Standard Target Contrast: A Visibility Parameter Beyond Luminance To Evaluate the Quality of Roadway Lighting

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An additional yardstick to evaluate the quality of fixed highway lighting is proposed, specifically, the contrast of a critical-size standard target object, such as a 20 × 20-cm (8 × 8-in.) square middle-gray card placed vertically on the road surface perpendicular to the road axis. The proposed measure of standard target contrast would be used in conjunction with other currently used yardsticks, such as luminance and glare. The concept of a standard target contrast is demonstrated with reference to a test section of conventionally designed luminaires. Although luminance levels meet the standards for uniformity, spots of unsafe low contrast are clearly revealed by the new yardstick. Contrast has been defined in such a way that values for silhouette vision range from no contrast at zero to a maximum contrast of −1, representing a comfortable range for all practicable evaluation work. The prospect of more effective nonsymmetrical luminaires for one-way traffic is also investigated. It is shown that about half the light output must be widely and uniformly distributed to meet luminance requirements and that the remaining light can be effectively directed toward the driver for enhancing contrast values. Conventional symmetrical luminaires need a distinct overlap of main beams to provide sufficient contrast for silhouette vision at all points along the road.

In the field of roadway and expressway lighting, considerable research has resulted in the adoption of luminance (reflected light) as a design standard for fixed lighting systems. Before this, the methods and standards of design were based on incident light (illuminance) only. Design and evaluation of lighting systems with road surface luminance as an additional standard is just one small forward step toward a true visibility criterion. Performance evaluation of fixed highway lighting is still inadequate, as will be shown in this paper.

At present, research efforts are directed toward finding a visibility index. However, there are difficulties with such an index, because it contains too many transient quantities that are difficult to turn into standard values. In the case of luminance, there were only a few values, such as the viewing angle α, that could still be standardized (although not easily). The visibility index, as it is being discussed now, is apt to be loaded with physical and human factors, and thus it becomes much more difficult to agree on representative or standard values for system parameters.

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PROPOSED YARDSTICK

The solution proposed here is not to try a perfect modeling or definition of such an index but rather to concentrate on a less sophisticated parameter that can easily be computed at each location on the roadway surface by using only the physical dimensions and properties of the lighting system. Such a parameter can be used in the same way as glare, illuminance, or luminance, namely, as a system evaluation yardstick revealing weaknesses of the system much more clearly than any other design parameter.

The parameter suggested for use is the contrast of a critical-size standard target object on the road surface perpendicular to the line of sight or road axis. Only two quantities of such a target must be defined:

- Reflectance properties (such as middle gray, 20 percent reflectance, and nonspecular perfectly diffusing surface), and
- Height above ground (such as 20 cm), which appears to be less important.

Note that it is possible to use several standard values of reflectivity (say, 20 percent, 50 percent, etc.).

UNDERSTANDING AND INTERPRETING TARGET CONTRAST

To understand the concept of standard target contrast, imagine a square 20 × 20 cm (8 × 8 in.) cut from a Kodak middle-gray card (which has a diffuse surface of 18 percent reflectance). This card is positioned vertically on the pavement surface perpendicular to the road axis and in this position can be moved along the surface forward and sideways. In each position, the contrast of the target object against the background of the pavement surface at a normal driver viewing angle can be determined. The target surface can be specified as a perfect diffuser with a uniform reflectance such as 20 percent or another chosen value. Further, imagine a driver who is 80 to 100 m (about 300 ft) away from the gray card, approaching it as a "critical-size" object situated in his driving path. "Critical size" means that the driver is sufficiently motivated to take evasive action when detecting such an object. Note that the capability of the driver to detect this card in time for evasive action is proportional primarily to the contrast between the card surface and the pavement background. Only secondarily does this capability depend on the level of luminance on the road surface.

In this context, contrast is defined as the difference between the object and background luminance divided by the background luminance, that is, $(L_o - L_b)/L_b$. In this way, a powerful and well-understood additional criterion can be established to measure the quality of roadway lighting. Defined in this way, the contrast can be calculated or measured for each grid point on the road surface in terms of a definite number. The meaning of such a number should be immediately clear. For instance,

- A contrast close to –1 means a strong silhouette effect. This is favorable for detecting objects but not necessarily for recognizing what they are, which fortunately is less important.
- A contrast close to zero means that the target almost disappears, which can be an unsafe condition.
- A large positive number means that the gray card appears bright against a darker background.

It should be noted that the visibility of such targets under fixed roadway lighting is determined predominantly by negative contrast or silhouette effect against the brighter background luminance of the roadway surface.

IMPLEMENTATION

With relatively little effort, the target contrast parameter can be incorporated into existing computer programs for illumination design so that values of contrast (C) can be calculated in the same manner as that currently used for illuminance, luminance, and disability veiling glare.

It is also possible to subscript the contrast parameter C (for example, C_{10} or C_{20}) to denote the percentage of reflectivity of the target object (10 percent, 20 percent, etc.). Further, it is possible to add a term to the vertical target illuminance to take into account the additional illumination of the target object by vehicle headlights. However, headlights are not very effective at 90 m viewing distance and beyond.

According to current knowledge, major highways need an average luminance of 0.5 to 1.2 cd/m^2. It is conceivable that the higher value is needed for situations of poor contrast, whereas the low values of luminance could be adequate in cases of good contrast over the whole surface.

