Design and Operation of a Glare Evaluation Meter

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A new physical photometer has been designed to measure the spatially weighted average equivalent luminance of all visible areas of the total visual field, relative to the average luminance of a task background subtending two degrees in diameter. The spatial weighting follows traditional practice in general. The glare evaluation meter (GEM) uses two parallel optical systems with identical components. The left system collects the average luminance of the task background at 2 degrees. The right system has a modified disability glare lens mounted in front of the objective lens. The photometer measures L and L_V and then computes the glare contrast factor (GCF). All three values are output to a backlit 3½ digit LCD meter calibrated in cd/m². The fixed-focus, hand-held GEM is battery operated. Calibration of the meter is performed by using a variable level (up to 17,000 cd/m²) source of known solid angle and rotating the meter to generate various off-axis angles. The 2-degree task background luminance can also be varied. The operation of the GEM is described and sample values of GCF are given for sample glare situations. The new meter will allow dynamic and static conditions to be measured. Sample values of GCF are given for different glare conditions and with different values of the individual disability glare factor. The readaptation correction caused by continuous exposure to the glare source will be discussed for a sample glare situation involving the headlights of an oncoming vehicle.

The concept of a visual process designated "disability glare" has a scientific background, beginning with the work of Holladay in 1927 (*1*) and Stiles in 1929 (*2*). These two researchers found independently that off-axis lighted areas of the visual field reduce on-axis visual contrast sensitivity, operating as though a veil of equivalent luminance had been placed over the central visual field commonly accepted as 2 degrees. Gradually, evidence accumulated in support of the idea that disability glare was in fact caused by the ocular stray light produced by the off-axis lighted areas, in accordance with the following general relationship:

$$L_V \sim \frac{\mathbf{E}}{\Theta^2} \tag{1}$$

where

L_V = equivalent veiling luminance,
$\mathbf{E}$ = focused retinal illuminance, and
Θ = angle between an off-axis glare source and the ocular line of sight.

Calculations were made using Equation 1 covering simple patterns of luminance that provide appreciable amounts of ocular stray light. However, these calculations were generally considered insufficient to support a practical technology for dealing with disability glare under realistic conditions.

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HISTORY OF DISABILITY GLARE RELATIONSHIPS

In 1963, Fry, Pritchard, and Blackwell (*3*) produced a point-to-point mathematical approach to the calculation of ocular stray light and equivalent veiling luminance on the basis of a more explicit formula for the relationships among the parameters.

$$L_V = K \sum_{\Theta=1°}^{90°} \frac{L_s \cos \Theta}{\Theta\,(1.5 + \Theta)}\, \omega \tag{2}$$

where

L_V = equivalent veiling luminance (cd/m²),
L_S = luminance of an individual glare element of the task surround (cd/m²),
Θ = angle between the glare element and the task (degrees),
ω = solid angle of an individual glare element (sr), and
K = disability glare factor, a proportionality parameter expressing the degree to which the eye of an individual observer produces scattered light per unit of glare element luminance.

The summation is taken between the values for Θ of 1 and 90 degrees.

Fry et al. also reported the design and use of a "disability glare lens," which represented an optical analogue of the process of stray light in reducing visual contrast sensitivity. The curvature of the aspheric lens was established by ray-tracing methods to work together with a photometer developed by Pritchard. The combination of Pritchard Photometer and Fry-Blackwell disability glare lens has worked well and made it possible to proceed with development of a practical technology for handling the disability glare aspects of lighting design and evaluation.

One major contribution to disability glare technology was CIE Report 19/2 (*4*). The state of the art in the broad area of visual performance aspects of lighting is described, as is disability glare technology as applied to the engineering of interior lighting. Thorough reading of CIE 19/2 is recommended for understanding the contribution of disability glare to the visibility level (VL) equation. The basic approach of Report 19/2 is summarized by the following equation:

$$L_V = K \sum_{\Theta=1^\circ}^{90^\circ} \frac{L_s \cos \Theta}{\Theta^2} \omega \tag{3}$$

Note that the numerators for Equations 2 and 3 are the same and include the cosine theta term. This term allows for the effect of the first cosine law of illumination in reducing L_V as Θ is increased. The denominators for Equations 2 and 3 differ. The classical equation for the disability glare effect includes Θ^2 in the denominator and is usually referred to as the Stiles-Holladay Equation because it was derived in large part from the research of Stiles and Holladay. Equation 2 should perhaps be designated the Fry-Blackwell Equation because Fry et al. were the first to suggest replacing Θ^2 with $(1.5 + \Theta)$. Report 19/2 recommends use of the Stiles-Holladay Equation (3). However, current use among U.S. lighting engineers favors the Fry-Blackwell Equation (2). Use of the Stiles-Holladay Equation is recommended unless specified otherwise.

