

Analytic Study of Daytime Running Lights as Potential Sources of Disability and Discomfort Glare under Ambient Illumination Conditions Ranging from Dawn through Dusk

**Final Report
October 26, 1998**

Prepared for General Motors Corporation by:

**Frank Schieber, Ph.D. and Michael Harms, M.A.
Heimstra Human Factors Laboratories
University of South Dakota
Vermillion, SD 57069**

Technical Report No. HFL-98-10

I. Introduction

This study was commissioned pursuant to the following Statement of Work:

Conduct an analysis, utilizing existing research and first principles, which assesses both upper and lower beam daytime running lamps (DRLs) as a potential source of disability and/or discomfort glare, under ambient lighting conditions ranging from dawn to dusk.

The range of DRL luminous intensities examined was constrained by Federal Rule MVSS 108 (see details below).

The photometric definitions of dawn through dusk used in this analysis are operationalized as the following nominal values:

<u>Lighting Condition</u>	<u>Driver Adaptation State (cd/m²)</u>	<u>Typical Roadway Illumination (lux)</u>
road at night	1	100
late twilight/early dawn	50	
mid-twilight/mid-dawn	100	5000-7000
early twilight/late dawn	500	
overcast daytime sky	1000	
clear bright sky	5000-6000	70,000-85,000

II. Disability Glare.

Disability glare impairs vision without necessarily causing the experience of discomfort. The physiological basis of disability glare is well understood. Relatively intense sources of light that enter the eye tend to be scattered off-axis by the optic media. When the magnitude and spatial extent of such intraocular scatter is great enough, the contrast of the retinal image can be reduced to the point where visual sensitivity and performance decline.

a. Method of assessment

The traditional (and validated) manner of assessing the magnitude of disability glare is a 2-step process in which:

(1) The “equivalent veiling luminance” ($L_{\text{equivalent}}$) of the glare source across the retina (thus, reducing the contrast of the retinal image) is estimated based upon:

- a) the illumination of the glare source reaching the eye of the observer (E_{glare});
- b) the angle between the glare source and observer’s line-of-sight (θ); and,
- c) the age of the observer.

Adrian and Bhanji (1991), incorporating developments introduced by Fisher and Christie (1966) and Ijspeert, et al. (1990), have described a state-of-the-art formula for calculating the “equivalent veiling luminance” ($L_{\text{equivalent}}$) that models the effects of a disabling glare source. This formula will serve as the basis for the analyses of potential disability glare effects in this report and is defined as follows:

$$L_{\text{equivalent}} = k \cdot \frac{E_{\text{glare}}}{\theta^2} \quad (\text{Equation 1})$$

where:

E_{glare} is the illumination of the glare source
at the eye of the observer (lux)

$$k = 9.05 \left(1 + \left(\frac{\text{Age (in years)}}{66.4} \right)^4 \right)$$

θ is the angle between the glare source and
the observer's line-of-sight (degrees)

(2) The “equivalent veiling luminance” ($L_{\text{equivalent}}$) attributed to the glare source is then used to estimate the relative elevation of the contrast threshold (**Threshold_{elevation}**) as modified by the background luminance ($L_{\text{background}}$) or adaptation state of the observer’s eye.

The contrast threshold is usually defined as the minimum increment (or decrement) in the luminance of a target (ΔL) that is required to render said target as “just visible” against a particular background luminance ($L_{\text{background}}$) and is usually expressed as $\Delta L/L_{\text{background}}$.

The relative elevation of the contrast threshold due to the introduction of a glare source is given by:

$$\text{Threshold}_{\text{elevation}} = \frac{\Delta L/L_{\text{background}}}{\Delta L/L_{\text{background}} + L_{\text{equivalent}}}$$

Equation 2

According to Blackwell (1946), the contrast threshold for small to mid-sized objects representing critical details in the roadway environment is approximately 1% (i.e., 0.01) for drivers adapted to a wide range of photopic luminance levels (i.e., dawn through dusk). Substituting this value of 0.01 as the contrast threshold (in the absence of glare) into Equation 2 yields the following formula that shall be used in subsequent analyses to estimate the effects of disability glare due to daytime running lights:

$$\text{Threshold}_{\text{elevation}} = \frac{0.01}{0.01 (L_{\text{background}}) / L_{\text{background}} + L_{\text{equivalent}}}$$

Equation 3

Relative elevations in the contrast threshold following the introduction of a glare source must exceed 2.0 (i.e., a 2-fold increase) before significant disability glare effects can be said to be present (see Schmidt-Claussen and Bindels, 1974).

b. Analysis

The first step in the analysis of the magnitude of disability glare from daytime running lights is to calculate the illumination of the potential glare sources at the eye of the observer (i.e., E_{glare}). This value is dependent upon several factors, including: the geometry of the viewing conditions and the peak intensity of the daytime running lights measured at or above the horizontal plane of reference. Based upon the average location, height and separation of vehicular headlamps (Sivak, Flannagan, Budnick, Flannagan and Kojima, 1996), viewing distances of 20 m through 100 m (i.e., inverse-square law) and the assumption of opposing vehicles on a 2-lane road having 3.7 m lane widths, the geometry presented in Table 1 was devised to calculate the E_{glare} values used in subsequent analyses.

Viewing Distance	Glare Angle (deg)			DRL Luminous Intensity (cd)				
	Interior DRL	Exterior DRL	midpoint	1500	3000	5000	7000	10000
20 m	7.41	10.48	8.94	7.50	15.0	25.0	35.0	50.0
40	3.72	5.28	4.50	1.88	3.74	6.25	8.74	12.5
60	2.48	3.53	3.00	0.84	1.66	2.78	3.88	5.56
80	1.86	2.65	2.25	0.46	0.94	1.56	2.18	3.12
100	1.49	2.12	1.80	0.30	0.60	1.00	1.40	2.00

Table 1.