Finally, introducing standards of contrast would promote innovation toward new luminaires that yield more visibility for each unit of consumed energy. This point needs further comment. Fixed lighting with improved visibility on high-speed expressways can be achieved economically by nonsymmetrical luminaires with main beams turned toward the driver and with good cutoff characteristics. Besides a cutoff in the driver's direction between 80 and 85 degrees to minimize glare, there should be little light in the direction of travel, opposite to the driver's view, just enough to provide a minimum level of luminance on the road surface (say, 0.5 cd/m^2), which is important to maximize (negative) contrast. Luminaires with such characteristics are not yet on the market but could well be developed after contrast standards have been introduced.

The current design standards of illuminance and luminance are blocking such development because they are unable to reveal the spots of bad visibility (i.e., of low contrast), as will be shown in the next section. On the other hand, an innovative luminaire as just described would probably violate present uniformity standards, which have little to do with visibility. Thus, introducing a standard of contrast would greatly promote the state of the art of lighting systems design.

A CASE OF CONTRAST DISTRIBUTION MEASUREMENT

Measurements of illuminance, luminance, and contrast of a standard target object were carried out at a test in Ontario with luminaires of adjustable output *(1)*. The pole distance was 59.5 m (200 ft) and the mounting height 15 m (50 ft), using two 400-W high-pressure sodium (HPS) Type III luminaires per pole with 1-m (3.3-ft) overhang. The road width was 10.5 m (34 ft); that is, there were three lanes running east to west. The installation consisted of six poles in one row, with two luminaires installed at each pole and bracket arm (to maximize the range of lighting levels).

The measurement field was chosen in the center, between the third and fourth poles. The results of the measurements, carried out in the center of each lane, are plotted in Figures 1 and 2. Luminance and contrast distributions are shown for a driver who is looking from the right, that is, approaching from the right side of the figures. Figure 1 shows distributions for full illumination and Figure 2 for an illumination output reduced to 14 percent.

The standard target was a 20 × 20-cm middle-gray card of about 20 percent reflectance in a vertical position and perpendicular to the road axis. The contrast values, C_{20} (20 stands for 20 percent), in Figures 1c and 2c have been calculated from luminance measurements of the target object (L_o) and the road surface background (L_b) using the formula $C_{20} = (L_o - L_b)/L_b$. Each figure contains three lines or curves, one for each of the three lanes.

The results shown in Figures 1 and 2 are interpreted as follows:

1. The distribution of luminance in each lane is relatively uniform. This means that the luminance yardstick cannot be used to discover a deficiency in contrast; that is, no weakness in the system can be determined.
2. The standard target contrast is basically all negative, which means that there is silhouette vision almost all along the road section. The object appears dark against a brighter background.
3. There are contrast values that are close to zero somewhere between the entrance point (the fourth pole) and the center (i.e., toward the approaching traffic), which means that critical-size objects may almost disappear at certain spots. Thus, contrast measurements reveal a weakness in the system.

If the evaluation of this fixed lighting system were based on illuminance and luminance only, it would have to be judged satisfactory or fair. Note that the luminance distribution is very uniform. However, contrast values close to zero mean that critical-size objects in the driving path (mufflers, rocks, etc.) may disappear or almost disappear for a short period of time

