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A Method for Estimating Discomfort Glare from Exterior Lighting Systems

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Introduction

Because outdoor lighting is utilized at relatively low light levels and because outdoor lighting equipment (e.g., lamps and luminaires) tends to be relatively bright, there is a substantial potential for discomfort glare in outdoor lighting applications. *Discomfort glare* is defined as the annoying or even painful sensation that can be elicited from a bright source of light in the field of view (Rea 2000). It is distinguished from *disability glare*, which is defined as the reduction in visibility that a bright light might cause (Rea 2000), through scattered light in the eye that reduces the apparent luminance contrast of objects in the field of view. However, a lighting condition that produces disability glare—such as driving at night with the dashboard display set to its maximum luminance—might not necessarily create physical discomfort even as it reduces the forward visibility of a driver.

The effect of light on disability glare, and the mechanisms by which light creates disability glare, have been well understood for several decades (Fry 1954). In contrast, the mechanisms for discomfort glare are less well known. Attempts to formulate objective, physiological measures of discomfort glare such as pupil constriction, frowning and muscle tension, and electrophysiological measures have not yet identified a reliable and accurate method for measuring discomfort glare. Rather, the current state-of-the-art for assessing discomfort glare is the use of subjective rating scales, such as the De Boer (1967) scale, commonly used to assess vehicular headlamp glare and glare from other outdoor lighting. The De Boer (1967) scale uses a nine-point scale with odd-numbered values having the following equivalencies:

1	unbearable
2	
3	disturbing
4	
5	just permissible
6	
7	satisfactory
8	
9	just noticeable

Schmidt-Clausen and Bindels (1974) developed a computational model for discomfort glare in the context of oncoming headlamp glare. Their model used the illuminance from the glare source, the surrounding luminance, and the angular distance between the line of sight and the glare source as inputs. One shortcoming of this model is the necessity to specify a precise line of sight; when an observer looks more or less at the glare source, the model predicts infinite discomfort glare because it includes the term specifying to the angular location of the source in the denominator of the model equation. Further, specifying a precise angular distance between the glare source and the line of sight may be more practical for glare from oncoming headlamps, because the angular locations of oncoming headlamps are generally restricted to being within oncoming lanes of traffic, and driver's lines of sight are likely to follow the layout of the roadway ahead. In comparison, a pedestrian walking along an illuminated parking lot might occasionally glance directly toward a bright luminaire and his or her sensation of discomfort glare would not be able to predicted under such conditions by the Schmidt-Clausen and Bindels (1974) model.

To address these issues, Bullough et al. (2008) conducted a series of indoor laboratory and outdoor field studies of exterior lighting varying among several dimensions:

- Illuminance from the source (E_L)
- Luminance of the source (L_L)
- Illuminance from the area surrounding the source (E_S)
- Ambient illuminance in the location, if the glare source and the lighting system it was part of were not installed (E_A)

Subjects in these studies provided subjective ratings to each of the conditions using the De Boer (1967) rating scale. Based on these studies, it was found that ratings of discomfort glare were much more strongly related to the illuminance from the glare source than from the luminance of the glare source. From their data, Bullough et al. (2008) formulated the following model of discomfort glare (all illuminance values are in lux):

$$DG = \log(E_L + E_S) + 0.6 \log (E_L/E_S) - 0.5 \log (E_A)$$

From this quantity, it is possible to determine the corresponding De Boer (1967) rating scale value (DB):

$$DB = 6.6 - 6.4 \log DG$$

This model is part of the outdoor site-lighting performance (OSP) system of assessing the potential of an outdoor lighting installation to produce light pollution (Brons et al. 2008), and it has been used successfully to predict discomfort glare assessments of field installations of exterior lighting (Brons and Rea 2010). Despite the good agreement between predicted and measured discomfort glare ratings found by Bullough et al. (2008) and by Brons and Rea (2010), there is evidence that the luminance of a glare source also can influence discomfort glare under certain conditions, especially when the light source is large, or the viewing distance is small. When the glare source subtends more than approximately 0.3° in the field of view, Rosenhahn and Lampen (2004) found that the maximum source luminance was a better predictor of discomfort glare than the illuminance from the source. When the source was smaller, discomfort glare ratings were driven primarily by the illuminance from the source. Bullough (2011) measured discomfort glare ratings from sources ranging in luminance from 15,000 to approximately 1,000,000 cd/m² but producing equivalent illuminances at subjects' eyes, and found that the higher luminance sources produced significantly higher glare, resulting in lower De Boer (1967) rating scores.

The objective of the present document is to present an extension to the discomfort glare model from Bullough et al. (2008) that incorporates the source luminance, for use in conditions when the source subtends more than 0.3° at the eye.

Discomfort Glare Model Extension

The luminances used by Bullough et al. (2008) in their laboratory and field studies averaged close to 50,000 cd/m². The luminances used by Bullough (2011) ranged from lower than this value to substantially higher. The measured ratings of discomfort glare were closest to the predicted values when the source luminance was about 50,000 cd/m². Comparing the luminance differences with the De Boer (1967) rating scale value differences found by Bullough (2011), a luminance-based correction to the equation from the previous section in this document is proposed, when the source size is larger than 0.3° in visual angle:

$$DB = 6.6 - 6.4 \log DG + 1.4 \log (50{,}000/L_L)$$

Example Calculations

Suppose a location along a commercially developed roadway has an ambient illuminance (E_A) of 1 lx. A parking lot luminaire produces a direct illuminance (E_L) of 5 lx at the eyes of a pedestrian walking along the perimeter of the lot. Light reflected from a building located behind the luminaire produces a surround illuminance (E_S) of 0.2 lx. The luminaire is large enough to subtend a visual angle greater than 0.3° at the pedestrian's eyes. If the maximum luminance (L_L) of the luminaire's luminous element in the direction of the pedestrian were 500,000 cd/m², what would be the predicted De Boer (1967) rating value?

First, the discomfort glare (DG) quantity is determined:

$$DG = \log(5 + 0.2) + 0.6 \log (5/0.2) - 0.5 \log (1) = \mathbf{1.55}$$

Then, the predicted De Boer (1967) rating value (DB) is calculated:

$$DB = 6.6 - 6.4 \log DG + 1.4 \log (50{,}000/500{,}000) = \mathbf{3.97}$$

This value is just below a level of discomfort (a rating value of 4) that has been proposed by Bhise et al. (1977) as a limit for discomfort glare in the context of vehicle headlamps. It is not known whether this limit is appropriate for discomfort glare from fixed outdoor lighting. Nonetheless, if the maximum luminance of the luminaire could be reduced to 200,000 cd/m² by using some diffusing elements, the resulting De Boer (1967) rating would be calculated as follows:

$$DB = 6.6 - 6.4 \log DG + 1.4 \log (50{,}000/200{,}000) = \mathbf{4.53}$$

The resulting diffusion would be expected to reduce discomfort glare by about a half of a point on the De Boer (1967) scale, making the luminaire somewhat more acceptable in terms of rated discomfort.

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About ASSIST

The Alliance for Solid-State Illumination Systems and Technologies (ASSIST) was established in 2002 by the Lighting Research Center as a collaboration between researchers, manufacturers, and government organizations. ASSIST's mission is to facilitate broad adoption of solid-state lighting by helping to reduce major technical and market barriers.