Limitation of Disability Glare in Roadway Lighting

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Safety and comfort while driving at night depend on the visual detection of objects, which is based on contrast. The performance of this visual task is related to the relative contrast sensitivity of the lighting system provided, which is a function of roadway or background luminance and is adversely affected by disability veiling brightness or glare. The limitation of disability glare from luminaires by specifying a minimum value of effective relative contrast sensitivity for a particular road class is proposed. A simple formula has been derived for the effective relative contrast sensitivity of a lighting system by using curve-fitted, standardized data. Glare control by limiting the relative contrast sensitivity can be achieved by a permissible glare formula or a diagram. The method is demonstrated by examples. Relative-contrast-sensitivity glare control can also be combined with a method that is based on limiting the threshold increment of a critical-size object. The relative-contrast-sensitivity method and the visibility-index method both use the same concept of contrast-sensitivity change with glare.

Driving at night presents the driver with a visual task that is less comfortable and more critical for his or her safety than driving in daytime. Depending on the speed, headlights or fixed highway lighting or both are needed. If there is highway lighting, it must be of sufficient quality, since the visual task requires a certain level of luminance of the roadway surface, a certain degree of uniformity of this luminance, and a restriction of the glare from the luminaires in the visual field of the driver's eyes and from the headlights of opposing cars.

Glare has two effects on the driver: It creates feelings of discomfort and it interferes with vision. These effects are referred to as discomfort and disability glare respectively and are treated differently. In the design of roadway lighting, it is necessary to define and restrict both kinds of glare.

This report offers a concept that can be used to restrict disability glare. A driver's vision at night is concerned more with the detection than with the identification of objects. The detection of objects depends on the ability to distinguish luminance differences, and this ability is related to the reciprocal value of the contrast, which is called the contrast sensitivity. Any particular visual task requires a certain level of contrast sensitivity; the more difficult the task, the higher the level of contrast sensitivity required for it.

Methods for the evaluation of the visual-performance aspects of lighting have been recommended by the International Commission on Illumination (CIE) (2). The interference with vision by disability glare can be formulated within this framework by using well-known methods of glare calculation. This approach will develop a simple tool for evaluating the relative performance of lighting designs in terms of their relative contrast sensitivity (RCS).

RELATIVE CONTRAST SENSITIVITY

Vision during the operation of a vehicle at night is primarily a matter of the contrast between the object of vision and its background. In any visual task at low or medium luminance, if more light is available less contrast will be needed to fulfill the task successfully; i.e., higher contrast sensitivities can be permitted for the same visual task performed under better lighting.

The tabulated values of RCS as a function of background or adaptation luminance (for the vision of small objects) set the luminance of 10 000 cd/m^2, which represents daylight, at 100 percent. For lower values of background luminance, the RCS needed for the same visual task is a fraction of this maximum value.

For purposes of roadway lighting, only the lower part of this RCS function (that in the range of 0.2 to 2.5-cd/m^2 background luminance) is of interest.

As shown in Figure 1, in the luminance range between 0.15 and 2.5 cd/m^2, the standard RCS can be calculated by the following equation, which was obtained by curve fitting of the corresponding tabulated CIE values:

$$RCS = 13.7(L - 0.06)^{1/2} \tag{1}$$

where L = luminance in cd/m^2. This standard RCS will be modified by disability glare and eye adaptation when there are glare sources present in the visual field of the driver, so that the effective RCS values (RCS_{eff}) are smaller than the standard values for the same roadway luminance.

Therefore, this concept of RCS is appropriate for combining the following requirements for the visual task of night driving: (a) a sufficient level of roadway luminance and (b) a restriction of disability glare. The combination of these two can be achieved by specifying minimum values of RCS (RCS percentages) for various classes of highway lighting installations. This approach avoids introducing specific values of contrast into standard practice at the design level.

DISABILITY VEILING BRIGHTNESS

The physiological effect of disability glare has been described in terms of a scattering of light in the eye of the driver. The amount of scattered light is larger for older people, and the effect can be calculated in terms of a disability veiling brightness (DVB) that, in a manner similar to that of a veil, reduces the contrast of night vision. Of the many formulas that have been derived to calculate this veiling luminance or DVB value, the Holladay equation (4) may be the best:

$$DVB = 10E_v/2 \tag{2}$$

where E_v = vertical illuminance at the eye (in lux) = angle between normal line of sight (horizontal) and the glare source (in degrees). (The coefficient 10 is kept in accordance with the original reference.)