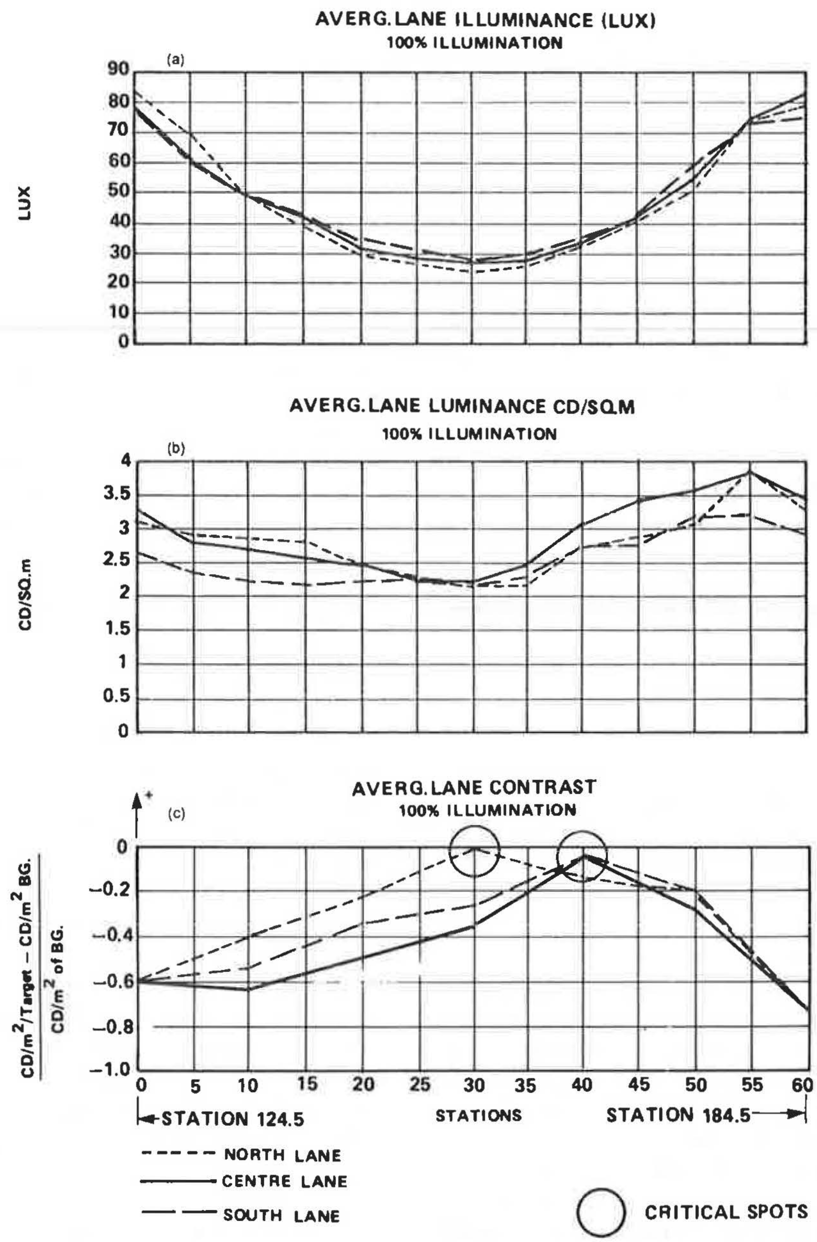


FIGURE 1 Distribution of illuminance, luminance, and standard target contrast for 100 percent output.

while one is driving along. Thus, it is important to look also at the standard target contrast distribution, which should be introduced as another important yardstick for the quality of fixed highway lighting, together with the currently used yardstick of luminance.

Negative contrast means that the target object is darker (has lower luminance) than the road surface in the background. Car headlights, which are effective at distances of less than 90 m (300 ft), increase the luminance on the target object, and thus may reduce the negative contrast. However, this requires further investigation; it is conceivable that headlights may worsen the situation.

Only the contrast diagrams in Figures 1 and 2 show the deficiency of the lighting system: between 30 and 45 m, that is, beyond the center of the section and toward the right in the direction of the approaching driver, contrast values are at or close to the zero line. The illuminance and luminance diagrams do not reveal any deficiency.

PILOT COMPUTATION AND ILLUSTRATION

System Parameters

Illumination systems for highways usually consist of rows of luminaires on poles. The relationship of each pole and luminaire with regard to the point *P* on the road surface as seen by an approaching driver is shown in Figure 3. Computer programs are available to calculate illuminance and luminance at predetermined grid points (*P*) for a standard viewing angle of

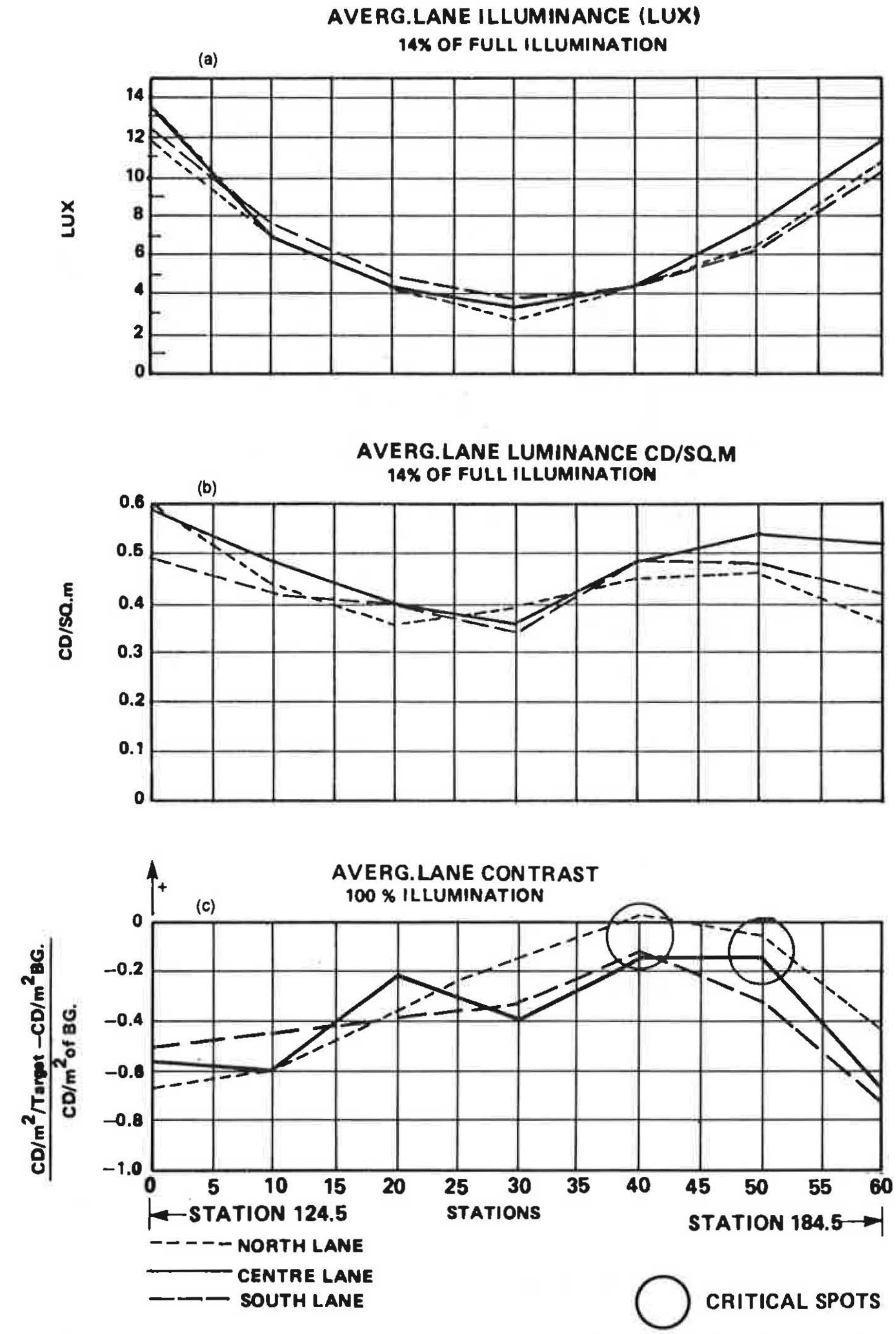


FIGURE 2 Distribution of illuminance, luminance, and standard target contrast for 14 percent output.

an approaching driver (α = 1 degree). Such programs can be extended easily to include the contrast of a standard critical-size object, a middle-gray perfect diffuser with a 20 × 20-cm surface perpendicular to the road axis. The strengths of such a new parameter can be evaluated by the following pilot study.