A way out of this dilemma, described by Blackwell (*5*), is suggested because of the similarity between the denominators of Equations 2 and 3. Consider the performance curves of disability glare lenses as described by Fry et al. A linear scale of Θ is plotted on the abscissa; a log scale of relative L_V is plotted on the ordinate, covering 5 log units of potential disability glare responses. Calibration of the disability glare lens involves the determination of the best fit of the measured lens data to either Equation 2 or 3. This is usually performed by either a least squares computer fit or by a visual analog fit of the theoretical curve to the measured data. Thus, two differing calibration factors (modifiers of the disability glare factor) for Equations 2 and 3 can be derived. The best fit of the measured lens data to each equation provides quite acceptable fits over the most commonly used glare source angles.

STATIC CONDITIONS AND CIE REPORT 19/2

In 1955, Blackwell (*6*) pointed out that there are conditions in which disability glare effects will be reduced relative to values calculated from either Equation 2 or 3. These conditions require that eye and source of ocular stray light be unmoved long enough so that the visual contrast sensitivity is increased at least somewhat because of light adaptation to the luminance $(L + L_V)$, when L equals the focused luminance of the task background. Blackwell suggested that calculations of disability glare effects always include allowances for somewhat improved sensitivity when light adaptation occurs. Nonetheless, further study of this subject has lead the authors to recommend that standard usage involves no assumptions concerning light adaptation unless specified otherwise.

CIE Report 19/2 also called attention to the question of which baseline should be used in measuring values of L_V. "Sphere lighting" is recommended in the report as the baseline for use in disability glare applications involving interior illumination. In these cases, the baseline value of L_V equals 1.074 times the focused luminance. Those interested in road lighting find the sphere lighting baseline unreasonable and will probably use L_V equal to zero as their working baseline.

CIE Report 19/2 contains reference to the problem of the appropriate value to assume for the disability glare parameter (K). There appears to be remarkable good agreement that the value of this important parameter is approximately equal to 10. Fry et al. used a value of K equal to 9.2. In 1980, Blackwell and Blackwell (*7*) reported values of K obtained for 193 observers between the ages of 20 and 30 years. Through use of the glare annulus test, the average value of K was found to be 10.8. The average of 9.2 and 10.8 is equal to 10.0 the value recommended for K in Equations 2 and 3.

Report 19/2 also contains reference to systematic differences in K as a function of age and as a function of luminance level. The pupil diameter of the eye varies with luminance. The higher the luminance, the smaller the pupil and the less scattered light in the eye system. The equations presented here are collated from work by de Groot and Gebhard (*8*). The relationship between K and observer age for the lowest luminance was made available by Adrian (personal communication with Werner Adrian). Data relevant to these issues can be found elsewhere (*5*), but are presented here for the reader's convenience. The relationship of pupil size p to luminance is illustrated in Figure 1.

1. Fixed age of 20
2. Solve for $K_{20} = 8.0 + 3.523(p - 1.82)$
   where $p = \text{antilog}[.8558 - .000401(\text{Log}\,L + 8.60)^3]$ (4)
3. Solve for K_{rel}
   $A < 42.8 \quad K_{rel} = 1$ (5)
   $A > 42.8 \quad K_{rel} = \text{antilog}[1.778(\text{Log}\,A - 1.631)]$
4. $K = K_{20} \times K_{rel}$ (6)

Values of Log L are in Log cd/m²; values of A are in years of age; values of p are in mm.

