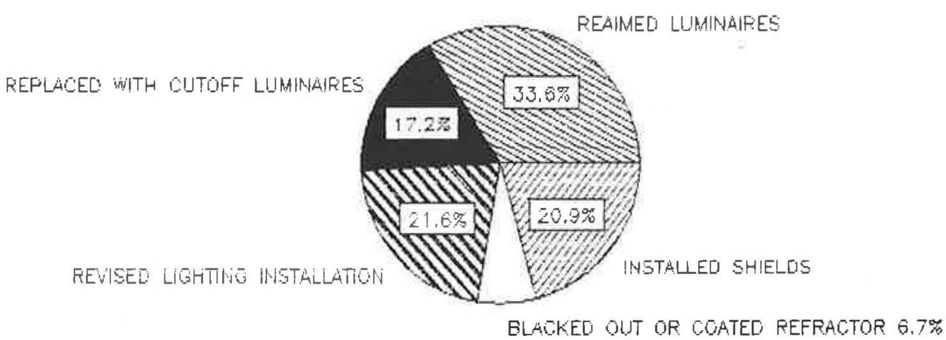



**FIGURE 10 Actions taken on light trespass complaints.**

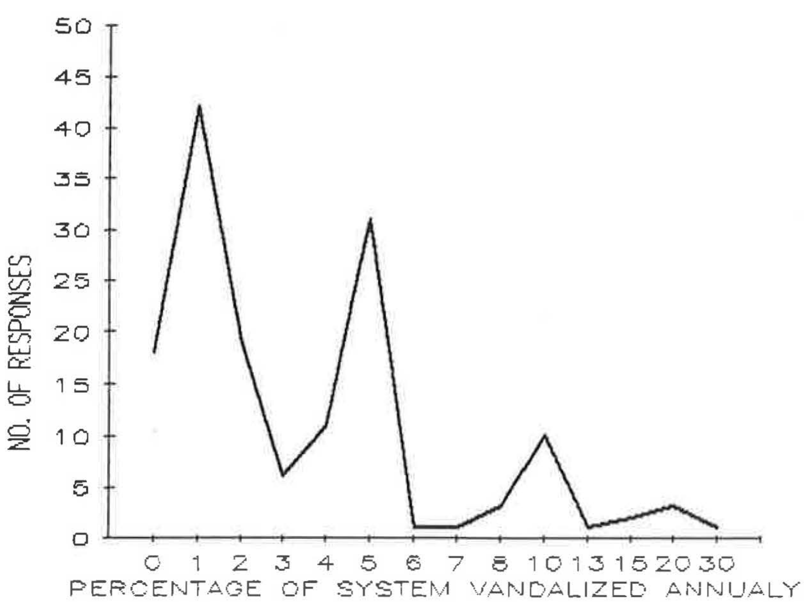



**FIGURE 11 Percentage of roadway lighting system vandalized.**

lems over the past 5 years, and about one-fourth of these involved design standards.

Approximately 24 percent of the utilities need expert testimony in lawsuits. The research requests urge the adoption of a better communication system among utilities regarding streetlighting legal matters.

Two other research areas suggested were the effectiveness of standards and the utility's liability when installing according to the design of others. A number of other legal responsibility questions need to be researched and solved.

### Reduced Lighting

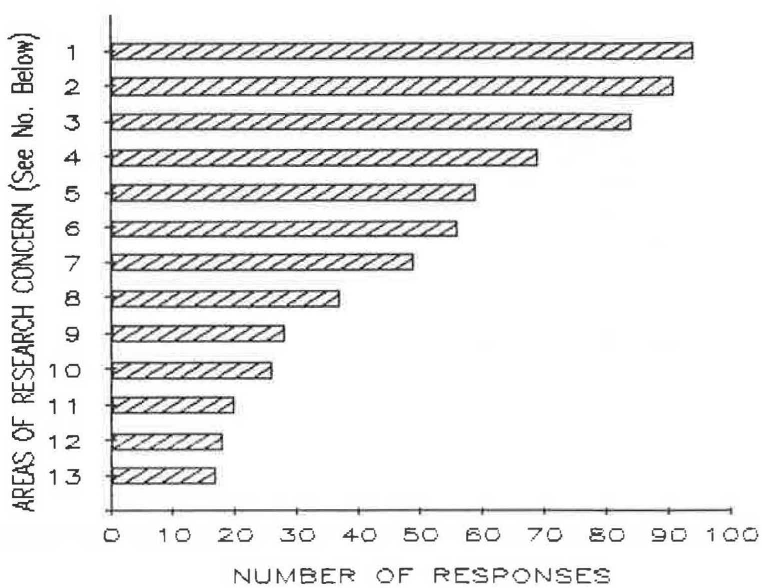
Another area of concern is reduced lighting during specific hours. The response indicated that less than 15 percent of the utilities provide other than dusk to dawn lighting, and most of that involves 24-hr lighting for underpasses and tunnels. Less than 5 percent provide reduced lighting or turn-off situations. About 20 percent of the utilities have received requests from various governmental agencies to reduce lighting during specific hours. While these requests may be based on the governments' need to cut costs, they do raise an important question. How far should the utilities reduce visibility, and its safety benefits, for the purpose of energy conservation or cost reduction? Research is needed to answer this and many other questions on reduced lighting.

### Theoretical Lighting Research

Figure 12 gives responses to the survey question devoted solely to the various areas of theoretical lighting research. Discomfort glare is emphasized, as it was throughout the survey wherever the matter of glare was addressed. The second and third preferences—driver visual requirements and night accidents versus lighting studies—indicate a desire to justify lighting standards. Results of these types of studies should resolve levels of lighting as well as some of the legal problems.

## Specialty Areas

The questionnaire covered items such as high mast lighting, tunnel lighting, breakaway devices for light poles, and other components of lighting systems that are not common to most




| Area Number | Area of Research Concern |
|---|---|
| 1. | Discomfort glare |
| 2. | Driver visual requirements |
| 3. | Night accident versus lighting studies |
| 4. | Pavement reflectance |
| 5. | Interaction of vehicle and fixed lighting |
| 6. | Color rendition necessary for peace officer (police identification) |
| 7. | Visibility contrast method C.I.E. 19/2 |
| 8. | Transient adaptation |
| 9. | Dark focus - Night Myopia |
| 10. | Determine critical visual elements by studying near accidents |
| 11. | Driver decision making process |
| 12. | Who is the night driver? |
| 13. | Use of parking lights for urban environment |

**FIGURE 12 Theoretical lighting research survey responses.**

of the utility companies. In general, the utilities were involved through maintenance agreements with other agencies.

### *High Mast*

Of the utilities responding, 29 percent indicated that they install or maintain high mast lighting. Of those, 31 percent cited a need for better overall component design, and 33 percent indicated a specific need for improved lowering or mechanical support systems.

### *Tunnel Lighting*

Tunnel lighting is installed or maintained by less than 16 percent of the respondents. Only 10 percent are involved in the design process. Of those polled, 20 percent agreed that there is a need for new tunnel lighting criteria, but there was no strong preference as to what areas needed improvement. Research suggestions concentrated on the need for better maintenance techniques and worker-safety provisions.

### *Luminaire Supports*

Information gathered regarding problems with luminaire supports is valuable and should be considered by the utilities. The need for research into breakaway devices is strong. A number of research suggestions involving product improvements in such areas as strength, durability, vibration resistance, and liability need to be considered to improve the design of luminaire supports and their application to streetlighting projects.

## CONCLUSIONS

The findings of this survey can be divided into three basic categories:

1. Theoretical research,
2. Equipment/product development, and
3. Information and technology transfer.

The particular areas that fall into the above categories can be given a high, medium, or low priority, depending on the utility response.

### Theoretical Research

Theoretical research needs in streetlighting are best documented by Figure 12. There are, however, many places in the survey where specific needs were suggested. The four areas of high response were

1. Discomfort glare,
2. Driver visual requirements,
3. Night accident versus lighting studies, and
4. Pavement reflectance.