Dual lamp E_{glare} dosage (lux) at the eye of the observer as a function of Viewing Distance and Daytime Running Light Intensity

Based upon the E_{glare} values in Table 1, the equivalent veiling luminance (Equation 1) and the relative threshold elevation (Equation 3) due to disability glare was calculated for daytime running lights having H-V spot luminous intensity of 7000 cd; viewing distances of 20, 40, 60, 80 and 100 m; observer ages of 25, 65, and 75 years; and, background luminance adaptation levels of 1 and 50 cd/m^2 , respectively. The 7000 cd intensity value was selected for analysis because it was the maximum level permitted under the current *Federal Rule MVSS 108*; and, hence, represented a “worst case” glare source exposure under “test bench” conditions.

Accordingly, reference to Table 2 reveals that under the lowest background luminance adaptation state found under daytime conditions (viz., 50 cd/m^2 at dawn and/or dusk) there are no significant (i.e., greater than 2) elevations in contrast threshold regardless of viewing distance and/or age of observer. That is, no disability glare occurs in the presence of 7000 cd daytime running lights.

In order to determine whether daytime running lights with horizontal plane luminous intensities of 7000 cd would represent as source of disability glare if operated under nighttime conditions, Table 2 also contains a summary of the elevations in threshold contrast that would be expected to occur given a luminance background adaptation state of 1 cd/m^2 (equivalent to a dark roadway at night). This analysis reveals that if such a daytime running light configuration was deployed at night that opposing drivers of all ages at all viewing distances (at least through 100 m) would demonstrate significant levels of visual impairment due to disability glare (i.e., elevations in contrast threshold ranging from 5 through 11-fold). This suggests that special care must be taken to minimize the likelihood of drivers’ mistakenly operating such daytime running light configurations at night.

Viewing Distance (m)	Glare Angle (deg)	E_{glare} (lux)	$L_{\text{equivalent}}$			$\text{Threshold}_{\text{elevation}}$					
						1 cd/m^2			50 cd/m^2		
			Age			Age			Age		
			25	65	75	25	65	75	25	65	75
20 m	8.93	35.0	4.1	7.6	10.4	5.1	8.6	11.4	1.1	1.1	1.2
40	4.50	8.74	4.0	7.5	10.3	5.0	8.5	11.3	1.1	1.1	1.2
60	3.00	3.88	4.0	7.5	10.2	5.0	8.5	11.2	1.1	1.1	1.2
80	2.25	2.18	4.0	7.5	10.2	5.0	8.5	11.2	1.1	1.1	1.2
100	1.80	1.40	4.0	7.5	10.3	5.0	8.5	11.3	1.1	1.1	1.2

Table 2.

$L_{\text{equivalent}}$ estimates of interocular light scatter due to glare and $\text{Threshold}_{\text{elevation}}$ estimates of loss in visual sensitivity due to disability glare as a function of Viewing Distance, Age of Observer and Luminance Adaptation State (Dark vs. Twilight) for 7000 cd Daytime Running Lights.

NHTSA's (1998) proposed revision of *Federal Rule MVSS 108* suggests that some vehicles using reduced-intensity high beam daytime running lights are actually operating with horizontal plane luminous intensities well exceeding the 7000 cd maximum limit (due to over-voltage "problems"). In order to evaluate the possibility of disability glare effects resulting from this condition, the glare analyses described above for 7000 cd lamps was repeated assuming daytime running light horizontal plane intensities of 10000 cd. The results of this supplemental analysis are summarized in Table 3. These findings essentially mirror the results obtained in the case of 7000 cd daytime running lights. That is, there are no disability glare effects in the presence of 10000 cd daytime running lamps when the eye of the observer is adapted to luminance levels greater than or equal to those prevailing at dawn and/or dusk (50 cd/m^2). As noted above, however, disability glare would be expected to result if the same daytime running lights were experienced by drivers in a dark, nighttime environment (1 cd/m^2).

Viewing Distance (m)	Glare Angle (deg)	E_{glare} (lux)	$L_{\text{equivalent}}$			$\text{Threshold}_{\text{elevation}}$					
						1 cd/m^2			50 cd/m^2		
			Age			Age			Age		
			25	65	75	25	65	75	25	65	75
20 m	8.93	50.0	5.8	10.9	14.9	6.8	11.9	15.9	1.1	1.2	1.3
40	4.50	12.5	5.7	10.7	14.7	6.7	11.7	15.7	1.1	1.2	1.3
60	3.00	5.56	5.7	10.7	14.7	6.7	11.7	15.7	1.1	1.2	1.3
80	2.25	3.12	5.7	10.7	14.7	6.7	11.7	15.7	1.1	1.2	1.3
100	1.80	2.00	5.7	10.7	14.7	6.7	11.7	15.7	1.1	1.2	1.3

Table 3.

$L_{\text{equivalent}}$ estimates of interocular light scatter due to glare and $\text{Threshold}_{\text{elevation}}$ estimates of loss in visual sensitivity due to disability glare as a function of Viewing Distance, Age of Observer and Luminance Adaptation State (Dark vs. Twilight) for 10000 cd Daytime Running Lights.

c. Summary

The potential for disability glare from daytime running lights was analyzed under a “worst case scenario” with the safe and reasonable assumption that failure to observe disability glare effects under “worst case” conditions would preclude their occurrence under less severe conditions. No evidence for disability glare was found for daytime running lights with horizontal plane luminous intensities as high as 10000 cd under daytime luminance adaptation conditions representing dawn and/or dusk. It follows, therefore, that any daytime running light meeting the current *Federal Rule MVSS 108* can be considered to be free of any glare-related reductions in driver visibility during daytime luminances ranging from dawn through dusk.

III. Discomfort Glare

Unlike *disability glare*, which can be objectively measured and related directly to the underlying mechanism of intraocular stray light scatter, *discomfort glare* is a completely subjective phenomenon. In fact, the mechanisms that trigger and modulate discomfort due to glare remain unknown (see Fry, 1991 and Berman, et al., 1991 for speculations in this regard). However, since discomfort glare is often reported at levels of illumination well below those that engender visual disability, it is often the type of glare that illuminating engineers find themselves most likely to be assessing and managing.

a. Method of assessment

Since discomfort glare is a subjective construct used to capture and quantify the psychological disturbance or suffering sometimes accompanying the introduction of bright illuminaires into the designed environment, it should come as no surprise that the conventional approach to assessing discomfort glare is based upon a 9-point rating system known as the *deBoer Discomfort Glare Scale* (see Table 4).