DEVELOPMENT OF GLARE EVALUATION METER

The foregoing accounts of various aspects of current disability glare technology demonstrate that the technology is no longer limited to a single instrument or single instrumental mode of operating. Furthermore, continued advances in the technol-

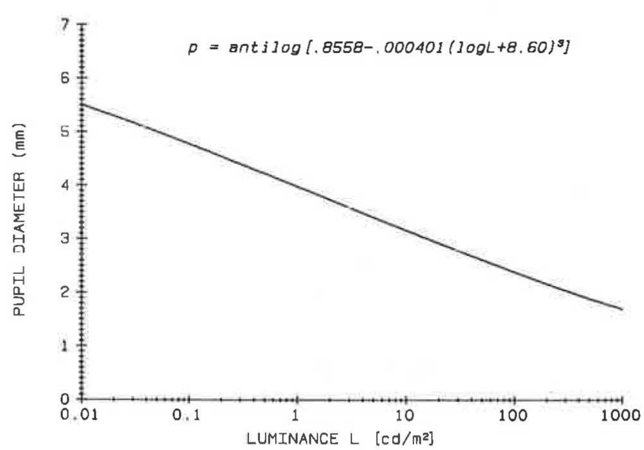

FIGURE 1 Relationship of pupil size *p* (mm) to adapting luminance (cd/m²).

ogy demonstrate the potential of its increased usefulness. It appears that the time has now come to offer a relatively sophisticated instrument for engineering problems in visibility and lighting.

The authors propose to designate this instrument as a glare evaluation meter (GEM). Its primary function is to measure the glare contrast factor (GCF), defined as follows:

$$\frac{L}{(L + L_V)} = \text{GCF} \qquad (7)$$

where L is the luminance of the immediate background of the task detail of interest and L_V measures the spatially weighted average equivalent luminance. In CIE Report 19/2 this equation is defined as the disability glare factor/index. The authors recommend the new term as more definitive in expressing the effect of glare (i.e., reducing the luminous contrast). In addition, the authors have chosen a GCF of 0.8 as implying a reduction in contrast of 20 percent, the level below which adverse impairment occurs. Figure 2 shows a schematic of the GEM and the respective fields of view.

Dynamic conditions, such as measurement of the disability glare from the headlights of an oncoming vehicle can be recorded easily as a function of the distance between vehicles or between a pedestrian and an oncoming vehicle. The portable GEM has an analog output jack that can be used with a RAM data logger for this purpose.

The meter consists of two identical optical systems with a fixed hyperfocal distance of 14 m, which allows objects from 7 m to infinity to remain in focus. The two systems are separated by 45 mm, or slightly more than 17 mm closer than the average human interocular separation. Each system has an objective lens, baffles, field lens, photopic filter, and silicon detector. The field of view of each system is fixed at the commonly accepted foveal angle of 2 degrees used in the determination of the luminous efficiency and color-matching functions of the CIE. The systems are electronically balanced.

One system accommodates the disability glare lens, which sums the weighted field of view up to an 85-degree half angle. The glare lens has been in production since 1963 by

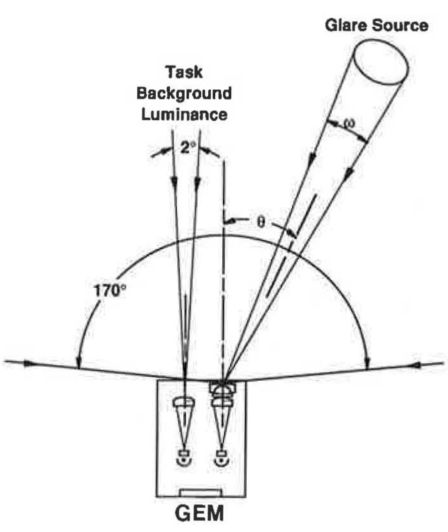

FIGURE 2 Schematic view of GEM and respective fields of view.

Visioneering Laboratories, Inc., and since 1983 by Advanced Retro Technology, Inc. This lens has been reduced in size from the type normally furnished to photometers but retains the important characteristics of fit to equations 2 and 3 over four logs of veiling luminance.

The meter is powered by lithium replaceable batteries to give the instrument a long life (which has not yet been determined) and measures selectively the 2-degree task background, the veiling luminance, and the glare contrast factor. Task background luminances from 0.1 to 1,999 cd/m² using two manual ranges are within the GEM's measurement capability.