Theoretical research needs also include the special visibility requirements of intersection lighting involving complex dynamic movement of objects in the visual scene. This area rated a medium priority, as did the daylight entrance zone visibility requirements of tunnel lighting. Reduced lighting during off-peak or other hours also rated medium priority. The nature of astronomical interference requires major investigation and appears to be a serious problem for astronomers. This area does not affect the majority of utility companies and therefore received a low priority rating.

### Equipment/Product Development

High priority must be given to the operation of high pressure sodium lamps. Lamp field data to compare with published laboratory results and research to improve lamp auxiliary operating components received a strong response. Interchangeability of starters and lamp cycling were frequently mentioned as needed improvements. The entire high pressure sodium system is a high priority in terms of equipment improvement.

Luminaire supports using breakaway devices are also a high priority area. There is considerable controversy over the use of the equipment and problems with the failure mode. A more reasonable and definite standard is required.

Research to improve life and color of the high pressure sodium lamp was requested wherever there was discussion on lamps. It was classified as a medium priority based on the responses received, as was luminaire optical control. A luminaire is needed that will distribute light to avoid glare and still provide economical unit spacing.

Vandal-proof equipment was a medium priority item in terms of the number of companies involved; however, with some companies it is a serious problem.

Photo control component improvements, such as longer life, received a good response, but a more sophisticated visibility-related control was given low priority. Alternative control methods were shown to have some, but little, need.

### Information and Technology Transfer

Highest priority ratings were given to updating maintenance procedures and roadway lighting training. This is despite the fact that many companies had updated maintenance procedures and conducted training in roadway lighting. The area of greatest concern for maintenance is that of records and system analysis. Personnel training in all aspects of roadway lighting was given a strong response.

Legal responsibility was also a high priority, especially in the area of information transfer, which was suggested by respondents several times. The number of lawsuits is growing, and the utility liability responsibility must be defined. There is a need to know what other companies are doing or have done in regard to these legal matters. Reduced lighting also has some legal ramifications.

Design aids are on the high priority list both by response to questions and by inclusion in the general category of suggested research responses. A simplified research-backed method of designing lighting is needed.

TABLE 1 RESEARCH PRIORITIES

| Priority | Item | Research Areas |
|---|---|---|
| Theoretical Research | | |
| H | Theoretical lighting research | Discomfort glare, night accident studies, driver visual requirements, pavement reflectance |
| M | Reduced lighting implications | Effects of reduced lighting on visibility and accidents |
| M | Intersection lighting | Study of complex movements to determine best visual scene |
| M | Tunnel | Daylight entrance zone |
| L | Astronomical interference | Define and recommend solutions |
| Equipment/Product Development | | |
| H | High pressure sodium lamp operation | Research to improve starters and ballasts and eliminate cycling |
| H | Lamp field factors | Comparison of field operation with published laboratory results |
| H | Luminaire supports | Breakaway or slip base research |
| H | High mast | Lighting design criteria; lowering equipment |
| M | Luminaire optical control | Research to reduce glare and improve beam pattern and efficiency to obtain better spacing-to-mounting-height ratio |
| M | High pressure sodium lamps | Research to improve life, color, etc. |
| M | Vandalism | New approaches to deter; tougher equipment |
| L | Photo controls | Improved quality, reliability, life, and variability of setting |
| Information and Technology Transfer | | |
| H | Maintenance procedures | Detailed study and procedures update; programs for system analysis, records, etc. |
| H | Roadway lighting training | Comprehensive training course using text and visuals, video cassette, or lighting consultants |
| H | Design aids | Computer programs; design standards (intersections, arterials) |
| H | Legal responsibilities of utility | Liability for design; installation according to others' designs; validity of standards |
| M | Luminaire maintenance | Techniques |
| M | Trespass lighting | Solutions to problem caused by roadway or commercial lighting |

NOTE: H = high priority; M = medium priority; L = low priority.

A medium priority status was given to trespass lighting. This problem seems to be resolvable in most instances, although the problem is growing and there is a trend toward ordinances in this area. A study of principles and methods of control is required.

Finally, in Table 1, research priorities are assigned as high, medium, or low based on the responses of the public and private utilities. Some of these needs are being addressed, but a good deal of research must be initiated to find answers to many others.

## REFERENCE

1. M. Savitz, R. Stark, and R. Vincent. *Development of Streetlighting Research Plan.* Final Report EPR. Lighting Research Institute, New York City, Feb. 1986.

# Effects of Asymmetric Distributions on Roadway Luminance

HERBERT A. ODLE

**The current recommended practice (ANSI/IESNA RP-8) calls for uniform luminance on the roadway surface. This paper summarizes the results of an investigation to determine the effects on the luminance-producing ability of luminaire distributions as various distribution factors were changed while other variables were held constant. It was concluded that (a) the luminance-producing ability of the distribution increases as the vertical angle of the beam maximum increases; (b) in a bidirectional distribution, the maximum luminance-producing ability was obtained when the luminaire, the point to be lighted on the roadway, and the driver were all in line; (c) as the lateral angle of the beam maximum decreases, the luminance-producing ability of the system decreases; and (d) the luminance-producing ability of light toward the driver is much greater than that of light away from the driver (as much as 10 times under certain circumstances), which makes a "counterbeam" system practical.**

Before 1983, horizontal illuminance (the amount of light falling on a square unit of horizontal roadway surface) had been the main criterion for roadway lighting in North America. Since that time (and much earlier in Europe), the preferred method has been to light the roadway surface in such a way that the driver sees a uniformly lighted roadway. This method, known as uniform luminance, is specified by *ANSI/IESNA RP-8* (*1*). The rationale for this recommendation is that a uniformly lighted roadway is the best way to reveal objects on the roadway. The objects are revealed in silhouette, with a dark object on a light background.

This theory has several flaws, including the following:

- Headlights from the driver's vehicle "fight" with this system by lighting up the object, which changes the seeing condition to reverse silhouette (with the object brighter than the background).
- On a busy highway, the driver mostly sees the backs of other cars rather than the roadway surface.

Some experts argue that roadway luminance is good but should not be uniform (in other words, it should have bands of light and dark).

The luminance concept causes some design complications that do not exist with illuminance. For example, the observer location, the lightness of the roadway surface, the reflection characteristics of the roadway surface, and the system layout geometry must be considered. Therefore, a computer is necessary to deal properly with the increased number of variables and the complexity of the calculations.

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More important, however, is the need for the lighting system designer to choose the optimum luminaire distribution for each situation. This is not an easy task; it is not always obvious which way the distribution variables should move to achieve the desired results. In addition, because the variables are interactive, optimizing one variable may be disastrous to another. Optimizing the many variables is a serious problem for the luminaire designer, who attempts to produce the ideal luminaire distribution to gain the maximum luminance per watt of electricity.

Nevertheless, *ANSI/IESNA RP-8* calls for uniform luminance on the roadway surface, so this investigation was conducted to determine the effects on the roadway luminance-producing ability of luminaire distributions as various distribution factors were changed while other variables were held constant. It is emphasized that this investigation did not try to optimize all variables or predict what the various changes would do to all variables. Only the effects on pavement luminance were considered.

## VARIABLES INVESTIGATED

The following variables in the distributions were changed over as large a range as available photometric data would permit (while holding all other variables constant):

- Vertical angle of beam maximum (max),
- Lateral angle of beam max, and
- Effect of moving the luminaires off the roadway.

Most of the photometric data were on conventional bidirectional luminaires with the upstream and downstream beams symmetrical (the same maximum candela, same vertical angle of beam max, and same lateral angle of beam max). Other distributions were investigated as follows:

- Conventional symmetrical bidirectional;
- Bidirectional with the upstream and downstream beams being drastically different (counterbeam): (a) with a strong beam in the direction of driver motion and (b) with a strong beam against the driver; and
- Unidirectional lighting: (a) with the direction of driver motion and (b) against the driver.