1	Unbearable
2	
3	Disturbing
4	
5	Just Acceptable
6	
7	Satisfactory
8	
9	Just Noticeable

Table 4.
The deBoer Discomfort Glare Scale

Originally developed in the Netherlands by J.B. deBoer in 1974 (according to Olson, 1991), the scale has been translated into several languages and used extensively throughout the world to obtain systematic and repeatable estimates of the degree of psychological discomfort resulting from various lighting configurations. Despite its near universal application, however, the deBoer scale is known to suffer from deficiencies in some of its critical psychometric properties (see Gellatly and Weintraub, 1990). For example, ratings given on the deBoer scale are known to be influenced by the so-called “range effect”. That is, the level of subjective discomfort reported to be associated with a glare source of a given intensity is known to be systematically affected by the “range of stimulus intensities” previously judged by the observer. Hence, a group of observers who have previously viewed a series of sample glare sources no greater than 100 units in magnitude might give a rating of “3” or “4” (i.e., “disturbing”) to a test glare source with a magnitude of 100. However, another group of observers who experienced a range of

glare sources up to 500 units in magnitude might, in turn, be more likely to judge the very same 100 unit stimulus as a “5” (i.e., “just acceptable”). Kirkpatrick and Marshall (1989) have demonstrated such range effects on the order of one full point in the central region of the deBoer scale (see Sivak, Flannagan and Aoki, 1995). A related phenomenon that can systematically influence deBoer scale ratings has been noted by Sivak, Olson and Zeltner (1989), who found that experienced European drivers reported greater levels of deBoer scaled discomfort glare in a laboratory experiment than did their counterparts who were experienced U.S. drivers. The authors attributed the average 0.7 increase in deBoer ratings among American drivers (and, hence, a *reduction* in discomfort) to their prolonged experience with the increased glare dosages emitted by U.S.-style low beam headlights during routine nighttime driving. That is, the U.S. population had more opportunity for “adaptation” or “habituation” to occur; and, hence, systematically shifted their discomfort criterion as a result. In fact, Sivak, et al. point out that this “recalibration” of American drivers can account for a systematic difference of between 0.5 and 1.0 deBoer points seen in a series of studies conducted on opposite sites of the Atlantic Ocean.

Other related psychological factors such as the presence (as opposed to absence) of a concurrent visual task (Guth, 1951), increasing concurrent task difficulty (Sivak, Flannagan, Ensing and Simmons, 1991) and increased general arousal (Boyce and Beckstead, 1991) have been shown to systematically decrease deBoer scale ratings (i.e., increase discomfort) by as much as 0.8 full-scale units. The degree to which these factors interact (in either an additive or multiplicative manner) remains entirely unknown at present.

Despite these shortcomings, which are inherent problems with the application of any complex psychological scale, the deBoer Discomfort Glare Scale has been widely and successfully used in automotive lighting design and tradeoff studies (see Olson (1991) for a review). Schmidt-Clausen and Bindels (1974) have developed an analytic model for the evaluation of discomfort glare in automotive lighting applications. This model predicts deBoer scale discomfort ratings based upon the intensity of the glare source measured at the eye of the observer, the angle of separation between the glare source and the observer’s line-of-sight, and, of course, the adaptation state of the observer’s visual system (specified in terms of the background scene luminance). The Schmidt-Clausen and Bindels model is specified as Equation 4 below:

$$\text{deBoer} \\ \text{Discomfort} = 5.0 - 2 \log \frac{E_{\text{glare}}}{0.003 \left(1 + \sqrt{\frac{L_{\text{background}}}{0.04}} \right) \Theta^{0.46}} \\ \text{Glare Rating}$$

where:

E_{glare} is the illumination of the glare source
at the eye of the observer (lux)

$L_{\text{background}}$ is the background adaptation state
of the observer (cd/m²)

Θ is the angle between the glare source and
the observer's line-of-sight (minarc)

Equation 4

The Schmidt-Clausen and Bindels formula is arguably the most extensively validated model of discomfort glare available today. It was developed using a wide range of stimuli (with careful attention to the “range effects” mentioned above) and with observer adaptation states well into the photopic range (a characteristic necessary for any analysis of discomfort due to daytime running lights). Recent studies by Sivak, Flannagan and Aoki (1995) and Sivak, Flannagan, Traube and Miyokawa (1998) have extended the application of the model well into the range of bright daytime luminances. Given these considerations, the Schmidt-Clausen and Bindels model depicted in Equation 4 will be used in the analytic study of discomfort glare which follows in the remainder of this report.

Before beginning the analytic studies of deBoer ratings of daytime running lights, it is first necessary to establish a “cutoff” value or criterion level that will be considered as “entry level” discomfort glare. The first value that one is likely to consider is the rating value of 4.99 since it is just beyond “5” (i.e., “just acceptable”). However, the properties of psychological scales such as these are such that an argument can be made that the “just acceptable” rating can be said to belong to the entire interval ranging from 4.5 to 5.5. This consideration, together with the knowledge that the Schmidt-Clausen model was developed using “more glare sensitive” European drivers (see the discussion of Sivak, Olson and Zeltner (1989) above) led to the adoption of a 4.0 criterion as the threshold value establishing discomfort for the purposes of this study. However, all analyses are reported using numbers generated via the original Schmidt-Clausen and Bindels equation so that those wishing to apply a more or less conservative criterion are free to do so with the deliverables of this report.

b. Analysis

The results of the comprehensive discomfort glare analysis using the aforementioned model are graphically depicted in Figures 1 through 7 below. Reference to Figure 1 reveals the predicted discomfort glare ratings for a daytime running light configuration delivering 1500 cd of luminous flux along the horizontal plane (a value representing the maximum DRL intensity under NHTSA's proposed rule making). Note the line bisecting the graph into zones of "comfort" (top) and "discomfort" (bottom). The most remarkable characteristic depicted by Figure 1 is that NHTSA's new proposed maximum DRL intensity appears to eliminate almost all opportunities for discomfort glare. Discomfort appears to present itself only at the closest viewing distance (20 m) under early twilight/late dawn (100 cd/m^2) and/or late twilight/early dawn (50 cd/m^2) ambient conditions.