The contributions of DVB from all light sources in the driver's field of view are cumulative. Their geometric relationships are shown in Figure 4 and described by Equations 4 to 9 of the preceding paper.

Figure 2 presents a comparison of DVB equations derived by various authors (5, 6, 7, 8, 9) for a row of luminaires situated vertically above the driver's line of vision. The behavior of the function f for the very important smaller values of θ varies considerably among the different expressions, but Equation 2 appears to be as good as any other.

Because of the windshield framing, the angle (θ) is limited to the field of vision beneath an approximately 20° plane with the roadway level and therefore must be less than, or equal to, 20° (1).

Since all of the luminaires within this visual field contribute to the DVB,

$$L_v = DVB = \sum_{i=1}^{n} 10E_v/2 \qquad (3)$$

where

n = number of luminaires within the visual field of the driver, indexed with i, and
L_v = veiling luminance in cd/m².

PERMISSIBLE DISABILITY GLARE

The calculated luminance cannot be directly related to the night-driving task without modification. Whereas discomfort glare does not necessarily interfere with this task, disability glare does so by reducing the visibility of objects. This reduction can best be described by a reduction in contrast.

Figure 1. Relative contrast sensitivity.

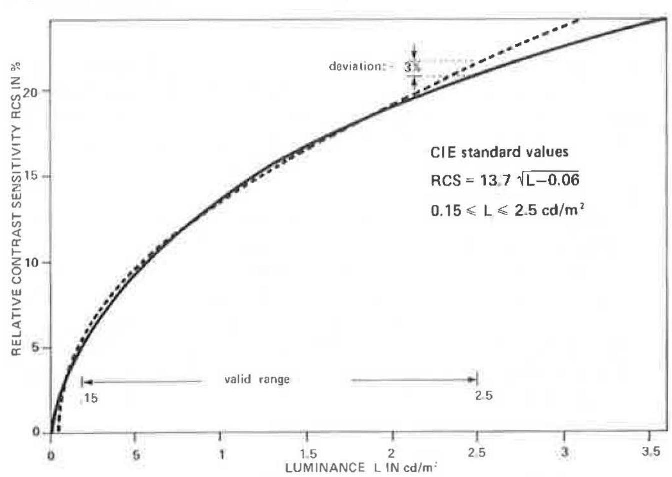
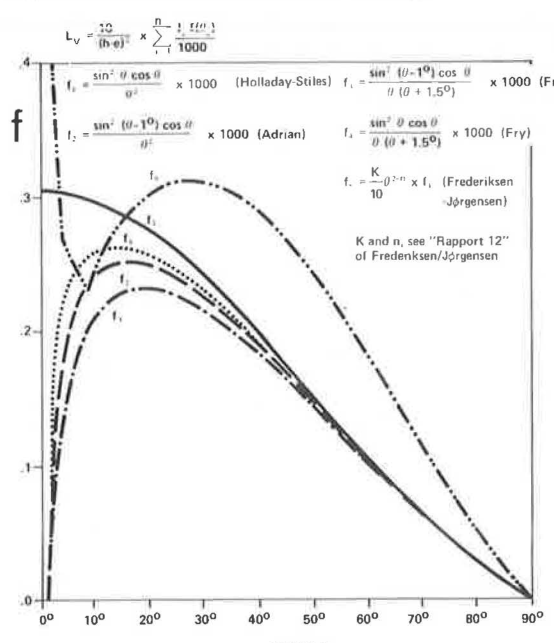


Figure 2. Functions f(θ) for C_o line or δ = 90°.



Denote

L = background luminance,
L_0 = object luminance,
L_v = veiling luminance (DVB),
C = contrast without the presence of veiling luminance, and
C_v = reduced contrast when veiling luminance is present.