For illustration, the system is simplified to two dimensions longitudinally along the axis of a straight horizontal road of a few lanes. One row of luminaires is arranged in the center position at a mounting height (H) above the road surface. This system is shown in Figure 4 and may be understood as accommodating either one-directional traffic from left to right or two-way traffic.

Terms used in this discussion denote the following variables:

H = mounting height (m);
S = spacing of luminaires (m);
λ = S/H = ratio of spacing to mounting height;
ζ = fraction of distance between point P and the pole at $i = -1$ in terms of pole spacing;
i = index of location of light poles;

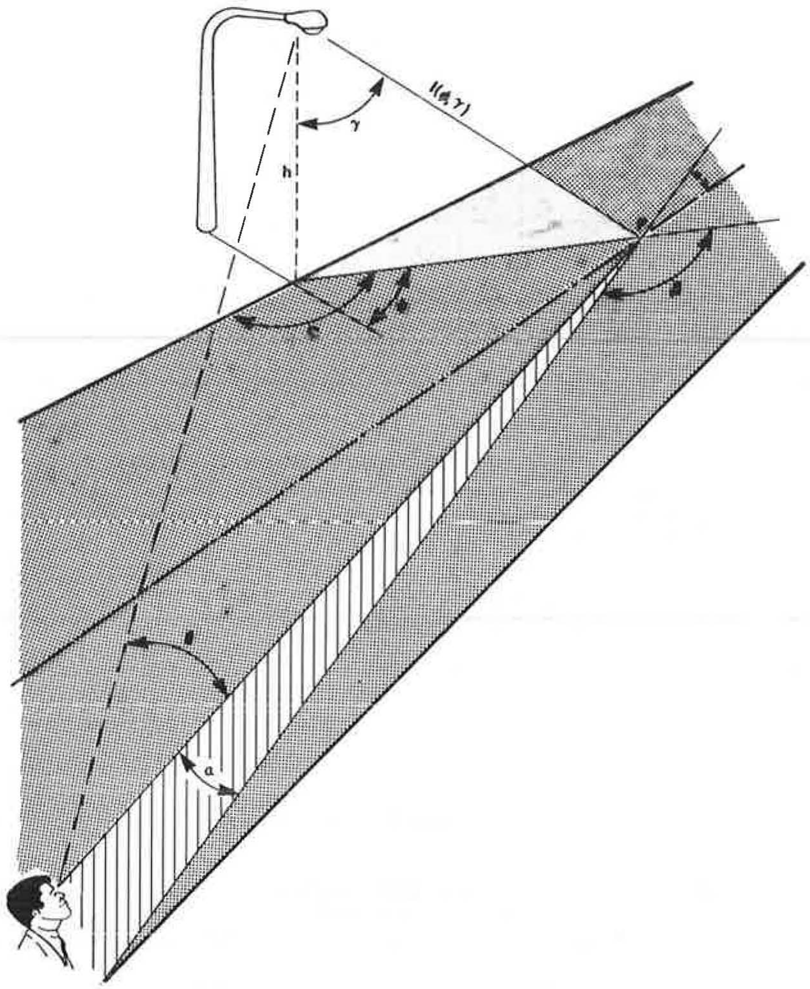
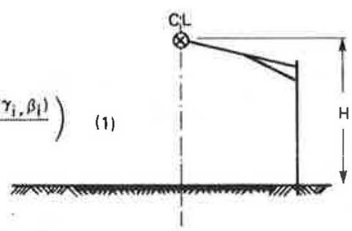


FIGURE 3 Illumination system parameters for highways.

$$L_p = \sum_{i=-2}^{i=+3} \left(\frac{I(\gamma_i, \phi_i) \cdot R(\gamma_i, \beta_i)}{H^2} \right) \quad (1)$$



$$\tan \gamma_i = \frac{(1-\xi)\,\lambda H - i\lambda H}{H} \quad (2)$$

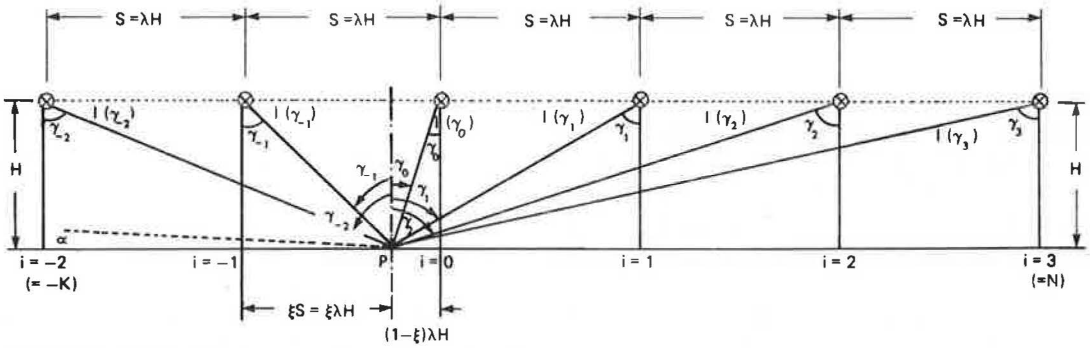


FIGURE 4 Simplified system (two-dimensional).