Figures 2 through 4 depict the results of parallel discomfort glare analyses performed upon daytime running light configurations that deliver 3000, 5000 and 7000 cd of luminous intensity, respectively. As can be seen by examining Figure 2, increasing DRL intensity to 3000 cd is accompanied by only slightly more discomfort glare than that observed for the case of 1500 cd. Specifically, some "threshold level" discomfort would be expected to occur but only at the closest viewing distance (20 m) and, then, only at deep-to-moderate dawn and/or dusk. At 5000 cd, the depth and extent of the expected levels of discomfort glare have spread somewhat farther. Referring to Figure 3, it can be seen that twilight/dawn discomfort experienced at a viewing distance of 20 m has deepened to the level of "disturbing" and broadened to become "just unacceptable" at the 40 m viewing distance. In addition, mild levels of discomfort would now be expected for the first time outside of the problematic, but short duration, dawn and dusk periods of the daylight cycle (albeit only at the short viewing distance of 20m). At 7000 cd, the current maximum for reduced-intensity high beam DRLs, the level of discomfort experienced during dawn/dusk has crossed well-over the border of "disturbing" at the 20 m viewing distance while noticeable levels of discomfort are just beginning to emerge at a viewing distance of up to 60 m. Perhaps more significant, however, is that the model predicts noticeable levels of discomfort at a 20 m viewing distance under ambient viewing conditions like those prevailing on a relatively bright but overcast day (i.e., 1000 cd/m^2). This analysis is consistent with NHTSA's claim that 7000 cd DRLs are sufficiently bright so as to foster complaints regarding glare-based discomfort.

The discomfort glare analysis was also applied to the special case of an "out of specification" condition in which the luminous intensity of a reduced-intensity high beam DRL reached an effective output level of 10000 cd. The results of this analysis are graphically depicted in Figure 5. The most remarkable characteristic of Figure 5 is that noticeable discomfort is predicted at a viewing distance of 20 m even under the midday sun on a clear afternoon. Hence, even a single vehicle with such an "out of specification" DRL could be expected to cause a lot of discomfort among drivers in the opposing lanes of traffic along a busy urban thoroughfare.

The graphical analyses presented separately for each of the 5 levels of DRL intensity in Figures 1 through 5 are summarized in Figure 6. Here the outputs of the Schmidt-Clausen and Bindels model are plotted on a normalized discomfort glare axis with the “relative borders” between “comfort” (above the line) and “discomfort” (below the line) denoted for each DRL intensity level examined - all on a single graph to foster comparison across conditions (Recall that the border between comfort and discomfort in this analysis is based upon a deBoer score of 4.0). Figure 7 also represents another summary tool designed to graphically depict the “area of the curves beneath the comfort-discomfort border” across Figures 1 through 5 as DRL intensity increases from 1500 to 10000 cd, respectively. Although the “area” beneath such a reference point is a dimensionless (some might say meaningless) unit, it nonetheless captures the rate of global change in increasing discomfort as DRL intensity and adaptation luminance increase and viewing distance decreases. With this caveat, it can be noted that the multidimensional development of discomfort due to glare appears to be advancing in a relatively linear fashion as DRL intensity increases between 3000 and 10000 cd.

Finally, to aid the reader with follow-on analyses, all of the data presented graphically in Figures 1 through 5 are also presented numerically in Tables 5 through 9, respectively. Each of these tables also contains the output of the discomfort glare model under nighttime viewing conditions (1 cd/m²) to permit an assessment of the discomfort glare levels that would result if the aforementioned daytime running lights were operated at night (see Tables 2 and 3 for disability glare analyses under these same nighttime conditions).

c. Summary

Analyses based upon the Schmidt-Clausen and Bindels (1974) model indicated that any pair of daytime running lights with horizontal plane luminous intensities of 7000 cd or greater represent a potentially significant source of discomfort glare to opposing drivers - even when approaching the brightest part of the daytime cycle. The 1500 cd maximum currently being proposed under new NHTSA rule making appears to represent little or no risk of discomfort glare over the entire range of daytime luminances considered.

Koonstra, et al.’s (1997) review of the world-wide DRL safety literature concluded that a significant safety benefit would continue to accrue in the U.S. (based upon an analysis of significant latitude effects) even if the maximum H-V luminous intensity of DRLs was reduced to 1500 cd. However, what is not known is how much improvement in safety-related daytime conspicuity could be realized if higher intensities were adopted. With respect to the proposed 1500 cd maximum, NHTSA (1998) states that: “More intense DRLs do not offset the problems of glare with any significant increase in conspicuity. Because there is no tradeoff, the agency should be less tolerant of glare from DRLs than it is for headlamps”. Yet, Koonstra, et al.’s review makes it quite clear that there is evidence for substantial potential improvement in safety-related daytime conspicuity at DRL intensities above 1500 cd when the sky is clear and bright (a common meteorological condition in the U.S.). It therefore seems somewhat premature to take the position that no glare whatsoever will be tolerated from DRL’s - especially since the current analysis indicates that doubling the proposed maximum from 1500 cd to 3000 cd would result in only a modest increase in discomfort (and, then, only at dawn or twilight

where there's already plenty of glare from the sun anyway). It would appear that a systematic empirical study needs to be performed to examine the tradeoff between the potential mid-day conspicuity benefits of 3000 cd DRLs versus their expected but modest glare-based discomfort at dawn and dusk..