Then, for small objects,

$$C = (L_0 - L)/L \qquad (4)$$

If L_v is added to both L_0 and L, this becomes

$$C_v = [(L_0 + L_v) - (L + L_v)]/(L + L_v) = (L_0 - L)/(L + L_v) \qquad (5)$$

Since the luminance difference (L_0 - L) is constant, the reduction in contrast is

$$C_v/C = L/(L + L_v) \qquad (6)$$

This almost constitutes a disability-glare factor (DGF), except that, because this reduction of contrast is partially countered by human-eye adaptation (2), it must be modified. The modified factor can be written as follows:

$$DGF = [1.074L/(L + L_v)]\ RCS[(L + L_v)/1.074]/RCS(L) \qquad (7)$$

where RCS(L) = standard relative contrast sensitivity for luminance L.

When the DGF is multiplied by the standard RCS(L),

$$RCS_{eff} = DGF \times RCS(L) = [1.074L/(L + L_v)]\ RCS[(L + L_v)/1.074] \qquad (8)$$

where RCS_{eff} = modified relative contrast sensitivity that takes disability glare into account.

As illustrated in Figure 1, the standard RCS can be approximated by Equation 1, so that

$$RCS(L + L_v)/1.074 = 13.7\{[(L + L_v)/1.074] - 0.6\}^{1/2} \qquad (9)$$

Equation 9 must be substituted into Equation 8 and is valid for 0.15 ≤ L ≤ 2.5 cd/m², which is the range of streetlighting luminance for average and minimum values. Within this range, the accuracy of the approximation is within 3 percent.

The performance of a lighting installation can be evaluated by setting permissible values for the disability glare; i.e., the RCS_{eff} provided by the lighting installation in terms of average roadway luminance under the influence of glare must not fall below a certain specified minimum value. In other words, the roadway luminance must not be so low, nor the glare so severe, that the required contrast for the visual task of night driving becomes excessively large, i.e., the contrast sensitivity must not be excessively low.

With this concept, the permissible DVB value (ΣDVB) can be established as a function of the prevailing average background luminance and an effective standard minimum value of RCS, which is specified in accordance with road classes or lighting warrants.

Denote

RCS(L) = reference relative contrast sensitivity for the average luminance of the particular lighting system (in percent),
L_{vall} = maximum permissible DVB (ΣDVB) (in cd/m²),

L = average prevailing roadway luminance (in cd/m^2),

L_v = maximum veiling luminance or DVB of the lighting system [dynamic average value for the worst 10 m (30 ft) along the lane with the most glare] (in cd/m^2), and

RCS* = minimum specified RCS for a particular road class (minimum effective value required in percent).

Then, from Equations 8 and 9

$$RCS^* = [1.074L/(L + L_{vall})]\ RCS[(L + L_{vall})/1.074] \qquad (10)$$

If Equation 9 is substituted for $RCS[(L + L_{vall})/1.074]$ and Equation 10 is solved for L, a functional relation between L and L_{vall}/L is obtained:

$$L = (RCS^*/13.7)^2\ [(L + L_{vall})/1.074L] + 0.6/[(L + L_{vall})/1.074L] \qquad (11)$$

or, if Equation 10 is solved for $L_{vall/L}$,

$$L_{vall}/L = 0.537KL\left\{1 + [1 - (0.24/KL^2)]^{1/2}\right\} - 1 \qquad (12)$$

where

$K = (13.7/RCS^*)^2$ and

L_{vall}/L = disability glare as the allowable fraction of average roadway luminance.

Within its range of validity ($0.15 \leq L \leq 2.50$ cd/m^2), Equation 12 can be used to calculate a permissible maximum limit for the disability glare, $\Sigma DVB = L_v$. Figure 8 of the preceding paper shows the permissible L_v values, as a percentage of L, versus L, for various RCS* percentages. The calculated DVB (L_v) must be smaller than the permissible value that was calculated by Equation 12.

It has been suggested that the limitation of disability glare should be based on the maximum value of the calculated L_v, but this value is very sensitive to the windshield cutoff angle and the density of the selected grid points. A more appropriate base may be the average of the 10 m of driving lane that has the worst glare, which corresponds to about 11 percent of the implied stopping distance of 90 m.