L_p = luminance at point P (cd/m^2), added contribution from many luminaires;
I = luminous intensity function (lumens per space angle);
γ = angle of light incidence or vertical angle of the intensity function I;
Z = size of target object above ground (m);
ϕ = angle of azimuth (i.e., horizontal angle of the intensity function I; see Figure 3);
R = reduced luminance coefficient; and
β = angle between the direction of I and the road axis.

For simplicity of demonstration, the luminous intensity function (I) is assumed to be independent of the horizontal angle ϕ. Further, the angle β is assumed to be between zero and 10 degrees, so that a simplified assumption can be made for the reduced luminance coefficient (R). These two simplifications mean that variations perpendicular to the road axis are neglected. With ϕ and β being zero, the equation to calculate the luminaires' contributions at point P is

$$L_p = \frac{I(\gamma) * R(\gamma)}{H^2} \qquad (1)$$

where

$$\tan \gamma = (1 - \xi)\,\lambda + (i * \lambda) \qquad (2)$$

Reduced Reflectance Coefficient $R(\gamma)$

The aforementioned assumption for the reflectance coefficient is shown in Figure 5. The curve shown is represented by the equation

$$R = 0.0305\,[\cos \gamma + 0.37 \cos (2\gamma)] \times \frac{q_0}{0.070} \qquad (3)$$

where q_0 is the brightness parameter *(2–5)*. This curve is assumed to sufficiently approximate the function R for small angles of β derived from the standard reflectance table ($R3$). Note that there are variations in age and location of the reflectance parameter along any type of pavement, so approximations of this kind are appropriate.

Luminous Intensity Function $I(\gamma)$

In the two-dimensional simplified system here, luminous intensity functions for luminaires vary with the vertical angle only. For example, if a cutoff point is assumed at some angle between 80 and 90 degrees, the functions could be expressed as a function of γ by a polynomial such as the following:

$$I = f(d + a\gamma + m\gamma^{\mu} - t\gamma^{\nu}) \quad > 0 \qquad (4)$$

If uneven exponents are chosen, such as $u = 3$ and $v = 5$ or 7, the intensity distribution would be nonsymmetrical. Such nonsymmetrical functions may also be expressed by two polynomials, different for positive or negative values of γ, and so forth.

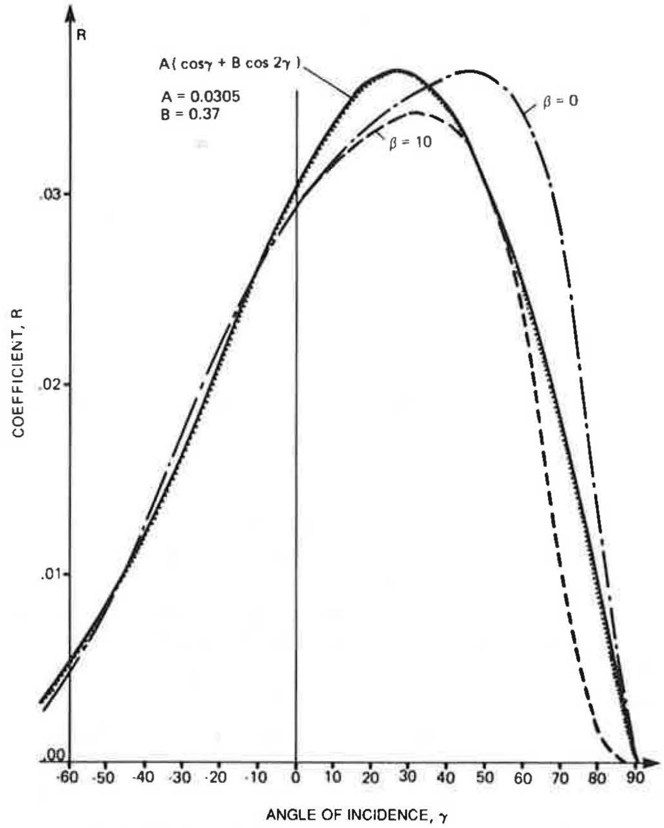


FIGURE 5 Reduced reflectance coefficient *R* for two-dimensional system.

A nonsymmetrical luminaire could be described as shining mainly backward, toward the driver. This type of luminaire would be most economical and should therefore be included in the investigations.

It should be understood that Equation 4 represents theoretically assumed intensity distributions, disregarding whether a luminaire can be built according to this or similar specifications.

At present, the luminaires of street lighting systems are symmetrical, with main beams reaching far in both directions, because this is perceived to be an economical feature. The luminous intensity function of a symmetrical luminaire can be simulated by the following function, with even values of u and v, setting $a = 0$ and $d = 1$:

$$I = 1{,}000 * (1 + m\gamma^{\mu} - t\gamma^{\nu}) \quad > 0 \qquad (4a)$$

Modeling of Contrast C_{20}

The area of the standard target object should generally be defined as a perfect diffuser, so that deviations from a perpendicular viewing angle or variations in the angle of light incidence have no influence on the contrast calculations.