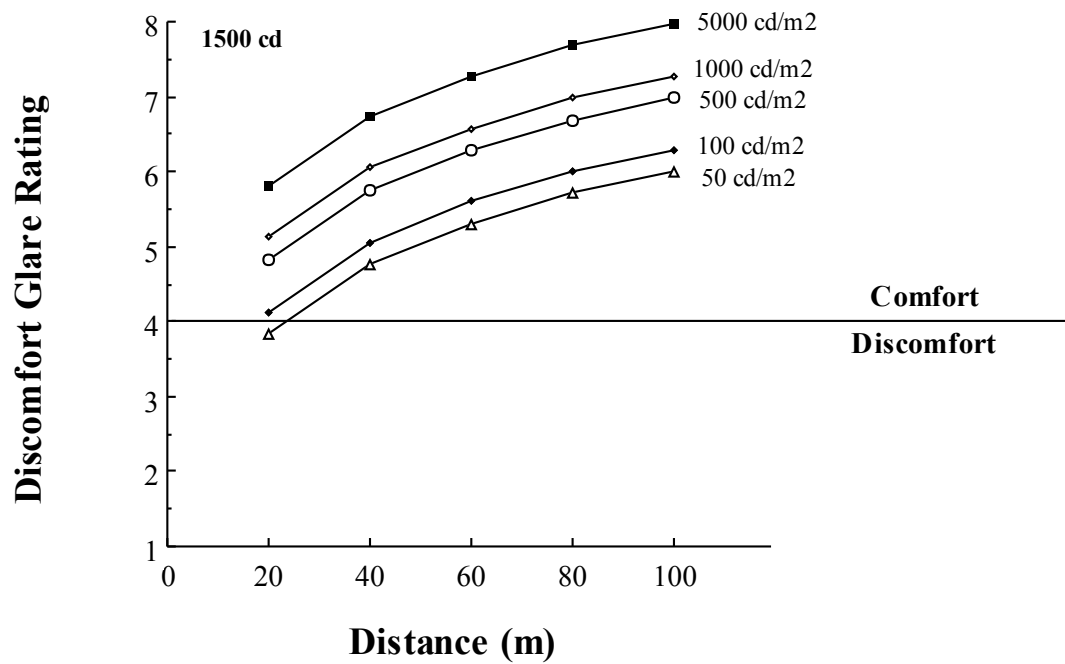


Figure 1. Predicted deBoer Discomfort Glare Rating as a function of Viewing Distance and Luminance Adaptation Level for 1500 cd Daytime Running Lights.

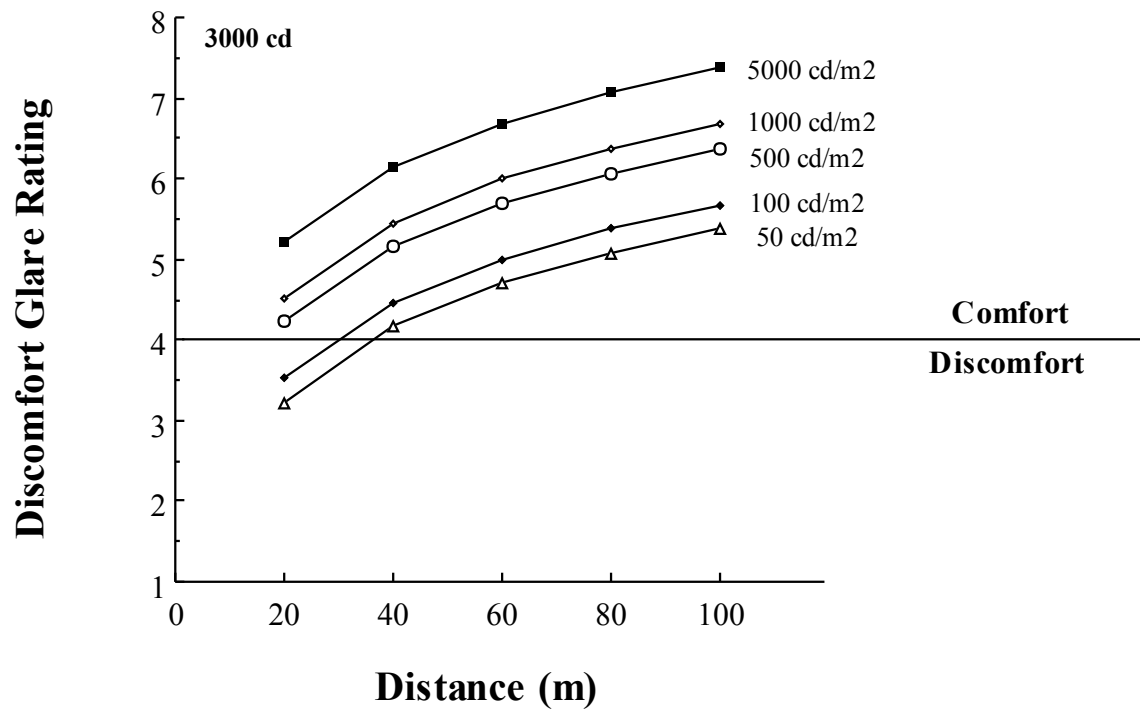


Figure 2. Predicted deBoer Discomfort Glare Rating as a function of Viewing Distance and Luminance Adaptation Level for 3000 cd Daytime Running Lights.