COMPARISON WITH THRESHOLD-INCREMENT CRITERION

Adrian and Schreuder (9) have proposed limiting disability glare by limiting the threshold increment (TI) for the detection of a critical object within 8 min of viewing angle. For the RCS criterion, the TI due to glare is unimportant so long as the ability to detect by contrast remains at the same level for a particular visual task of night driving. For higher, effective average-luminance values of the system, the permissible TI due to disability glare may also be higher, i.e., higher average luminance may be permitted to counter the visual disability from higher glare. On the other hand, the TI criterion implies that the increase in this threshold should be about the same for installations with high, average, or low luminance.

The TI due to glare is defined by

$$TI = (\Delta L_G - \Delta L_0)/\Delta L_0 \times 100\% \qquad (13)$$

where

ΔL_0 = threshold of luminance difference for detecting a critical object without glare interference and

ΔL_G = threshold of luminance difference for detecting a critical object under the influence of glare.

For given standard values of TI, L_{vall} can be calculated by using the following equation, which is valid for $0.05 \leq L \leq 5$ cd/m^2:

$$L_{vall} = (TI \times L^{0.8})/65 \qquad (14)$$

Curves for Equation 14 are plotted in Figure 8 of the preceding paper.

For L = 0.78 cd/m^2 (which is close to a proposed standard minimum value), both criteria, TI and RCS, are identical for RCS* = 10 percent and TI = 30 percent, but this TI value is twice as high as the maximum proposed by Adrian (9).

CONCEPT OF DISABILITY-GLARE CONTROL

Gallagher (3) has carried out visibility studies that use the same concepts (2) of RCS and the visibility-glare factor presented and defined in this paper. The relation between RCS_{eff} and Gallagher's visibility index (VI) can be expressed as follows:

$$RCS_{eff} = VI/C \qquad (15)$$

where C = physical contrast.

The evaluation of roadway lighting systems should be based on the RCS as defined by Equations 8 and 15, which eliminates any reference to a specified standard target for average design work. In particular, disability-glare control should be based on a diagram such as that shown in Figure 3, which shows limit lines for disability glare that, for any installation, can be plotted as percentages of average roadway luminances.

The steep limit lines at the left of the figure show that installations that have low glare can also have slightly lower values of average roadway luminance for the same level of visibility.

The horizontal limit lines are determined by approximately constant TI values. This diagram can be used directly for relative comparisons of installations. It is also potentially useful for extending this concept toward including (adding) values of headlight glare.

The RCS_{eff} or RCS* values are strictly design values to be calculated or measured by using lighting installation data only. They are not directly related to the visibility of a particular object at a particular stopping distance. This is an advantage over the visibility-index concept for average design work.

EXAMPLES

Example 1

Figure 4 (10) presents a design for a lighting installation. The average luminance and DVB values calculated for this installation with the Illum 1 program (11), which is discussed by Jung and Blamey in the preceding paper, are L = 0.686 and 0.980 cd/m^2 for black asphalt and for concrete respectively and L_v = 0.281 cd/m^2. For black asphalt at point 1A, $100L_v/L$ = 41 percent, and for concrete at point 1C, $100L_v/L$ = 29 percent.

Example 2

This example is based on an Illum 1 computer simulation of the existing lighting on Highway 401, the Toronto Bypass, and uses a maintenance factor of 0.8. The average luminance and DVB values are L = 0.68 and 0.97 cd/m^2 for black asphalt and concrete respectively and

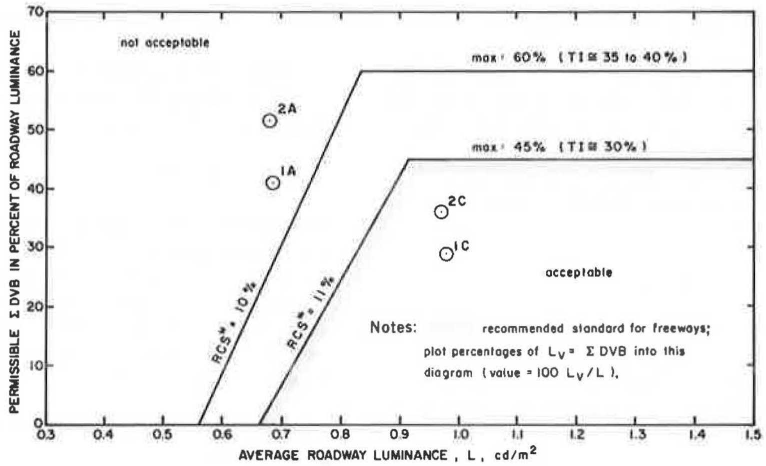


Figure 3. Glare-control concept.