The luminance of the target surface must have sufficient contrast against the background luminance of the road surface behind the target. Details of the target geometry may be seen in Figure 6. With respect to target contrast, the vertical illumi-

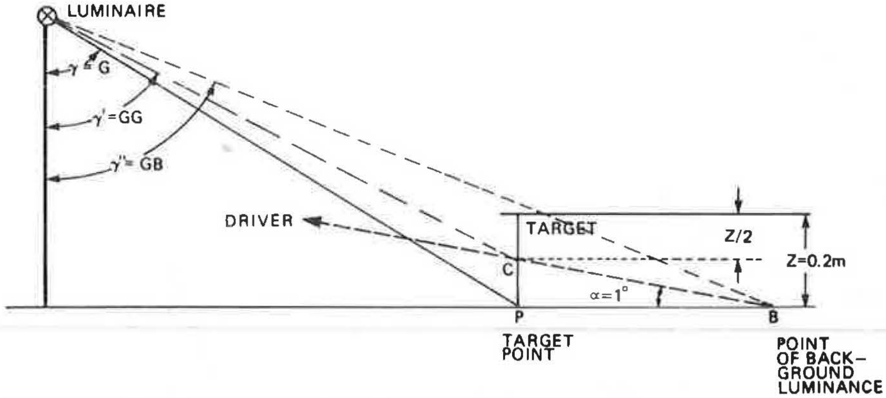


FIGURE 6 Details of critical-size target geometry (two-dimensional).

nance must be calculated at point C, the front center point of the target. The corresponding background luminance must be in the driver's line of sight.

In expressway driving, it is necessary to perceive a critical object at a distance of about 90 m. Car headlights are not very effective at that distance. Under these conditions, therefore, objects are seen predominantly by silhouette vision, that is, by the negative contrast generated by fixed roadway lighting.

Adopting a standard using the visibility of a critical object in the calculation or measurement of contrast would permit a true comparison of lighting systems based on the quality of night visibility that they provide.

As shown in Figure 4, there are three different angles of γ involved:

$$\tan \gamma = (1 - \xi) * \lambda + (i * \lambda) \quad (2)$$

$$\tan \gamma' = [(1 - \xi) * \lambda + (i * \lambda)] * \{H/[H - (Z/2)]\} \quad (5)$$

$$\tan \gamma'' = [(1 - \xi) * \lambda + (i * \lambda)] * \{Z/[2 * H * \sin(\alpha)]\} \quad (6)$$

The vertical illuminance at point C is calculated as follows, adding up contributions from luminaires in front of the target only:

$$E_{vc} = \frac{I(\gamma') \cos^2 (\gamma') \sin (-\gamma')}{[H - (Z/2)]^2} > 0 \quad (7)$$

The horizontal luminance at point B is calculated by using Equation 1, except for the larger angle γ'':

$$L_b = \frac{I(\gamma'') R(\gamma'')}{H^2} \quad (8)$$

The contrast C of the target object at point P can then be computed:

$$C_{20} = \frac{E_{vc}(0.20/\pi) - L_b}{L_b} \quad (9)$$

In an actual lighting program, Equations 7 and 8 are more complex, containing expressions of the angles β and ϕ (Figure 3), whereas Equation 9 remains the same.

As shown in Figure 4, contributions from all luminaires must be added. Because the target surface is defined as a perfect diffuser, the luminance coefficient is independent from the viewing angle of the driver and from the angle of incidence; for 20 percent reflectivity, it is simply $0.20/\pi$.

Contrast Calculations of Two Types of Luminaires

In accordance with Figure 4, contrary to the results of measurements in the last section, the traffic is assumed to be moving from left to right.

Symmetrical Luminaires

The following example has been calculated for various symmetrical luminaires:

Mounting height: $H = 12.5$ m,
Pole spacing: $S = 4 * H = 50.0$ m, $\lambda = 4$.

The results of the contrast calculations are plotted in Figure 7. There is predominantly negative contrast; that is, the background luminance is higher than the target luminance. The symmetrical luminaire always throws some light on the target, although very little at zero and between 30 and 50 m near the end. At the quarter point of the distance beyond a pole, the target is relatively bright, and the contrast may be close to zero if the main beams of the luminaires do not overlap sufficiently. It should be noted that the luminance distribution of symmetrical luminaires was found to be relatively uniform for all cases (1, 2, and 3).

Thus, for conventional luminaires with symmetrical light distribution, an important design principle has been confirmed by introducing contrast as a quality measure:

The quality of fixed highway lighting using symmetrical luminaires depends on the degree of overlap of the main beams, provided that glare can be held to a minimum acceptable value.

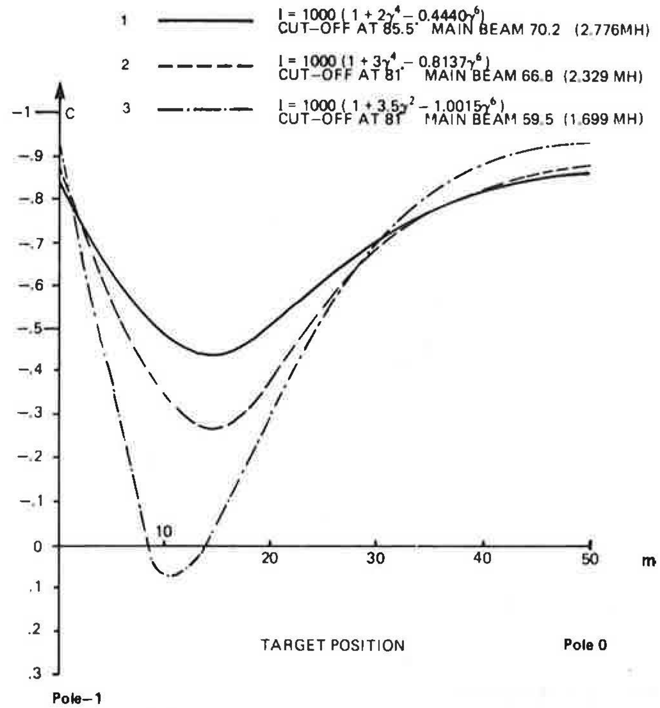


FIGURE 7 Distribution of contrast for symmetrical luminaires.