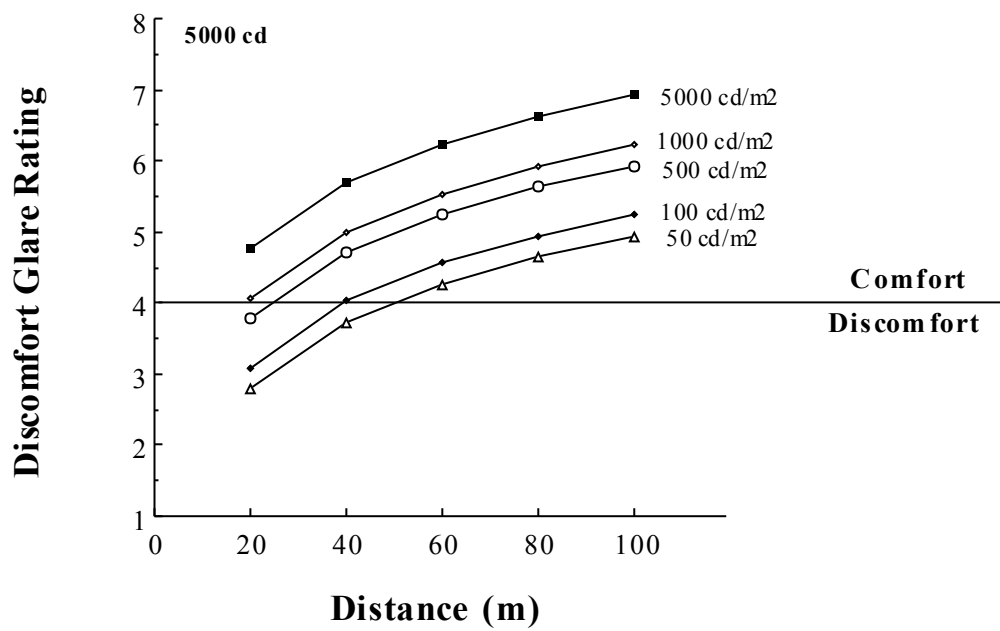


Figure 3. Predicted deBoer Discomfort Glare Rating as a function of Viewing Distance and Luminance Adaptation Level for 5000 cd Daytime Running Lights.

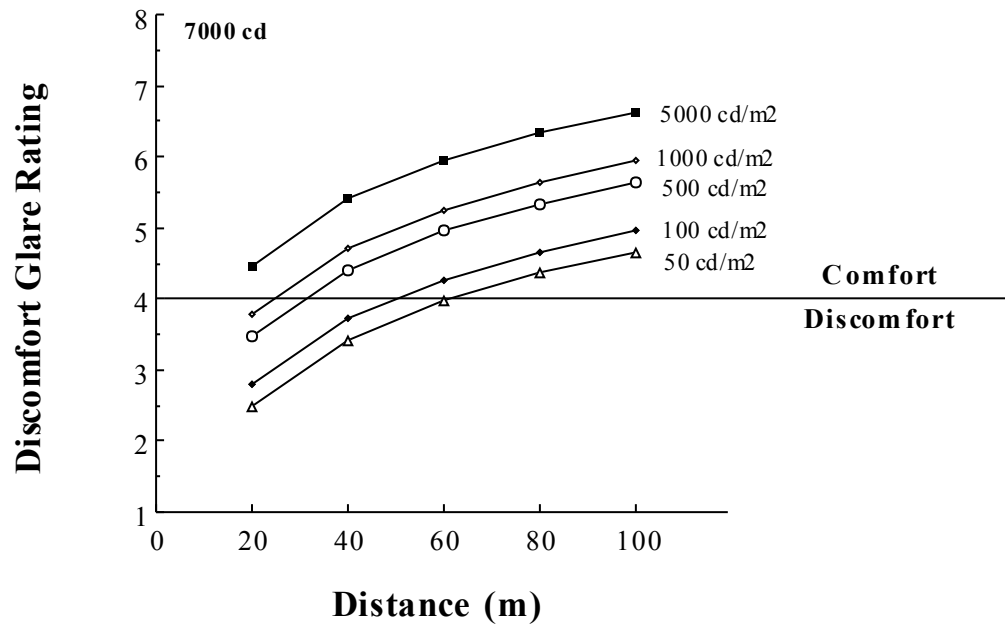


Figure 4. Predicted deBoer Discomfort Glare Rating as a function of Viewing Distance and Luminance Adaptation Level for 7000 cd Daytime Running Lights

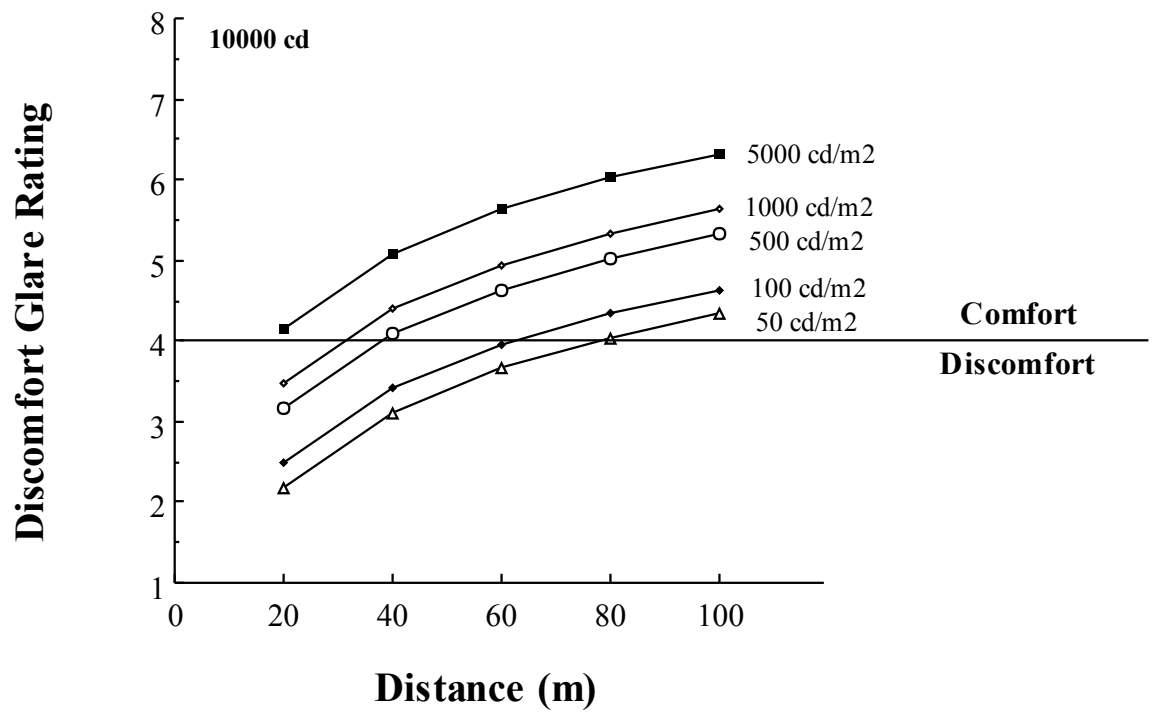


Figure 5. Predicted deBoer Discomfort Glare Rating as a function of Viewing Distance and Luminance Adaptation Level for 10000 cd Daytime Running Lights