Also investigated was the nature of the bidirectional reflectance characteristics of the typical pavement surface (an asphalt surface designated in *ANSI/IESNA RP-8* as an "R3" surface).

## PAVEMENT REFLECTANCE CHARACTERISTICS

Pavement reflectance characteristics are critical for producing luminance. Therefore, they are explored in some detail in this paper. First, however, a diagram of reference angles is explained along with a definition of how pavement luminance is calculated.

If Figure 1 is used as a frame of reference, then roadway luminance at point $P(L_p)$ with respect to the observer (driver) can be defined as

$$L_p = \frac{1}{\pi} \times \frac{q(B,Y) \times \cos^3 Y \times I_p(B,Y)}{H^2}$$

where

$q$ = pavement reflectance at the point,
$I_p$ = candlepower from a luminaire to the point,
$H$ = mounting height of the luminaire, and
$\pi$ = 3.14159.

Luminances at point $P$ on the pavement surface would then be a summation of $L_p$ from all luminaires in the system.

The R tables in *ANSI/IESNA RP-8*, such as R3 for asphalt (*1*,p. 29), take a portion out of the above equation and multiply all numbers by 10,000 as follows:

$$\text{R-table} = q(B,Y) \times \cos^3 Y \times 10{,}000$$

so that the simplified luminance calculation is

$$L = \frac{1}{\pi} \times \frac{\text{R-table}}{10{,}000} \times \frac{I}{H^2}$$

Figure 2 shows a plot of the R3 table in terms of iso-coefficient lines and illustrates the directionality of pavement reflectance.

### Luminance Production Versus Vertical Angle of Beam Max

The R3 table is reproduced in this paper as Table 1. The first column is in a longitudinal vertical plane parallel to the roadway direction. If that column is plotted, the values peak out at about 45° vertical (see Figure 3). This may be somewhat

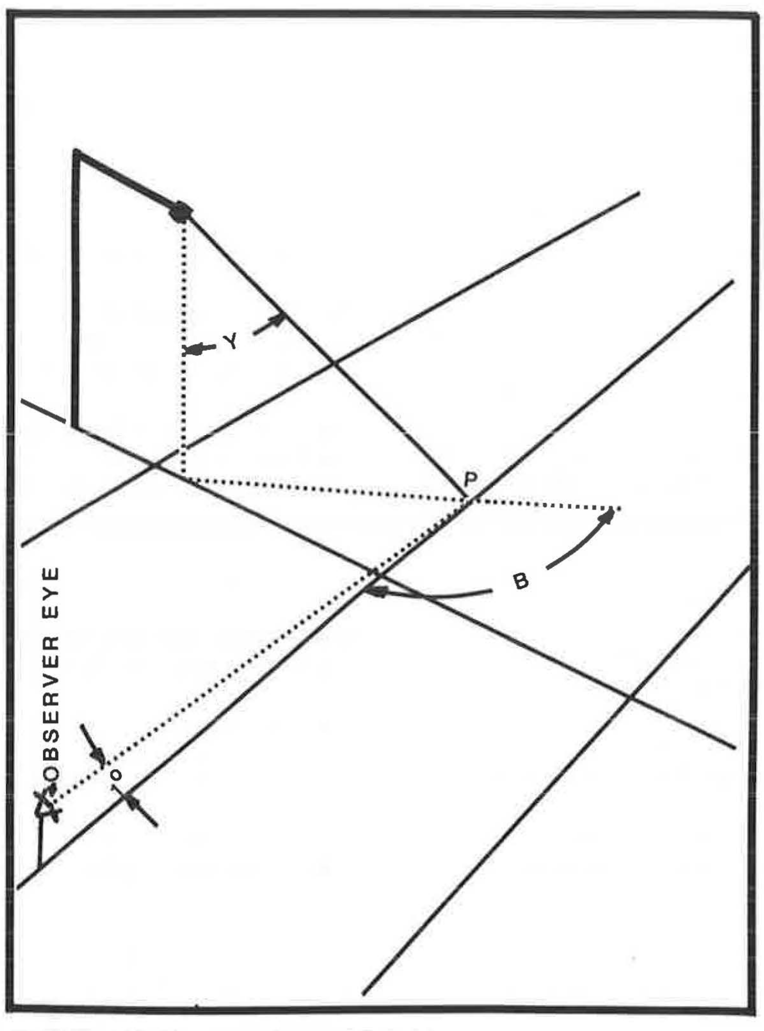


**FIGURE 1 Reference angles per RP-8 (*1*).**

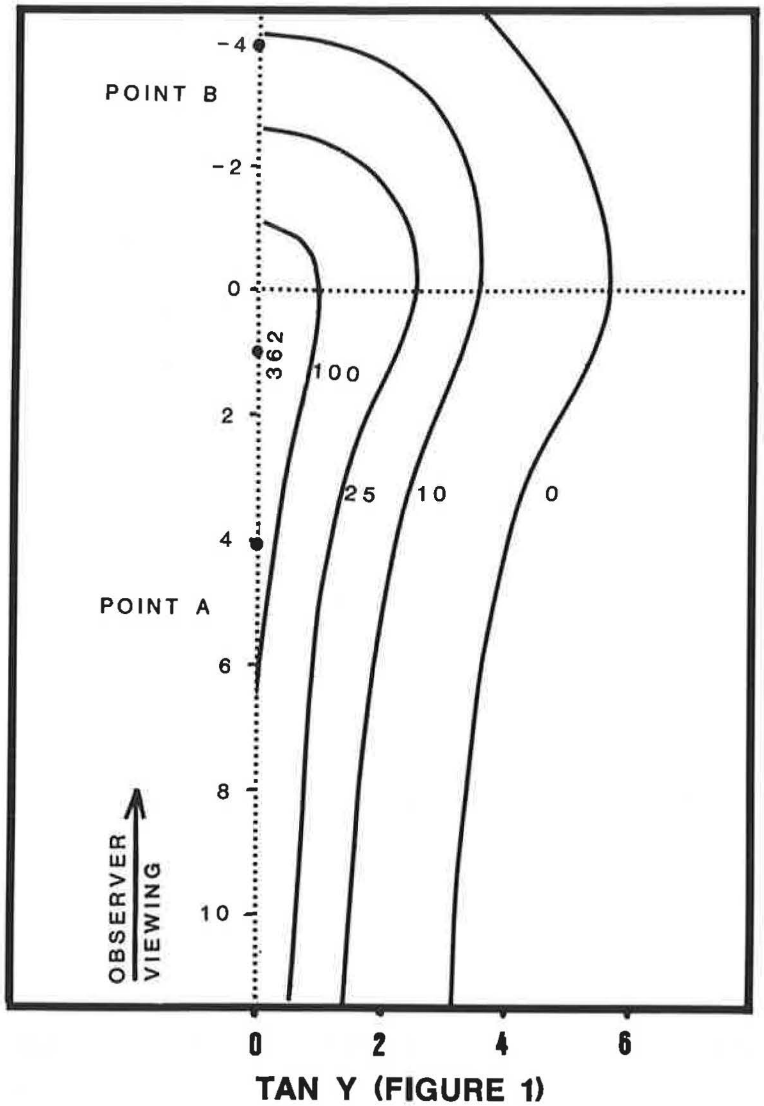


**FIGURE 2 Plot of R3 table isocoefficient lines.**

misleading unless it is noted that the cube of the cosine of the vertical angle has been included in the R-tables because it is used in every luminance calculation. This means that, as the vertical angle $Y$ gets bigger, the value of $\cos^3 Y$ gets much smaller. The actual reflectance values of the pavement surface become quite large at higher vertical angles, so the R-table depicts the value of pavement reflectance multiplied by the cube of the cosine. Figure 4 compares these values.

Because this multiplication peaks at about 45°, it can be concluded that a single luminaire will produce the maximum luminance per watt input if its beam peaks at 45°. In other words, above 45°, the cube of the cosine gets smaller at a faster rate than pavement reflectance gets larger (all other factors held constant).