Nonsymmetrical Luminaires

Introducing contrast as a criterion for the quality of fixed highway lighting (together with luminance) would mean that new luminaire types could be developed. For separated expressways or roads with one-way traffic, it is possible to maximize the negative contrast by directing the main beam toward the driver, that is, in the direction opposite that of the traffic. However, at the same time, the (longitudinal) luminance distribution should remain fairly uniform. This is difficult to achieve with large pole distances if no light is directed away from the driver, that is, in the direction of the traffic. In other words, some light is needed in all directions. Numerous calculations of systems were carried out in order to find criteria for such an innovative luminaire, at least for the simplified system of two dimensions.

Using the same example as that used for symmetrical luminaires, the luminance intensity distributions are listed and plotted in Figure 8. The assumed cutoff angles are ±81 degrees. Between these cutoff points, there is a block of constant light output of 1,000 lumens, and for $\gamma > 0$ there is additional output directed toward the driver of approximately the same order of magnitude.

The luminance and contrast distributions are plotted in Figures 9 and 10, respectively. Both parameters have large enough values and reasonable uniformity for all three distributions of intensity: *1*, relatively narrow; *2*, medium; and *3*, wide. Narrow and medium distributions such as those labeled *1* and *2* appear feasible. The following observation can be made:

> Innovative nonsymmetrical luminaires for unidirectional traffic should have about half their output evenly distributed and the other half directed toward the driver.

This is a tentative conclusion that must be investigated further.

CONCLUSION

The contrast of a standard critical-size target object with 20 percent diffused reflectivity has been studied and may be regarded as a powerful criterion for evaluating the quality of

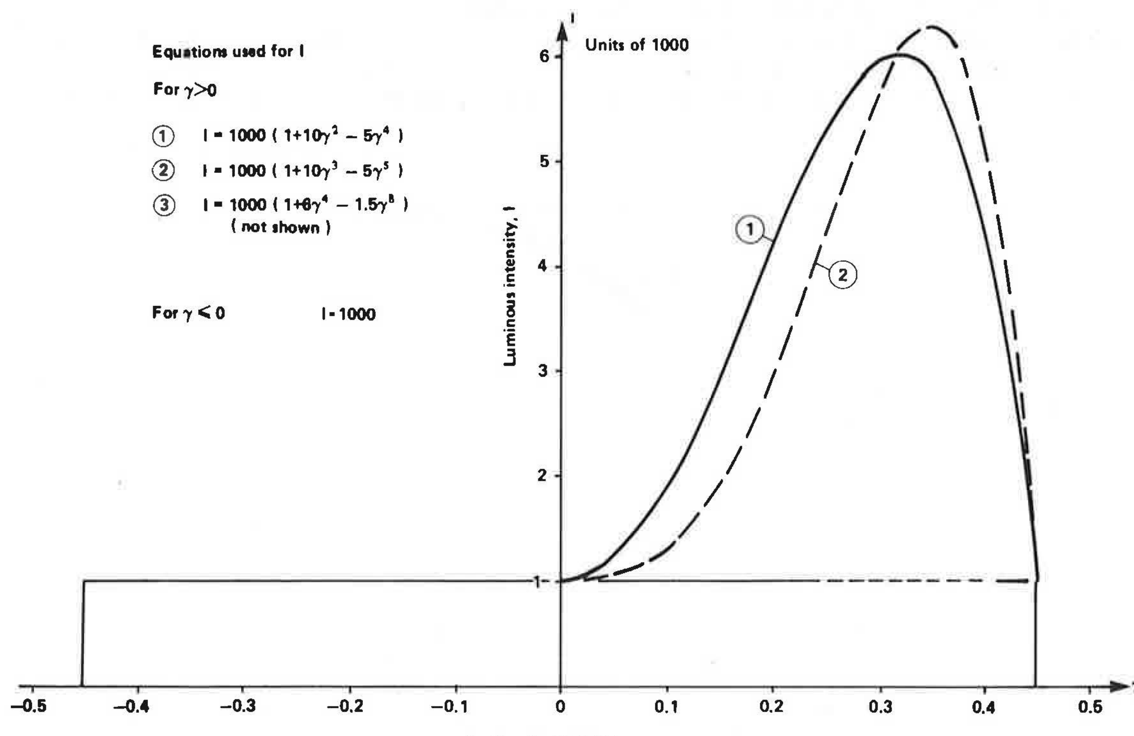


FIGURE 8 Luminance intensity for nonsymmetrical luminaires.