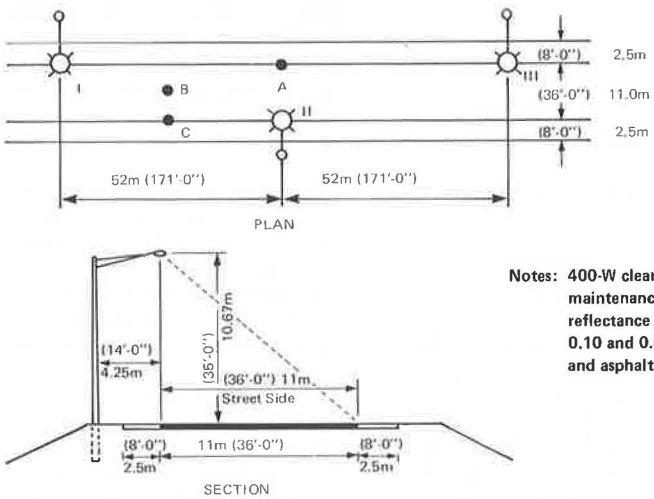


Figure 4. Design for a lighting installation.

Notes: 400-W clear mercury luminaire; maintenance factor = 0.68; reflectance surface: R3; q_o = 0.10 and 0.07 for concrete and asphalt respectively.

$L_v = 0.35$ cd/m^2. For black asphalt at point 2A, $100L_v/L = 51.5$ percent, and for concrete at point 2C, $100L_v/L = 36$ percent. The calculated disability glare is acceptable for concrete surfaces but not for black asphalt surfaces.

Neither of these examples would pass the visual TI criterion proposed by CIE, which may be too severe for North American luminaires. The maximum permissible value of TI, according to Adrian (9), is 15 percent, which is below the lower line on Figure 8 of the preceding paper.

CONCLUSIONS AND RECOMMENDATIONS

Disability glare, which is usually measured or calculated in terms of the DVB, reduces the necessary RCS_{eff} of roadway lighting for the particular visual task of night driving. The data available on the RCS (2) can be used to compare various lighting installations in terms of their visibility conditions under the influence of disability glare by establishing the percentage ratio of disability glare (ΣDVB) in relation to the average roadway luminance and then plotting these values into a glare evaluation diagram.

Any lighting design in which luminance method and disability-glare calculations have been applied can be represented by a point plotted in Figure 3, which can be used by designers to compare a variety of designs. These limit lines could also be more firmly established by research using standard targets and correlated driver-reaction time.

Recommendations about the calculation and measurement of DVB are as follows:

1. Use the Holladay formula (Equation 2) for calculations and a corresponding glare lens for measurement.
2. Calculate an average value of DVB over the worst 10 m of the worst lane, i.e., over those 10 m where the DVB is largest. This corresponds to a reasonably small fraction of the viewing or stopping distance.
3. Since the DVB depends on the visual field of the driver, and the windshield edge and the driver's eye form a limiting plane at a 20° angle with the roadway plane, evaluate this angle for passenger cars and drivers.

Since the RCS_{eff}, as defined and calculated in this paper, is identical with Gallagher's visibility index divided by the contrast (C) of his standard target, his method can be used to determine or verify standard RCS values.

REFERENCES

1. Calculation and Measurement of Luminance and Illuminance in Road Lighting. Commission Internationale de l'eclairage, Paris, Publ. 30 (TC-4.6), 1975.