CALIBRATION OF THE GEM

Typical Disability Glare Lens Calibration

Description of the disability glare lens is given by Fry, Pritchard, and Blackwell (*3*). Calibration of such a lens is performed in a photometric laboratory using a small intense projection source of constant luminous intensity. The lens is placed in front of a photometer, which in turn is mounted on a precision rotating table. The lens is rotated around its front surface (flat), and the photometer's response is recorded at various angles. The response data are normalized at 1 degree off the axis of the line of sight (LOS). These data are plotted as the relative veiling luminance L_V versus the angle (0) from the LOS.

A relative theoretical relationship from either Equation 2 or 3 is computed and normalized at $0 = 1$ degree. The lens data, also normalized at $0 = 1$ degree, are then compared with the relative theoretical relationship. Adjustment is then made in the ordinate of the theoretical curve until it closely fits the data (least square solution). The disability glare lens is calibrated absolutely with the photometer using a single glare source of known physical characteristics at $0 = 45$ degrees. If the "best fit" theoretical curve passes through the normalized lens data point at $0 = 45$ degrees, then the calibration constant G_C is the value obtained by direct absolute calibration. The calibration constant G_C may be adjusted if this does not occur for the general measurement situation, or if a discrete glare source at known angles is measured, individual G_Cs may be determined. This G_C can be considered a modification of the disability glare factor to allow for instrument and lens losses that normally occur in instruments of this type. Use of the G_C thus determined, together with absolute photometric readings, will yield equivalent veiling luminances (L_V) in cd/m².

Glare Evaluation Meter

In the GEM, calibration is performed in a similar manner but with a least-squares fit to Equation 2 or 3. The calibration constants are then electronically introduced in the GEM to yield the correct L_V. A final check of the GEM before shipment involves linearity measurements and verification of the values of L, L_V, and GCF using a variable luminance source ($L_S = 0 - 17{,}000$ cd/m²) with varying solid angle (ω). Checks are made at several glare source angles. Figure 3 shows the degree of fit, using a least-squares solution to the Fry-Blackwell and Stiles-Holladay equations. The calibration factors are different for these equations; the GEM may be adjusted

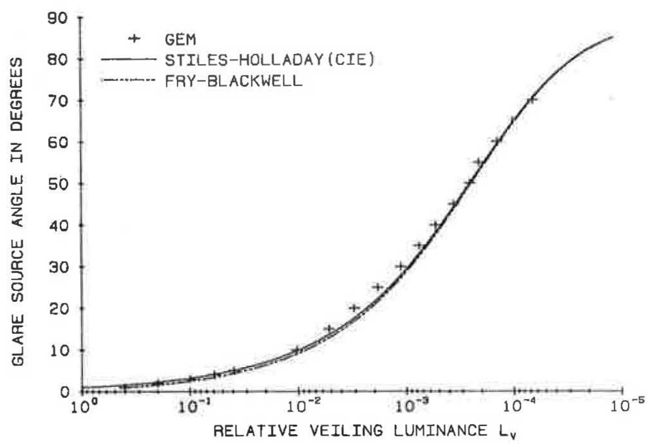

FIGURE 3 Plot of the two disability glare equations; the fit obtained to these equations by the GEM is shown by the crosses.

to yield results based on one or the other. Likewise the calibration factors may be weighted for the "best fit" to glare source angles from 1 to 20 degrees for tunnel entrances and other roadway lighting uses.

The baseline condition for the glare contrast factor differs for nighttime outdoor illumination and indoor lighting. For nighttime outdoor conditions without disability glare, L_V should equal 0. Under sphere lighting indoors, the GCF baseline condition involves setting L_V to $1.074L$.

EXAMPLES OF POSSIBLE USE OF THE GEM

The GEM was briefly field tested at different sites under static and dynamic conditions. Because the GEM is used to measure L, L_V, and GCF, various operational modes may be used. The simplest assumes that light adaptation does not occur and that the observer remains adapted to L. Under some static conditions, light adaptation does occur so that the observer is adapted to $(L + L_V)$. Calculational techniques are now available for use in tracking the observer's state of visual contrast sensitivity. A transient adaptation model assumes that the loss in visual contrast sensitivity is a result of contrast compression of an off-balance dynamic control system.