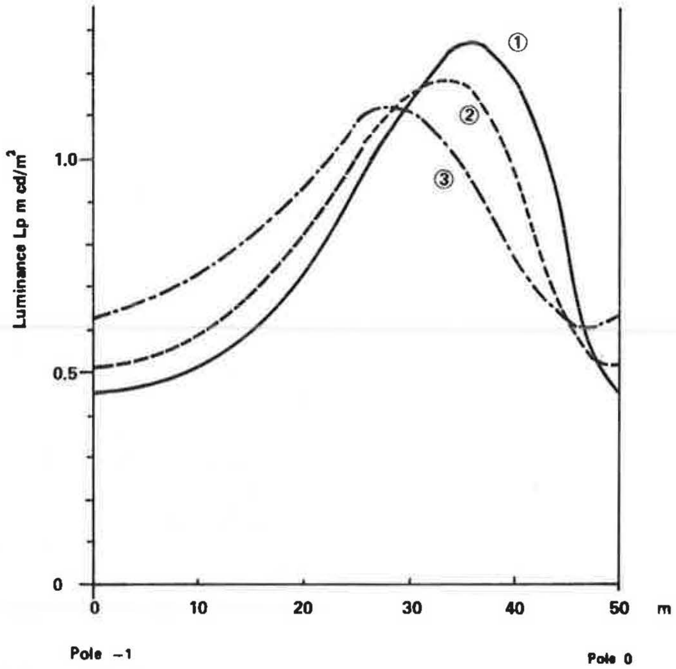


FIGURE 9 Luminance distribution for nonsymmetrical luminaires.

fixed lighting systems. Various reflectivity percentages may be chosen in a future system of standards.

This concept of contrast has been applied in a simplified systems calculation together with the usual illuminance and luminance distributions to find some basic criteria for the quality of roadway lighting with respect to night visibility and to evaluate the concept of standard target contrast.

In currently used systems with symmetrical luminaires, the overlapping of the main beams is important to avoid spots with low or zero contrast. Increased negative contrast can be achieved with nonsymmetrical luminaires directed toward the driver without having the main beams touch or overlap and with good distribution of luminance. Cutoff properties appear to be more critical in such innovative cases.

When this contrast concept is used (together with luminance and glare) to evaluate fixed roadway lighting systems, illuminance standards should be discarded.

These preliminary findings, once recognized, could lead to new and improved lighting standards and to an innovative development of new types of luminaires that are more energy efficient.

Without the introduction of additional standards of target contrast, manufacturers will have no incentive to develop innovative or improved conventional luminaire designs because the

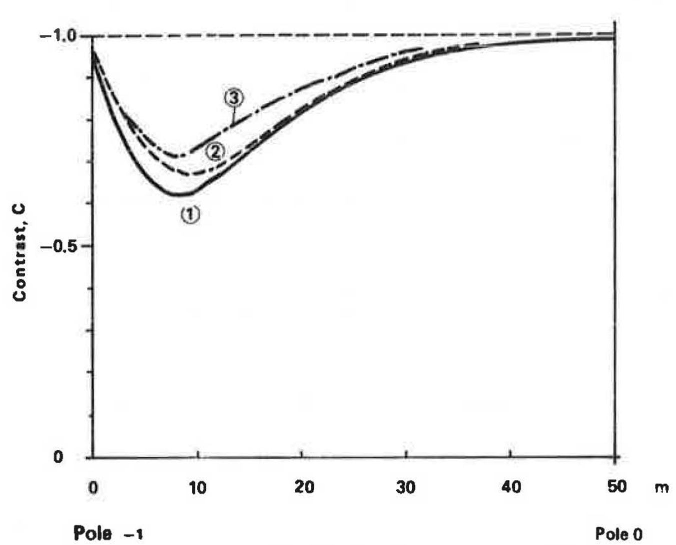


FIGURE 10 Contrast distribution for nonsymmetrical luminaires.

present standards of uniformity and level of illuminance and luminance in fixed highway lighting cannot reveal a system's weakness.

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A Method of Calculating the Effective Intensity of Multiple-Flick Flashtube Signals

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A method of determining the effective intensity of light flashes composed of multiple pulses (flicks) of light was devised. Detection thresholds were measured for such flashes when the flick frequency and flash duration were varied. Thresholds decreased with increasing flick frequency and flash duration. At each flick frequency the relationship between threshold and flash duration was well characterized by the Blondel-Rey relation (a = 0.2), provided a multiplicative frequency-dependent fitting parameter was chosen. The fitting parameter, β, increased linearly with frequency between 5 and 20 Hz. A method of determining effective intensity was described that uses the flick frequency, number of flicks, and the calculated effective intensity of a single flick to arrive at the solution. It was concluded that this method should be used for all multiple-flick signals, provided the single-flick duration is less than 0.01 sec and the frequency is between 5 and 20 Hz. The method of Allard should not be used, because it consistently overestimates effective intensity.

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A flashtube is a capacitive discharge device capable of emitting brilliant flashes of light in extremely brief time periods (on the order of microseconds). The highly intense flashtube burst can be detected at great distances and has been noted as a conspicuous signal in a typical aid-to-navigation system *(1)*. Moreover, the efficiency of converting input energy to visible output is greater than that of an incandescent light *(2)*. These factors make the flashtube attractive as an aid to navigation.

There are three major disadvantages associated with the use of flashtubes. The intense nature of the flick tends to momentarily blind the close observer *(3)*. Also, the duration of the single flick is so brief that mariners have difficulty fixing the exact location in the visual field *(3)*. Finally, mariners report difficulty judging the distance to the flashing source *(3)*. The latter two difficulties can be ameliorated by presenting several flicks in rapid succession so that the appearance is not one of individual flicks, but of a longer-duration flash. Previous studies have shown that individuals can take line-of-sight bearings with greater speed and accuracy when the flash duration is increased in this way *(4)*.

The detection distance of a lighted aid to navigation is valuable information because it not only allows one to calculate