Calculations using single luminaires on a roadway proved that, as the beam angle is raised from 45°, the ability to produce luminance drops off, following Figure 3 almost exactly. However, when a complete system of luminaires was used, the trend reversed. As the vertical angle of beam max increased (all other factors held constant), the average luminance on the roadway surface increased rather dramatically, as shown in Figure 5.

The answer to this apparent contradiction seems to be that, as the vertical angle of beam max increases in a system, more luminaires in front of the driver contribute to the luminance at each point. The luminance program calculates contributions from 10 luminaires ahead of each point.

## Luminance Production Versus Lateral Angle of Beam Max

In the R3 table (Table 1), the leftmost column represents values where the luminaire, the point under consideration on the roadway, and the driver are all in line as the driver looks straight ahead. If the lateral angle of beam max is in this 90° lateral plane, then this should be the condition of maximum luminance production because the leftmost column in the R-tables has larger numbers than any other column. Figure 6 shows this to be the case.

TABLE 1 R3 TABLE FROM RP-8 (ALL VALUES MULTIPLIED BY 10,000) (*1*)

| β / tan γ | 0 | 2 | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 60 | 75 | 90 | 105 | 120 | 135 | 150 | 165 | 180 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 294 | 294 | 294 | 294 | 294 | 294 | 294 | 294 | 294 | 294 | 294 | 294 | 294 | 294 | 294 | 294 | 294 | 294 | 294 | 294 |
| 0.25 | 326 | 326 | 321 | 321 | 317 | 312 | 308 | 308 | 303 | 298 | 294 | 280 | 271 | 262 | 258 | 253 | 249 | 244 | 240 | 240 |
| 0.5 | 344 | 344 | 339 | 339 | 326 | 317 | 308 | 298 | 289 | 276 | 262 | 235 | 217 | 204 | 199 | 199 | 199 | 199 | 194 | 194 |
| 0.75 | 357 | 353 | 353 | 339 | 321 | 303 | 285 | 267 | 244 | 222 | 204 | 176 | 158 | 149 | 149 | 149 | 145 | 136 | 136 | 140 |
| 1 | 362 | 362 | 352 | 326 | 276 | 249 | 226 | 204 | 181 | 158 | 140 | 118 | 104 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 1.25 | 357 | 357 | 348 | 298 | 244 | 208 | 176 | 154 | 136 | 118 | 104 | 83 | 73 | 70 | 71 | 74 | 77 | 77 | 77 | 78 |
| 1.5 | 353 | 348 | 326 | 267 | 217 | 176 | 145 | 117 | 100 | 86 | 78 | 72 | 60 | 57 | 58 | 60 | 60 | 60 | 61 | 62 |
| 1.75 | 339 | 335 | 303 | 231 | 172 | 127 | 104 | 89 | 79 | 70 | 62 | 51 | 45 | 44 | 45 | 46 | 45 | 45 | 46 | 47 |
| 2 | 326 | 321 | 280 | 190 | 136 | 100 | 82 | 71 | 62 | 54 | 48 | 39 | 34 | 34 | 34 | 35 | 36 | 36 | 37 | 38 |
| 2.5 | 289 | 280 | 222 | 127 | 86 | 65 | 54 | 44 | 38 | 34 | 25 | 23 | 22 | 23 | 24 | 24 | 24 | 24 | 24 | 25 |
| 3 | 253 | 235 | 163 | 85 | 53 | 38 | 31 | 25 | 23 | 20 | 18 | 15 | 15 | 14 | 15 | 15 | 16 | 16 | 17 | 17 |
| 3.5 | 217 | 194 | 122 | 60 | 35 | 25 | 22 | 19 | 16 | 15 | 13 | 9.9 | 9.0 | 9.0 | 9.9 | 11 | 11 | 12 | 12 | 13 |
| 4 | 190 | 163 | 90 | 43 | 26 | 20 | 16 | 14 | 12 | 9.9 | 9.0 | 7.4 | 7.0 | 7.1 | 7.5 | 8.3 | 8.7 | 9.0 | 9.0 | 9.9 |
| 4.5 | 163 | 136 | 73 | 31 | 20 | 15 | 12 | 9.9 | 9.0 | 8.3 | 7.7 | 5.4 | 4.8 | 4.9 | 5.4 | 6.1 | 7.0 | 7.7 | 8.3 | 8.5 |
| 5 | 145 | 109 | 60 | 24 | 16 | 12 | 9.0 | 8.2 | 7.7 | 6.8 | 6.1 | 4.3 | 3.2 | 3.3 | 3.7 | 4.3 | 5.2 | 6.5 | 6.9 | 7.1 |
| 5.5 | 127 | 94 | 47 | 18 | 14 | 9.9 | 7.7 | 6.9 | 6.1 | 5.7 | | | | | | | | | | |
| 6 | 113 | 77 | 36 | 15 | 11 | 9.0 | 8.0 | 6.5 | 5.1 | | | | | | | | | | | |
| 6.5 | 104 | 68 | 30 | 11 | 8.3 | 6.4 | 5.1 | 4.3 | | | | | | | | | | | | |
| 7 | 95 | 60 | 24 | 8.5 | 6.4 | 5.1 | 4.3 | 3.4 | | | | | | | | | | | | |
| 7.5 | 87 | 53 | 21 | 7.1 | 5.3 | 4.4 | 3.6 | | | | | | | | | | | | | |
| 8 | 83 | 47 | 17 | 6.1 | 4.4 | 3.6 | 3.1 | | | | | | | | | | | | | |
| 8.5 | 78 | 42 | 15 | 5.2 | 3.7 | 3.1 | 2.6 | | | | | | | | | | | | | |
| 9 | 73 | 38 | 12 | 4.3 | 3.2 | 2.4 | | | | | | | | | | | | | | |
| 9.5 | 69 | 34 | 9.9 | 3.8 | 3.5 | 2.2 | | | | | | | | | | | | | | |
| 10 | 65 | 32 | 9.0 | 3.3 | 2.4 | 2.0 | | | | | | | | | | | | | | |
| 10.5 | 62 | 29 | 8.0 | 3.0 | 2.1 | 1.9 | | | | | | | | | | | | | | |
| 11 | 59 | 26 | 7.1 | 2.6 | 1.9 | 1.8 | | | | | | | | | | | | | | |
| 11.5 | 56 | 24 | 6.3 | 2.4 | 1.8 | | | | | | | | | | | | | | | |
| 12 | 53 | 22 | 5.6 | 2.1 | 1.8 | | | | | | | | | | | | | | | |