Corrections for Age and Luminance

One of the most important computations derived from the GEM data are the corrections for age and luminance. The design parameters for the GEM are based on adaptation at task background levels of 100 cd/m^2 and the age group 20 to 42.8 years.

Task background luminances may range from low conditions at night (0.01 cd/m^2 to 10 to 20 cd/m^2 or more). Today's design driver is older than 42.8 years (see Equation 5). One can use Equations 4–6 to compute the effect of luminance on pupil size and make corrections for luminance and age. Use of nomographs would make such computations unnecessary. Figure 4 is a nomograph that relates the K parameter to age and luminance. The resultant K parameter is then used to correct the GCF measured by the GEM (Figure 5). For example, a static nighttime task background of 5 cd/m^2 $(L + L_V)$ for a 60-year-old driver yields a K factor of 25. The veiling luminance effect for this driver is 2.5 times that of a 20- to 42.8-year-old driver adapted to 100 cd/m^2. If the GEM measured a GCF of 0.9, this driver would have an equivalent GCF of 0.8, a level at which 20 percent of his or her VL would be lost.

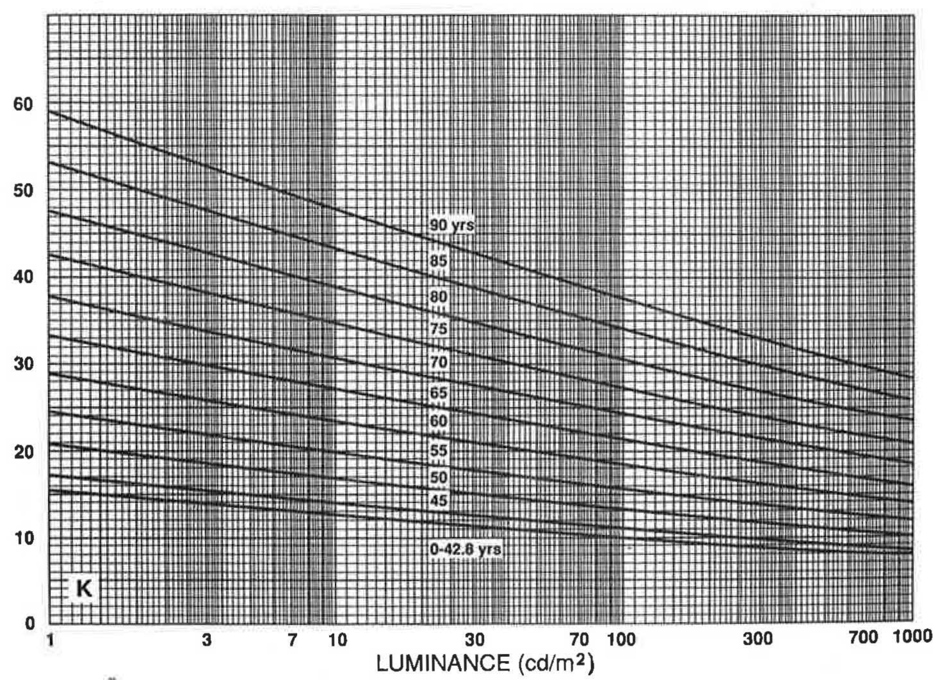

FIGURE 4 Nomograph of the disability glare factor *K*, adaptation luminance and age.