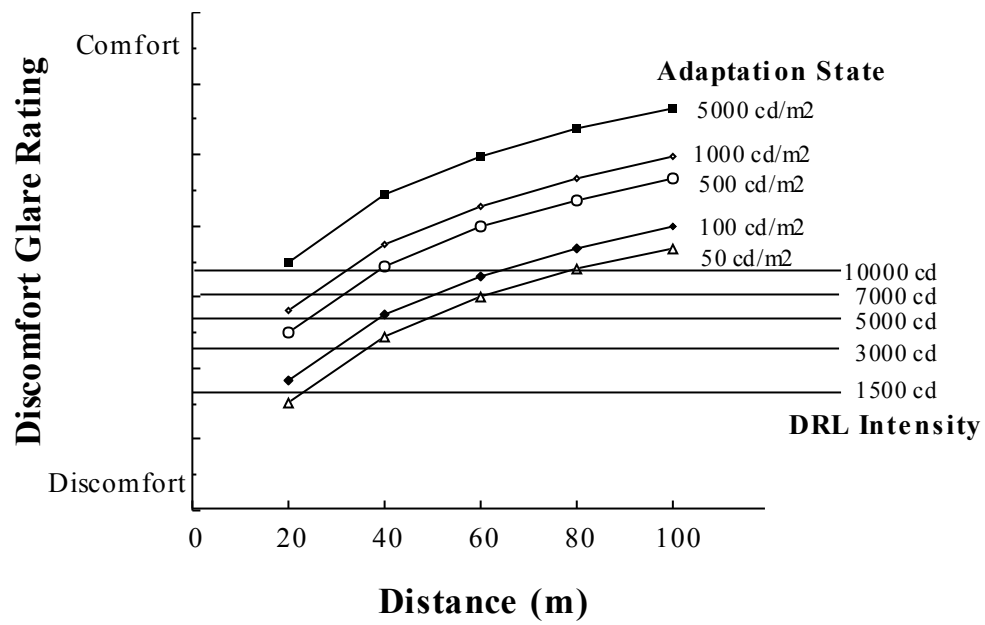


Figure 6. Predicted deBoer Discomfort Glare Ratings as a function of Viewing Distance, Luminance Adaptation Level and Daytime Running Lamp Intensity.

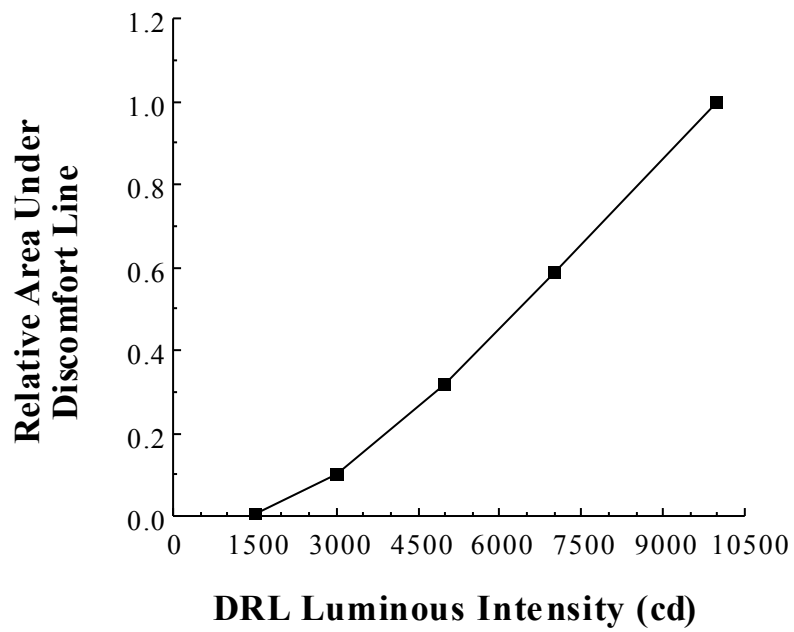


Figure 7.

Overall area under the “border line of discomfort” as a function of Daytime Running Light Intensity.

Viewing Distance (m)	Glare Angle (minarc)	E_{glare} (lux)	<u>Background/Adaptation Luminance (cd/m^2)</u>					
			1	50	100	500	1000	5000
20	536	7.50	2.27	3.84	4.13	4.82	5.12	5.81
40	270	1.88	3.20	4.76	5.06	5.75	6.05	6.74
60	189	0.84	3.74	5.30	5.60	6.29	6.58	7.28
80	135	0.46	4.14	5.71	6.00	6.69	6.99	7.68
100	108	0.30	4.43	5.99	6.29	6.98	7.27	7.97

Table 5.

Estimated deBoer Discomfort Glare Rating as a Function of Viewing Distance And Background Luminance for 1500 cd Daytime Running Lights.

Viewing Distance (m)	Glare Angle (minarc)	E_{glare} (lux)	<u>Background/Adaptation Luminance (cd/m^2)</u>					
			1	50	100	500	1000	5000
20	536	15.00	1.67	3.23	3.53	4.22	4.52	5.21
40	270	3.74	2.60	4.17	4.46	5.15	5.45	6.14
60	189	1.66	3.15	4.71	5.00	5.69	5.99	6.69
80	135	0.94	3.52	5.09	5.38	6.07	6.37	7.07
100	108	0.60	3.82	5.39	5.68	6.37	6.67	7.37

Table 6.

Estimated deBoer Discomfort Glare Rating as a Function of Viewing Distance And Background Luminance for 3000 cd Daytime Running Lights.

Viewing Distance (m)	Glare Angle (minarc)	E_{glare} (lux)	<u>Background/Adaptation Luminance (cd/m^2)</u>					
			1	50	100	500	1000	5000
20	536	25.00	1.23	2.79	3.08	3.77	4.07	4.77
40	270	6.25	2.16	3.72	4.01	4.70	5.00	5.70
60	189	2.78	2.70	4.26	4.56	5.25	5.54	6.24
80	135	1.56	3.08	4.65	4.94	5.63	5.93	6.63
100	108	1.00	3.38	4.94	5.24	5.93	6.23	6.92

Table 7.