Q0 = 0.07; S1 = 1.11; S2 = 2.38

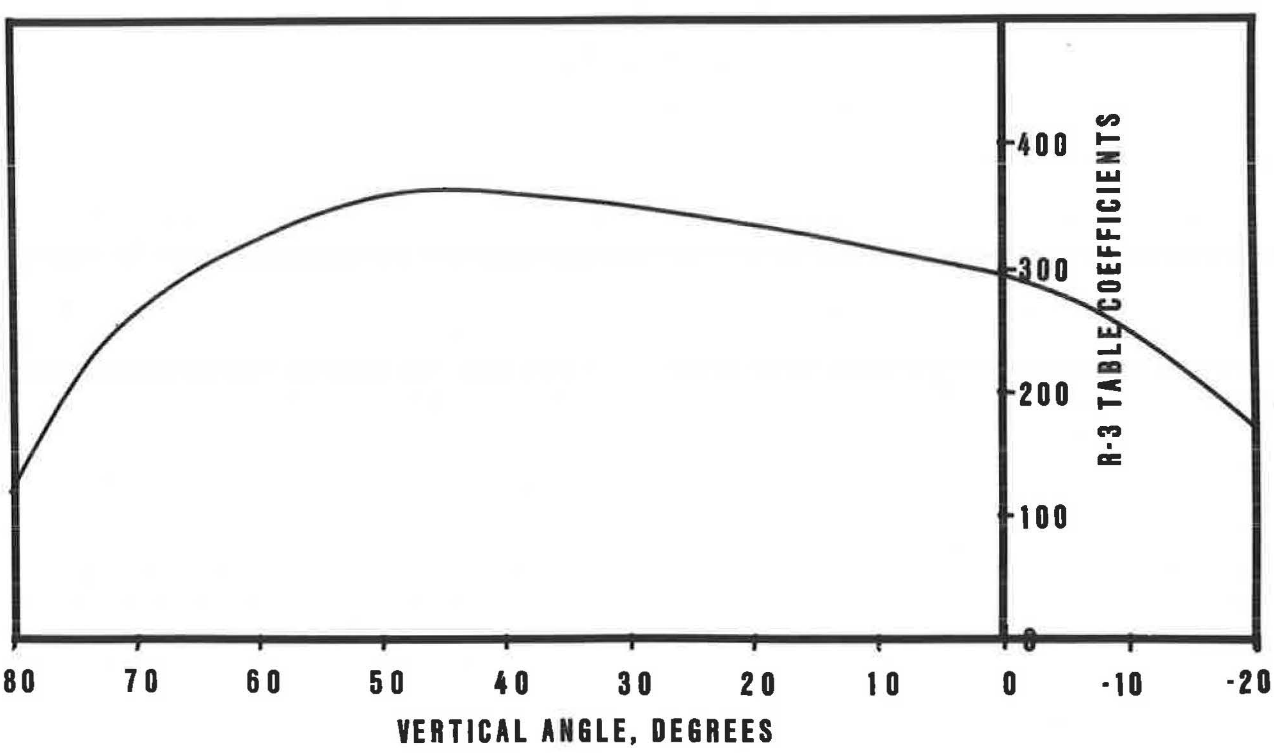


FIGURE 3 R3 coefficient in vertical plane of observer, pavement point, and luminaire.