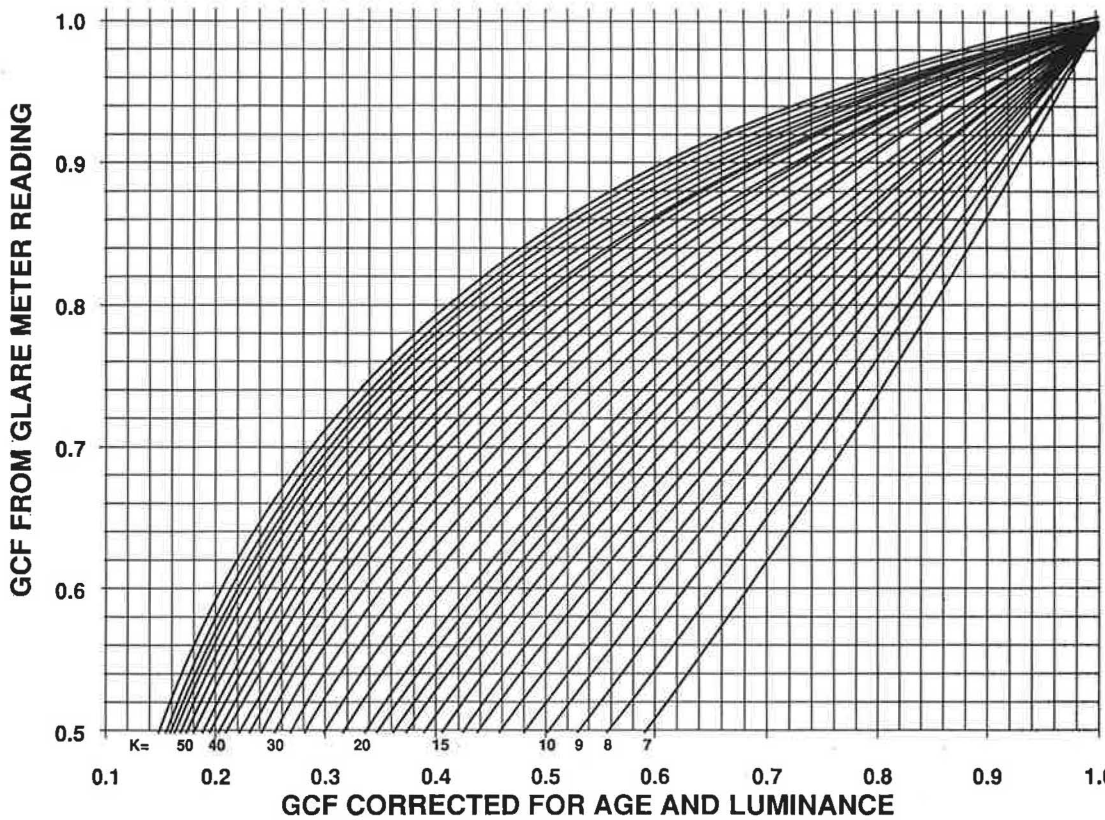

FIGURE 5 Nomograph of *K*, and GCF measured with the GEM and the corrected GCF.

Static Field Measurements

Table 1 presents measurements taken with the GEM at some typical nighttime scenes. For these static scenes the adaptation luminance is given in the $(L + L_V)$ column. The measured GCF is then corrected for the adaptation luminance and given in the column labeled "GCF corr." The asterisks denote those scenes that have more than a 20 percent loss in visibility level. The GCF, L_V values are those using the Stiles-Holladay Equation (2).

Dynamic Field Measurements

Measurements were taken with the GEM just outside a parked vehicle at the driver's eye height and at a distance of 120 ft

TABLE 1 EXAMPLES OF VARIOUS NIGHTTIME SCENES

	Description	L cd / m²	L + Lv cd / m²	GCF Meas.	GCF Corr.
1.	Parking lot with Low Pressure Sodium building lights - GM looking at entrance to suite.	0.5	.909	.55	.44*
2.	Same scene tilted downward toward sidewalk	1.3	1.55	.84	.78*
3.	Hi Pressure Sodium luminaire on 30' mask -95' from luminaire looking at pavement under source.	2.3	2.35	.98	.97
4.	Same scene 25' from luminaire.	2.3	2.53	.91	.88
5.	Store front with bare fluorescent lamps (diffuse sign missing) GM looking at store entrance.	0.9	1.73	.52	.44*
6.	Shopping center parking lot 120' from parked cars and one luminaire - 3 Hi Pressure Mercury lamp luminaires in vicinity.	2.6	3.61	.72	.65*
7.	80' away	2.6	3.21	.81	.75*
8.	25' away	2.9	3.29	.88	.84
9.	Another Hg luminaire 35' away looking at parking area.	3.1	3.60	.86	.81
10.	Same area, looking at entrance to store.	0.9	1.41	.64	.56*

* Scenes having over 20% loss in visibility level.