2. A Unified Framework of Methods for Evaluating Visual-Performance Aspects for Lighting. Commission Internationale de l'eclairage, Publ. 19, 1972.
3. V. P. Gallagher. A Visibility Metric for Safe Lighting of City Streets. Journal of the Illuminating Engineering Society, Jan. 1976.
4. American National Standard Practice for Roadway Lighting. Illuminating Engineering Society, New York, 1972. Appendix C.
5. L. L. Holladay. The Fundamentals of Glare and Visibility. Journal of the Optical Society of America, Vol. 12, 1926.
6. G. A. Fry. A Reevaluation of the Scattering Theory of Glare. Illuminating Engineering, Vol. 49, 1954, p. 102.
7. G. A. Fry. Physiological Bases of Disability Glare. Proc., Commission Internationale de l'eclairage, Zurich, 1955, Vol. 1, 1.42.
8. W. Adrian. The Principles of Disability and Discomfort Glare. Visibility Symposium, Texas A&M Univ., College Station, 1968.
9. W. Adrian and D. A. Schreuder. A Simple Method for the Appraisal of Glare in Street Lighting. Lighting Research and Technology, Vol. 2, No. 2, 1970, pp. 61-73.
10. A. Ketvirtis. Highway Lighting Engineering. Foundation of Canada Engineering Corp., Toronto, 1967.
11. F. W. Jung and others. Computer Program for Fixed Highway Lighting. Ontario Ministry of Transportation and Communications, Interim Rept. IR 59, March 1976.

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Effect of Improved Illumination on Traffic Operations: I-76 Underpass in Philadelphia

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An experimental lighting system in an underpass on I-76 in Philadelphia was evaluated. The lighting system was designed to provide five levels of illumination ranging from 5382 lx (500 ft·c) horizontal to 22 lx (2 ft·c) horizontal. Low-pressure sodium-vapor lamps were used. The internal level was automatically set by a series of photocells external to the underpass and provided a ratio of internal to external illuminance of approximately 10 percent. Four measures were used to determine the effect of the improved illumination on traffic operations. These were (a) the effect on the number of traffic accidents, (b) the effect on vehicle-velocity maintenance, (c) the effect on deceleration (braking) characteristics, and (d) the effect on subjective responses of drivers to the new lighting. The photometric characteristics of the new lighting were evaluated and the Illuminating Engineering Society and the American Association of State Highway and Transportation Officials tunnel-lighting recommendations were compared. The results indicated that (a) the new lighting caused decreases in the velocity variability and in brake applications at the portal, (b) in general, as the internal lighting level increased, both the velocity variability and the number of brake applications decreased, indicating safer and smoother traffic operations, (c) drivers responded positively when the internal lighting levels were increased and there were no noticeable adverse effects caused by the low-pressure sodium-vapor lamps, (d) the Illuminating Engineering Society recommendations for tunnel lighting appear to be preferable to those of the American Association of State Highway and Transportation Officials, and (e) there was a reduction in the number of accidents inside the underpass and at the portal in the 6 months after installation of the new lighting.

The first object of this program was to evaluate the effects on traffic operations of lighting improvements in the eastbound section of the Thirtieth Street underpass on I-76 in Philadelphia. The improvements included a variable-level lighting system, the resurfacing of the roadway, and new reflective walls (both the side wall and a temporary center wall).

The second object was to determine whether the selected luminaires are adequate for their purpose and to compare whether Illuminating Engineering Society (IES) (1) or American Association of State Highway and Transportation Officials (AASHTO) (2) recommendations are better design guidelines for tunnel lighting.

SYSTEM DESCRIPTION

Original Lighting System

The original daytime lighting system (the before condition) consisted of two rows of 1500-mA fluorescent lamps supplemented by thirteen 400-W mercury-vapor lamps in the first 73 m (240 ft) of the underpass. The illumination provided by this system during the daytime was approximately 355 lx (33 ft·c) at an average position and about 538 lx (50 ft·c) at the portal entrance.

Present Lighting System

The present lighting system (the after condition) consists of five continuous rows of overhead fixtures in the first 49 m (160 ft) of the underpass, one row of fixtures in the next 30 m (100 ft), and the original fluorescent lamps for the remainder of the tunnel. Each fixture in a row houses two 180-W low-pressure sodium-vapor lamps, except that, in the center row, a 90-W lamp is substituted for one of the 180-W lamps in every eighth fixture.

The electrical circuitry is designed so that five different lighting configurations are possible. The control is monitored by a series of four photoelectric cells mounted outside the underpass. The inside design levels, the outside illuminations at which the circuits are ener-