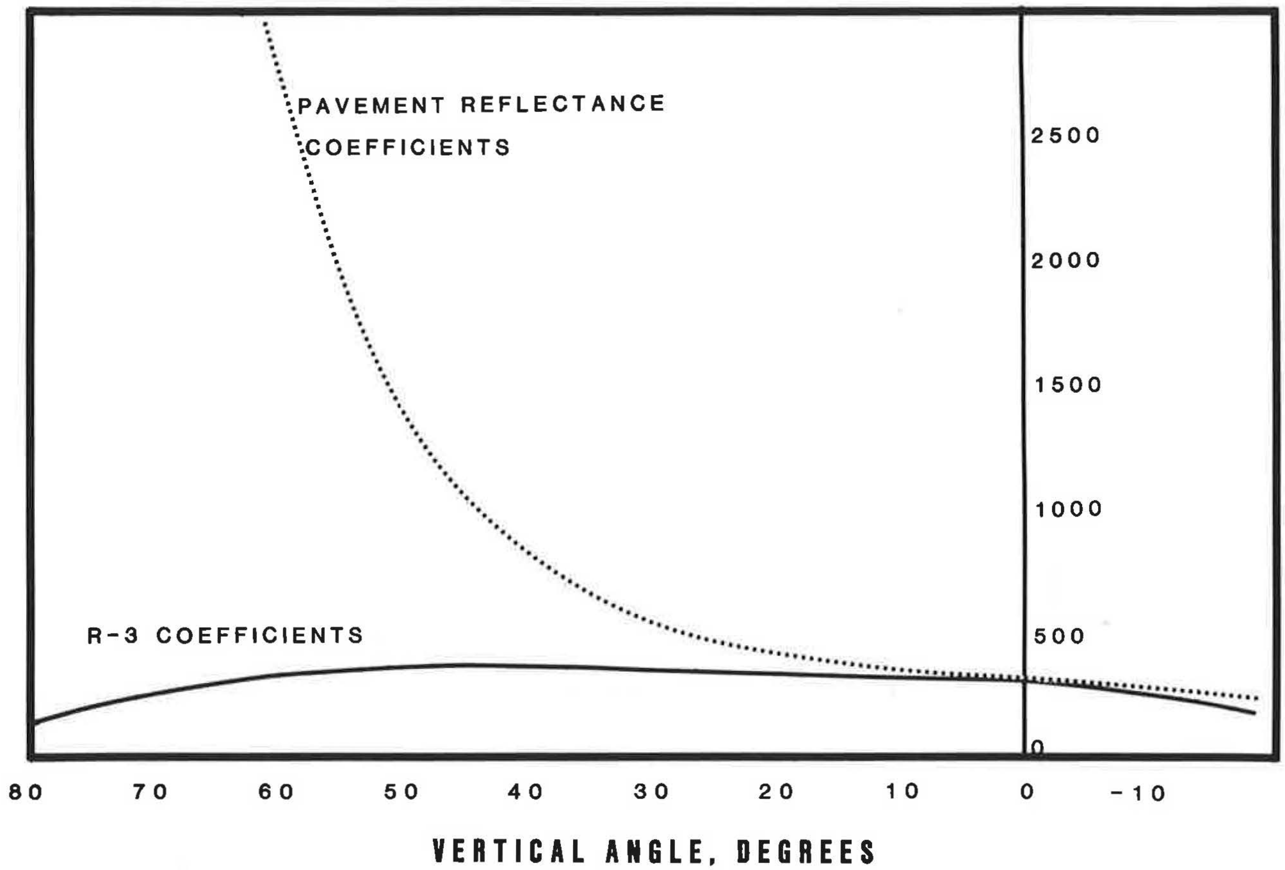


**FIGURE 4** Comparison of R3 coefficients with reflectance coefficients.

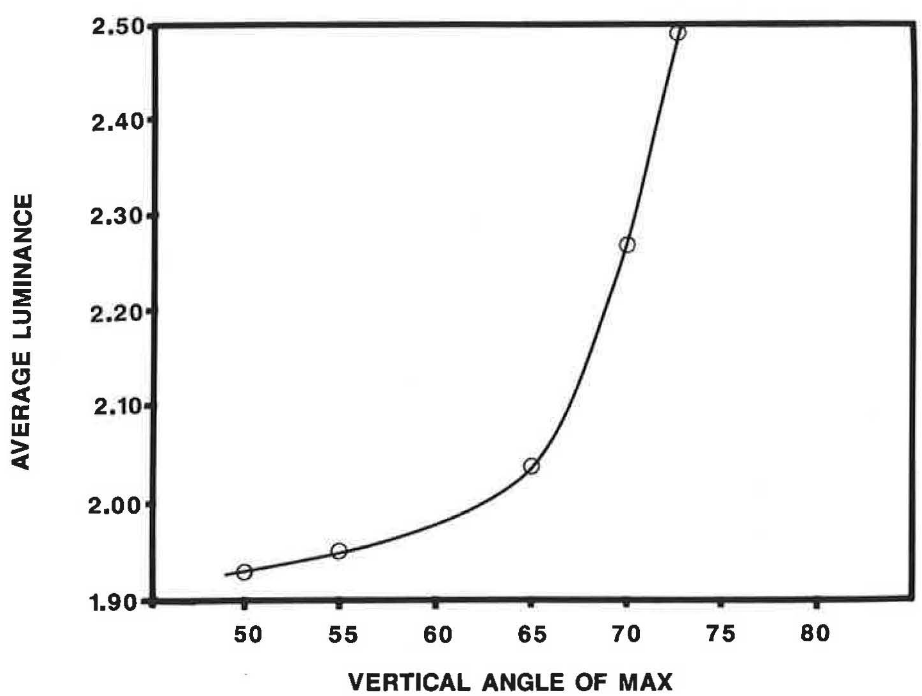


**FIGURE 5** Average luminance on roadway surface versus vertical angle of beam max.

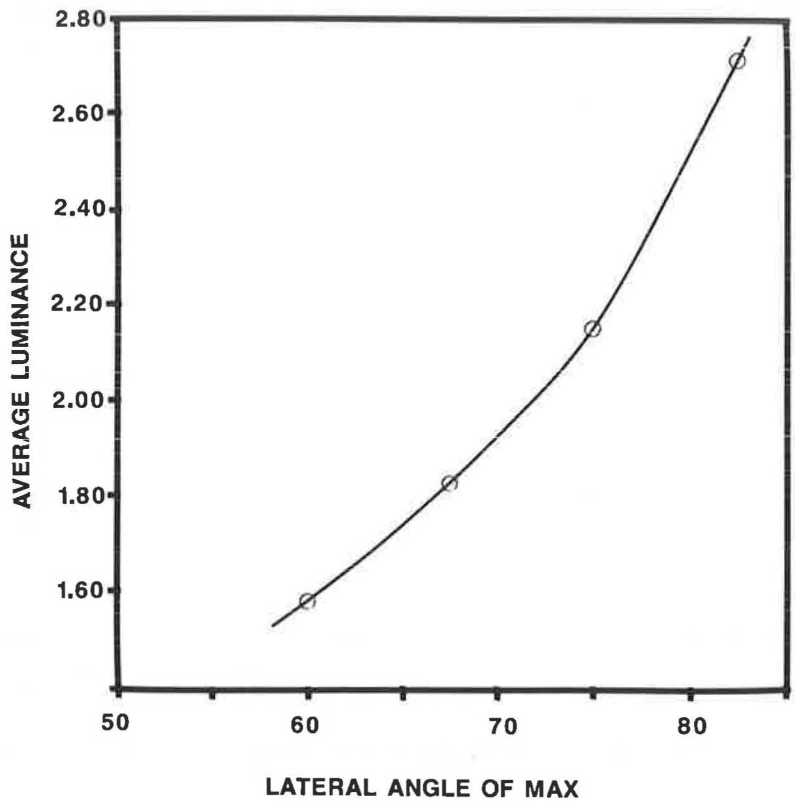


**FIGURE 6 Average luminance on roadway surface versus lateral angle of beam max.**

### Unidirectional Lighting

So far, this paper has focused on bidirectional distributions, which have all had upstream and downstream symmetry. An obvious variation from the bidirectional luminaire distribution is the unidirectional distribution, and this can be further broken down as being either against the driver or in the direction of driver travel. Many experiments and trial installations, as well as some real installations, have been conducted using unidirectional distributions.

#### *Unidirectional Lighting in Direction of Driver Travel*

This type of lighting has the advantage of making all objects appear in reverse silhouette (bright against a darker background). In addition, the use of headlights enhances visibility by making objects still brighter against their background.

This method also has several disadvantages. For example, the reflectance coefficient of the roadway surface is quite low, so luminance on the roadway surface is not produced efficiently. Also, those who use unidirectional lighting in the direction of driver travel tend to use beams at high vertical angles to permit longer spacings. However, Figure 7 shows that raising the beam offers no advantage from a luminance-producing standpoint. Also, when using distributions with very strong beams (high candela), an annoying phenomenon takes place. At a certain point in the system, depending on the vertical angle of the beam, the inside of the car is suddenly lighted to a high level. Since this occurs once each luminaire cycle, it becomes an irritating flashing.

It should be obvious that a unidirectional system can only be effective when the light can be completely shielded from drivers traveling in the opposite direction.

#### *Unidirectional Lighting Against the Driver*

The advantage of this type of lighting is that the directional reflectance factor of the roadway surface is much higher than it is with the beam going in the direction of driver travel. Therefore, luminance is produced much more efficiently. In addition, there is a tendency among those using this type of system to raise the vertical angle of beam max to produce luminance more efficiently. As shown in Figure 7, when the vertical angle of the beam is as high as 80°, the luminance-producing capability is as much as 10 times that produced when the beam is in the direction of driver travel.

However, this highly efficient luminance-producing system is not without drawbacks. When the vertical angle of beam max becomes large, the glare of the system becomes prohibitive. (This aspect of the two systems was not analyzed in this investigation.) Another disadvantage is that, under the fixed lighting, all objects appear in silhouette (dark against a light background). When the object comes within the effective range of headlights, it disappears at a certain point (the object and background have equal luminance), then appears again in reverse silhouette as the headlights make the object lighter than its background.

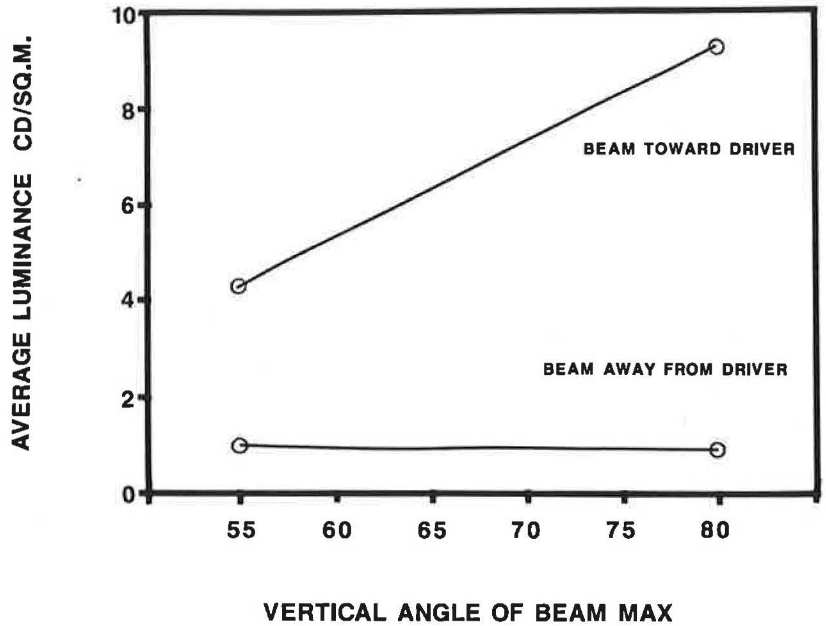


**FIGURE 7 Effect on luminance of raising the beam.**

*A Reasonable Compromise*

Assuming there are real advantages in having light in the direction of driver travel, and at the same time realizing the greater luminance-producing potential of light toward the driver, some sort of bilaterally asymmetric distribution would perhaps yield results superior to either bilaterally symmetric distribution or either unidirectional distribution.

Some experimenting has already been done with this concept. A distribution called "counterbeam" is currently being used in the tunnels of Switzerland and is specified for tunnels now being built in Seattle, Washington. Figure 8 illustrates a typical counterbeam distribution. Table 2 shows that, with the beam toward the driver, more than twice the luminance is produced than if the beam were in the direction of driver travel.

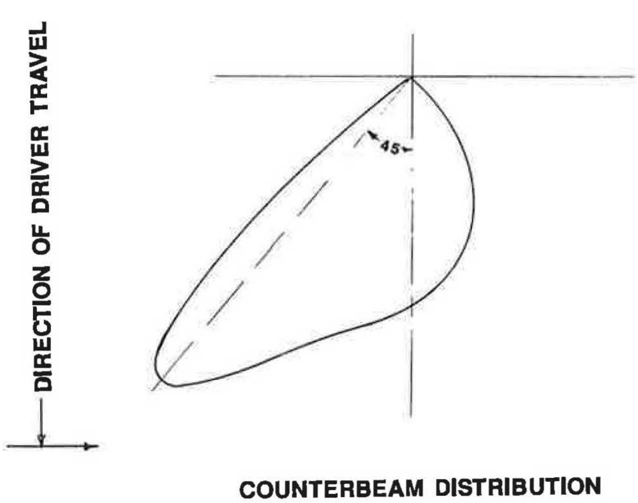


**FIGURE 8 Counterbeam distribution.**

## SUMMARY

All luminance calculations in this investigation were performed using a fixed geometry of a 40-ft roadway, 4-ft overhang, and 40-ft mounting height, spaced 160 ft on one side only. The luminaires used a 400-watt, clear high pressure sodium, 50,000-lumen lamp, and all calculations used a maintenance factor of 1. Table 2 shows a summary of the luminances produced in each computer run. While it lacks the rigor of having all coefficients of utilization exactly equal, the luminance produced in each case is probably a fair represen-