Estimated deBoer Discomfort Glare Rating as a Function of Viewing Distance And Background Luminance for 5000 cd Daytime Running Lights.

Viewing Distance (m)	Glare Angle (minarc)	E_{glare} (lux)	<u>Background/Adaptation Luminance (cd/m^2)</u>					
			1	50	100	500	1000	5000
20	536	35.00	0.93	2.49	2.79	3.48	3.78	4.47
40	270	8.74	1.86	3.43	3.72	4.41	4.71	5.41
60	189	3.88	2.41	3.97	4.26	4.96	5.25	5.95
80	135	2.18	2.79	4.36	4.65	5.34	5.64	6.34
100	108	1.40	3.09	4.65	4.95	5.64	5.94	6.63

Table 8.

Estimated deBoer Discomfort Glare Rating as a Function of Viewing Distance And Background Luminance for 7000 cd Daytime Running Lights.

Viewing Distance (m)	Glare Angle (minarc)	E_{glare} (lux)	<u>Background/Adaptation Luminance (cd/m^2)</u>					
			1	50	100	500	1000	5000
20	536	50.00	0.62	2.19	2.48	3.17	3.47	4.16
40	270	12.5	1.55	3.12	3.41	4.10	4.40	5.09
60	189	5.56	2.09	3.66	3.95	4.64	4.94	5.63
80	135	3.12	2.48	4.05	4.34	5.03	5.33	6.03
100	108	2.00	2.78	4.34	4.63	5.33	5.63	6.32

Table 9.

Estimated deBoer Discomfort Glare Rating as a Function of Viewing Distance
And Background Luminance for 10000 cd Daytime Running Lights.

IV. References

- Adrian, W. & Bhanji, A. (1991). Fundamentals of disability glare: A formula to describe straylight in the eye as a function of glare angle and age. In W. Adrian (Ed.), Proceedings of the First International Symposium on Glare. New York: Lighting Research Institute. Pp. 185-193.
- Berman, S.M., Jacobs, R.J., Bullimore, M.A., Bailey, I.L., Ghandi, N. & Greenhouse, D.S. (1991). An objective measure of discomfort glare. In W. Adrian (Ed.), Proceedings of the First International Symposium on Glare. New York: Lighting Research Institute. Pp. 183-184.
- Blackwell, H.R. (1946). Contrast thresholds of the human eye. Journal of the Optical Society of America, 36, 624-643.
- Boyce, P.R. & Beckstead, J.W. (1991). Influences on discomfort glare ratings. In W. Adrian (Ed.), Proceedings of the First International Symposium on Glare. New York: Lighting Research Institute. Pp. 93-100.
- Fisher, A.J. & Christie, A.W. (1966). The effect of glare from street lighting lanterns on the vision of drivers of different ages. Transactions of the Illuminating Engineering Society, 31, 93-108; 114-120.
- Fry, G.A. (1991). The relation of pupil constriction experienced under discomfort glare. In W. Adrian (Ed.), Proceedings of the First International Symposium on Glare. New York: Lighting Research Institute. Pp. 173-181.
- Gellatly, A.W. & Weintraub, D.J. (1990). User reconfigurations of the deBoer Rating Scale for discomfort glare. Report No. UMTRI-90-20. Ann Arbor, MI: University of Michigan Transportation Research Institute.
- Guth, S.K. (1951). Comfortable brightness relationships for critical and casual seeing. Illuminating Engineering, 46, 65.
- Ijspeert, J.K., de Waard, P.W.T., van den Berg, T.J.T.P. and de Jong, P.T.M. (1990). The intraocular straylight function in 129 healthy volunteers; Dependence on angle, age and pigmentation. Vision Research, 30, 699-707.
- Kirkpatrick, M. & Marshall, R.K. (1989). Evaluation of glare from daytime running lights. DOT-HS-807-502. Washington, DC: National Highway Traffic Safety Administration.
- Koornstra, M., Bijleveld, F. & Hagenzieker, M. (1997). The safety effects of daytime running lights. Leidschendam, The Netherlands: SWOV Institute for Road Safety Research. 175 pp.
- NHTSA (1998). Federal Motor Vehicle Safety Standards: Lamps, Reflective Devices and Associated Equipment. 49 CFR Part 571 [Docket No. NHTSA 98-4124; Notice 1] RIN 2127-AG86. Federal Register, 63(152), 42348-42360.

Olson , P.L. (1991). Research on discomfort glare at UMTRI. In W. Adrian (Ed.), Proceedings of the First International Symposium on Glare. New York: Lighting Research Institute. Pp. 165-171.

Schmidt-Clausen, H.J. & Bindels, J.T.H. (1974). Assessment of discomfort glare in motor vehicle lighting. Lighting Research and Technology, 6, 79-88.

Sivak, M., Flannagan, M. & Aoki, M. (1995). Glare and mounting height of high beams used as daytime running lamps. Report No. UMTRI-95-40. Ann Arbor, MI: University of Michigan Transportation Research Institute.

Sivak, M., Flannagan, M., Budnick, E.A., Flannagan, C.C. & Kojima, S. (1996). The locations of headlamps and driver eye positions in vehicles sold in the U.S. Report No. UMTRI-96-36. Ann Arbor, MI: University of Michigan Transportation Research Institute.

Sivak, M., Flannagan, M., Ensing, M. & Simmons, C.J. (1991). Discomfort glare is task dependent. International Journal of Vehicle Design, 12, 152-159.

Sivak, M., Flannagan, M., Traube, E.C. & Miyakawa, T. (1998). Conspicuity and glare properties of daytime running lights: Effects of lamp separation and intensity. Report No. UMTRI-98-30. Ann Arbor, MI: University of Michigan Transportation Research Institute.

Sivak, M., Olson, P.L. & Zeltner, K.A. (1989). Effects of prior headlighting experience on ratings of discomfort glare. Human Factors, 31, 391-395.