in front of the vehicle at the right edge of the pavement. The low beam of the vehicle was turned on, and measurements of the GCF were obtained from an oncoming vehicle (Nissan Maxima) whose headlight distribution pattern was unknown. Figure 6 shows the GCF as a function of approaching distance for the high-beam case on a two-lane road. The visual angle between the GEM and the vehicle was between 2 and 8 degrees. This road was straight with a slight downgrade. The oncoming vehicle turned a corner into the right lane at about 530 ft. Figure 7 is similar to Figure 6, but in this case the oncoming vehicle was stopped at 730 ft and its headlights were turned on before it proceeded toward the GEM. In each figure the level at which a 20 percent loss in visibility level occurs is indicated, first for 20- to 42.8-year-old drivers and then for 65-year-old drivers. Vertical lines show the intersection distances at points at which the 20 percent impairment begins. In Figures 6 and 7 these threshold levels indicate that the 20 percent loss for a 65-year-old could result in a greater distance over which objects on the roadway of low contrast might not be seen as compared the distance for with younger drivers.

SUMMARY

The convenience of obtaining the photometric and glare measurements with one meter will provide greater ease in measuring conditions in which disability glare has an adverse effect. Although the examples given are preliminary in nature,

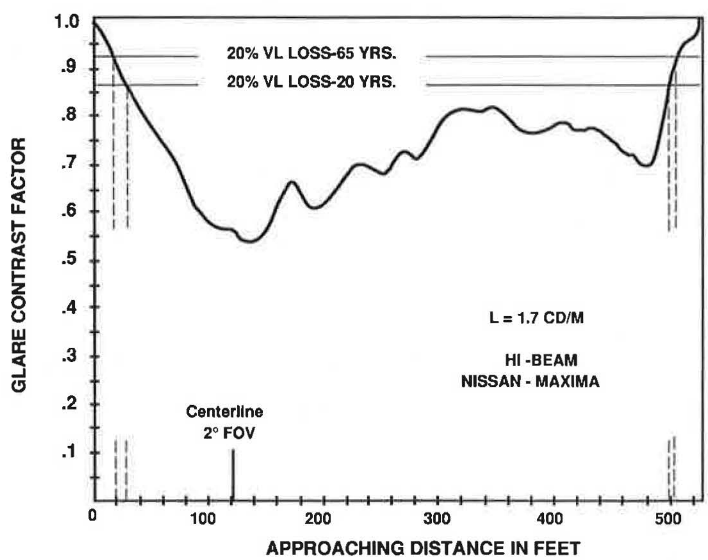

FIGURE 6 Dynamic measurement of oncoming vehicle headlight glare for high beams; vertical lines show the distance at which the transition occurs.

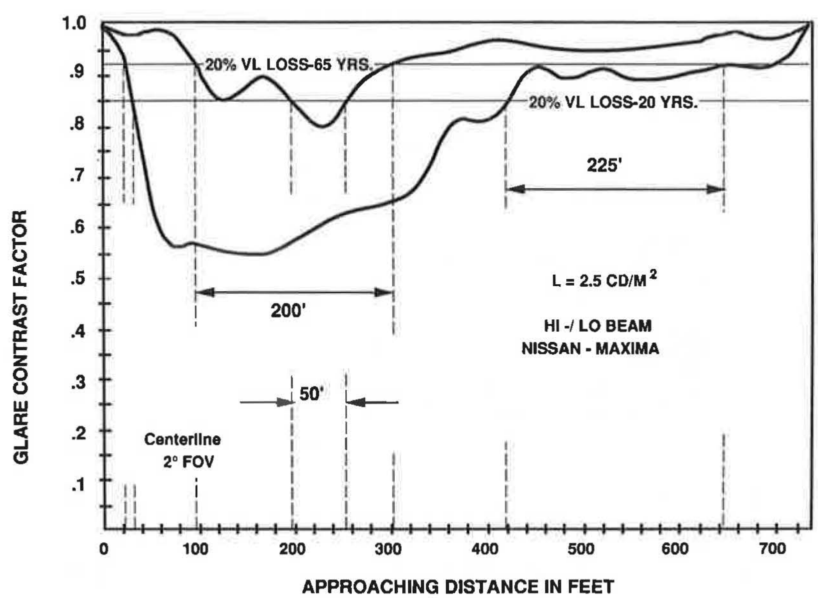

FIGURE 7 Dynamic measurement of oncoming vehicle headlight glare for low and high beams at a longer distance over an undulating roadway.

the method holds promise for quantifying disability glare in dynamic conditions.

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