TABLE 2 PAVEMENT LUMINANCE VALUES

| Type of Distribution | Average Luminance (cd/m$^2$) |
|---|---|
| Bidirectional (with symmetry) | |
| 50°V beam (75°L) | 1.93 |
| 55°V beam (75°L) | 1.98 |
| 65°V beam (75°L) | 2.04 |
| 70°V beam (75°L) | 2.27 |
| 72°V beam (75°L) | 2.49 |
| 60°L beam (67-½°V) | 1.59 |
| 67.5°L beam (67-½°V) | 1.82 |
| 75°L beam (67-½°V) | 2.15 |
| 82.5°L beam (67-½°V) | 2.71 |
| Unidirectional | |
| With driver | |
| 55°V beam | 1.02 |
| 80°V beam | 0.91 |
| Against driver | |
| 55°V | 4.33 |
| 80°V | 9.30 |
| Counterbeam (50°V) | |
| With driver | 0.95 |
| Against driver | 2.84 |

tation of the particular system's luminance-producing ability in terms of system watts.

## CONCLUSIONS

Several conclusions can be drawn from this investigation:

- In a bidirectional distribution system, the luminance-producing ability of the distribution increases as the vertical angle of beam max increases.
- In a bidirectional distribution, the maximum luminance-producing ability is obtained when the luminaire, the point to be lighted, and the driver are all in line.
- In a bidirectional distribution, the luminance-producing ability of the system decreases as the lateral angle of beam max decreases (with the beam angled more into the street).
- In a unidirectional system, the luminance-producing ability of the distribution toward the driver is much greater than the system aimed in the direction of driver travel (up to 10 times as much depending on the vertical angle of the beam). With the beam toward the driver, an increase in the vertical angle of beam max increases the luminance-producing ability of the system; with the beam in the direction of driver travel, the vertical angle of beam max makes no appreciable difference in luminance-producing ability.
- In a counterbeam system with a distribution similar to the prototype shown in Figure 8, the resulting luminance-producing ability is approximately 45 percent higher than in a typical bidirectional system with the beams at about the same vertical angle as the toward-the-driver beam of counterbeam.

## REFERENCE

1. *American National Standard Practice for Roadway Lighting, ANSI/IESNA RP-8*. Illuminating Engineering Society of North America, New York, 1983.

# New CIE and ANSI/IES Recommendations for Vehicular Tunnel Lighting

A. KETVIRTIS

**In 1987 and 1988, two important documents were developed concerning the lighting recommendations for vehicular tunnels. These were CIE's *Guide for the Lighting of Road Tunnels and Underpasses* (CIE 26/2) (draft), and the ANSI/IES *American National Standard Practice for Tunnel Lighting* (ANSI/IES RP-22). Although these organizations kept a close liaison throughout the preparation of these documents, the photometric values in tunnel threshold zone and the length of supplementary lighting recommended in the documents differ considerably.**

In 1987 and 1988, two important documents were prepared by the Commisson Internationale de l'Eclairage (CIE) (*1*) and the Illuminating Engineering Society of North America (IESNA) (*2*), offering recommendations for vehicular tunnel lighting design.

The CIE document was prepared by the TC-4-08 Committee on Tunnel Lighting. This committee consists of 15 members and 3 consultants, representing 11 member countries. The ANSI/IES *Standard Practice* was prepared by the Subcommittee on Tunnels and Underpasses of the Roadway Lighting Committee (IESNA).

A close liaison was maintained between the CIE Committee on Tunnel Lighting and the IES Subcommittee on Tunnels and Underpasses, and four IES members (R. N. Schwab, R. E. Stark, A. Ketvirtis, and Dr. W. Adrian) served on both IES and CIE committees. However, the photometric values recommended for a tunnel threshold and its interior, as well as the procedures used to arrive at these values, differed considerably between these documents.

To assist those who will study these documents, particularly the practicing engineers and highway administrators who may attempt to use one or both of them in practice, a brief discussion of their differences is presented.

## ANSI/IES RECOMMENDATIONS FOR TUNNEL THRESHOLD AND TRANSITION ZONE LUMINANCE VALUES

The ANSI/IES recommendations for threshold and transition zones are based on the following factors:

- Tunnel characteristics and immediate surroundings,
- Traffic speed and safe stopping site distance (SSSD), and
- Traffic volume.

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Table 1 (reproduced from the ANSI/IES publication) shows the recommended values for threshold zone luminance, ranging from 60 cd/m$^2$ for low-speed, low-volume tunnels to 330 cd/m$^2$ for high-speed, high-volume structures.

In the ANSI/IES document, the length of threshold and transition zones are related to SSSD; the length of one SSSD, counting from the adaptation point, is recommended for the threshold zone. In other words, the threshold zone length should be one SSSD minus the distance from the adaptation point (approximately 15 m) to the tunnel portal. A total of one SSSD is also recommended for the transition and adaptation zones, in order to achieve a gradual reduction of luminance level.

## ANSI/IES RECOMMENDATIONS FOR LIGHT SOURCE SELECTION

The ANSI/IES document stipulates that the following factors should be used in selecting a light source for tunnel lighting: efficacy, color renditions and their effect on sign and traffic signals, wattages or lumen output available, life, lamp lumen depreciation, ambient temperature, cost, restrike time, ability to control the light distribution, dimming capability, physical size, and physical durability. No further advice, recommendations, or preferences are offered regarding selection of the light sources, light distribution methods, or lighting system geometric arrangements.

## CIE ACCESS ZONE LUMINANCE, $L_{20}$ CONCEPT

According to the CIE document, "the correlation between equivalent veiling luminance and access zone luminance, $L_{20}$, indicates that the simpler of the two, the access zone luminance, can be used for practical tunnel lighting purpose. For this reason the luminance value required at the beginning of the threshold zone is based on the access zone luminance, $L_{20}$, measured one stopping distance in front of the portal."

The CIE document also provides a method for calculating $L_{20}$ values. In the assessment of $L_{20}$ values, sky, road surroundings, and the tunnel entrance (in percentages) are taken into account. In the case of new tunnel design, where these factors cannot be determined by field measurements, a table for $L_{20}$ values is included (see Table 2, reproduced from CIE Table 5.1). The $L_{20}$ value can be selected from this table.

TABLE 1 RECOMMENDED MAINTAINED THRESHOLD ZONE AVERAGE PAVEMENT LUMINANCE VALUES FOR TUNNEL ROADWAYS (2)

| Characteristics of Tunnel | Traffic Speed | | Traffic Volume AAD1* | | | |
|---|---|---|---|---|---|---|
| | Kilometers per Hour | Miles per Hour | < 25,000 | 25-89,999 | 90-150,000 | > 150,000 |
| | | | Candelas per Square Meter+ | | | |
| Mountain tunnels, gradual slopes where snow can accumulate or river tunnels with few surrounding buildings. East/west tunnel orientation. | ≥ 81 | 50 | 210 | 250 | 290 | 330 |
| | 61-80 | 38-49 | 180 | 220 | 260 | 300 |
| | ≤ 60 | 37 | 140 | 185 | 230 | 270 |
| Mountain tunnels with steep, dark slopes or climate conditions where snow cannot accumulate. Portal surroundings have medium brightness year round. | ≥ 81 | 50 | 145 | 175 | 205 | 235 |
| | 61-80 | 38-49 | 130 | 160 | 190 | 220 |
| | ≤ 60 | 37 | 105 | 140 | 170 | 200 |
| Concealed portals, dark surfaces, or buildings surrounding entrance. Artificial measures taken to reduce exterior brightnesses. North/south orientation. | ≥ 81 | 50 | 80 | 100 | 115 | 130 |
| | 61-80 | 38-49 | 70 | 90 | 105 | 120 |
| | ≤ 60 | 37 | 60 | 80 | 95 | 110 |

* Average Annual Daily Traffic in both directions.
+ For approximate values in candelas per square foot, multiply by 0.1.

TABLE 2 TABLE OF $L_{20}$ (cd/m$^2$) (*1*)

| Percentage of sky (%) in the 20° conical field of view (%) | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 35% | | | | 25% | | | | 10% | | | | 0% | | | |
| brightness situation in field of view | normal (1) | | snow (1) | | normal (1) | | snow (1) | | normal (2) | | snow (3) | | normal (2) | | snow (3) | |
| | low | high | low | high | low | high | low | high | low | high | low | high | low | high | low | high |
| stopping distance 60 m | (4) | | (4) | | 4000 | 5000 | 4000 | 5000 | 2500 | 3500 | 3000 | 3500 | 1500 | 3000 | 1500 | 4000 |
| stopping distance 100 m and 160 m | 5000 | 7500 | 5000 | 7000 | 4500 | 6000 | 5000 | 5000 | 3000 | 4500 | 3000 | 5000 | 2000 | 4000 | 2000 | 5000 |

Table 3 (CIE Table 5.4) recommends the ratio that should exist between $L_{th}$ (luminance in the threshold zone) and $L_{20}$.

It should be noted that the CIE recommendations make a significant distinction between a symmetrical lighting system and a counterbeam lighting system. If the latter system is used, a reduction of 30 percent of the luminance level in the threshold zone is permitted.

## CIE RECOMMENDATIONS FOR LENGTH OF THE THRESHOLD ZONE

CIE recommendations stipulate that "the total length of the threshold zone must be at least equal to the stopping distance." The reduction of the luminance level is permitted to begin from "half of the stopping distance onwards."

According to the CIE document, if stepwise reduction is made, the ratio between the steps should not exceed 3:1. The reduction of light in the transition zones using CIE recommendations would occur much more slowly than under IES recommendations. For example, the total length of the threshold zone recommended for a tunnel with a speed of 100 km/hr is on the order of 500 m (or approximately 20 sec of travel).

TABLE 3 RECOMMENDED RATIOS BETWEEN THRESHOLD ZONE LUMINANCE AND ACCESS ZONE LUMINANCE (*1*)

| | $L_{th}/L_{20}$ | |
|---|---|---|
| Stopping Distance (m) | Symmetrical Lighting System ($L/E_v < 0.2$) | Counterbeam Lighting System ($L/E_v > 0.6$) |
| 60 | 0.05 | 0.04 |
| 100 | 0.06 | 0.05 |
| 160 | 0.10 | 0.07 |

## ASYMMETRY IN LIGHT CONTROL ($L_b/E_v$)

According to the CIE guide, a lighting system which produces high road surface luminance ($L_b$) and low vertical illuminance ($E_v$) (i.e., high values of the ratio $L_b/E_v$) gives relatively high contrast values for most objects on the road. A system featuring such characteristics is often referred to as counterbeam lighting.

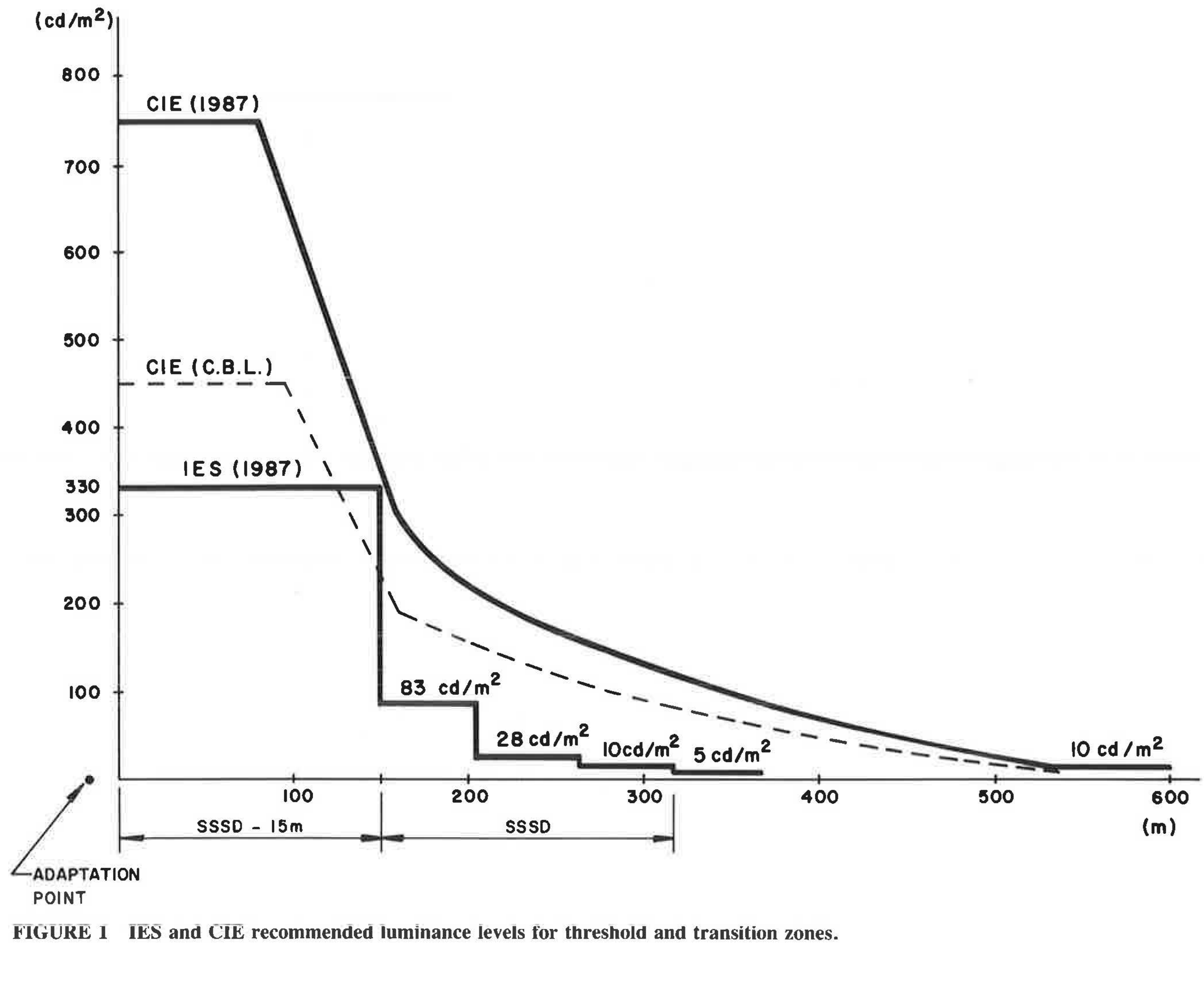


FIGURE 1 IES and CIE recommended luminance levels for threshold and transition zones.

## CIE AND ANSI/IES RECOMMENDATION SUMMARY AND COMPARISON

Figure 1 compares the suggested threshold and transition zone luminance values from the CIE and the ANSI/IES documents. From this figure, it is evident that using CIE recommendations will result in considerably higher luminance levels in the tunnel threshold and transition zones.

Total supplementary lighting length using ANSI/IES recommendations is equal to two SSSDs minus 15 m, or approximately 320 m; according to the CIE, the length of threshold and transition zones may reach 550 m.

A conclusion can be drawn that the CIE recommended practice will result in higher capital investment and higher maintenance and operation costs.

## REFERENCES

1. *Guide for the Lighting of Road Tunnels and Underpasses* (draft). CIE 26/2. Commisson Internationale de l'Eclairage, 1988.
2. *American National Standard Practice for Tunnel Lighting*. ANSI/IES RP-22. American National Standards Institute/Illuminating Engineering Society, 1987.