# Understanding Glare in Exterior Lighting, Display, and Related Applications

by John D. Bullough

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## 1 Introduction

Over the past two decades, lighting for the built environment has under-gone nothing less than a revolution. The advent of new lighting technologies, particularly through solid state lighting systems including the development of light emitting diode (LED) sources, has resulted in dramatic increases in lighting system efficacy and operating life.[1] Early on,[2] solid state lighting technologies had primarily been used for limited applications including signal indicators, signage, and low-light uses such as pocket flashlights. At present, LED sources are used in every general lighting application in homes, workspaces, outdoor areas, and vehicles. At the same time this lighting revolution has been underway, there has also been a growing, perhaps renewed[3] awareness of some of the problems that suboptimal lighting can create, including glare.

One well-known example of an application where glare has been viewed as a widespread problem is that of automotive lighting, especially vehicle headlighting.[4] Up until the mid-to-late 1990s, most vehicle headlights used filament (incandescent) sources, mostly halogen lamps and bulbs. These produced a yellowish-white illumination color seen as "warm" white. Around this time, some vehicles began to appear that had high-intensity discharge (HID) headlights,[5] using sources such as metal halide lamps with xenon fill gases to facilitate rapid starting. (Metal halide lamps had also been widely used for outdoor lighting in parking lots and streets; these lamps could take several minutes to achieve full light output upon starting,[6] a situation that would be unacceptable for vehicle headlights!) Not only did HID headlights have a "bluer" or "cooler" appearance than halogen headlights, but they also had higher efficacy, meaning they could produce roughly twice the light output (in lumens) as 55 W halogen headlights while using only 35 W of power. Vehicle headlights are strictly controlled by federal regulations[7] in terms of their maximum intensity in directions that correspond to the roadway directly ahead, but there are few limits on their intensities that correspond to peripheral directions. This may be advantageous to forward visibility[8] but could result in higher intensities reaching the eyes of oncoming drivers. More recently available LED headlights also tend to have a "bluer" color appearance than halogen headlights and yet higher efficacy than HID sources. As shall be seen later in this Spotlight, there is a correlation between "blue" light content and glare sensations.

Two other trends related to automotive lighting (at least in the United States) also occurred simultaneously with the shift in lighting technology. One is the increased proportion of pickup trucks and sport-utility vehicles (SUVs) in the overall vehicle fleet. These vehicles are taller than most passenger cars, and because headlight intensity standards[7] are made without regard to the mounting height of the headlights for consumer vehicles, the same headlight can produce higher intensities toward an oncoming driver when it is mounted on a pickup or SUV than when it is mounted on a passenger car. The second trend is that a illuminances at night), possibly increasing glare. As will be seen, glare in interior lighting is a smaller concern than outdoors at night, and this Spotlight will focus more on glare at night and in otherwise dim environments, but the same principles that can help mitigate nighttime glare can also do so for interior, daytime lighting.

The goal of this Spotlight is to provide the reader with a basic understanding of the definitions of different types of glare and the impacts it can have on occupant visibility and visual comfort. The emphasis will be on exterior lighting and visual display applications, although the discussion is relevant to interior lighting as well. The factors that can influence glare will also be described, with special reference to calculation models that can help the reader predict how different lighting configurations will impact occupants of lighted areas and spaces. A few considerations for the design and implementation of lighting to minimize glare will also be provided, with a brief discussion of the future for glare modeling and control, potentially leading to an Integrated Glare Metric (IGM).

## 2 What Is Glare and Why Does It Matter?

It could be argued that glare is a subjective response to lighting conditions and that one person's glare could be another person's useful illumination. Of the 5000+ responders to NHTSA's request for public comments on headlight glare,[11] it seems unlikely that most of them have a formal definition of glare in mind. Rather (with apologies to the late Justice Potter Stewart), most people "know it [glare] when they see it." In this chapter, the definitions for several different aspects of glare are provided. It may be possible for more than one of these aspects to be present in any given situation.

### 2.1 Disability glare

Disability glare is defined[6] as the reduction in contrast caused by light entering the eye that is scattered by the eye's optical media (e.g., cornea and lens). Some of this light falls on the retina, creating a luminous "veil" that is superimposed over the retina and over the retinal images of objects in the field of view. Figure 1 shows an image of a letter "C" that is not obscured, and the same letter obscured by a luminous veil. The luminance (or "brightness") of the background and the letter are both increased by the superimposed veil, and as a result its contrast is reduced. It is this contrast reduction that causes some objects to become less visible or even to disappear in the presence of a bright light source. As will be seen, the magnitude of the reduction in contrast depends upon the locations of the object being viewed, and of the source of glare, within the field of view.

Importantly, disability glare can just as readily be produced by a large, diffuse source of light as by a small, intense point source, and consequently be unnoticed by an observer. For example, while driving at night, a distant but bright intense


**Figure 2** Sources of light in the nighttime driving visual environment that could serve as sources of disability and/or DG.

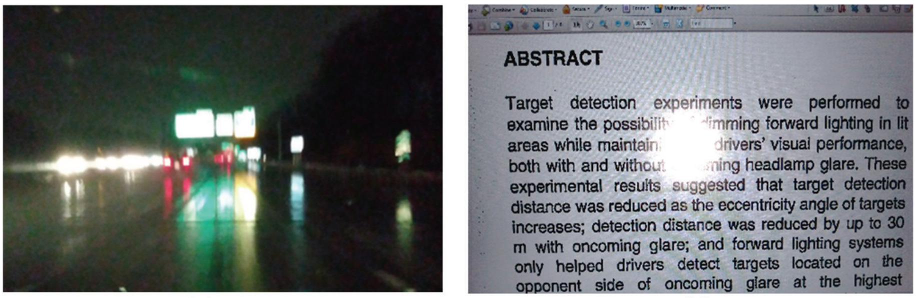
only those with a concentrated optical image (e.g., headlights, and some streetlights and traffic signals) would be likely to be major contributors to DG.

The preceding argument does not imply that DG is rarer than disability glare, however. In fact, people generally seem to be more aware of DG than disability glare. It is likely that among the thousands of respondents to NHTSA's request for public comments on headlight glare[11] that most of them expressed concerns about DG rather than disability glare.

Further, although the presence of DG does not by itself mean that someone has reduced visibility (a small light source viewed against a dark background could be uncomfortable in the field of view but might not produce a luminous veil bright enough to hamper visibility), this does not mean that DG has no implications for safety. A large body of research literature indicates that driving is safer when a driver maintains a constant speed along the road[21] and a constant lateral position within the driving lane.[22] Just as stressors such as thermal discomfort can lead to increased driving behaviors that are related to reduced safety, so can visual discomfort from the presence of headlight glare.[23,24] For example, drivers may move their heads to look away from the road and fluctuate their driving speed in response to oncoming headlight illumination or a view of headlights in their rear-view mirrors.

## 2.3 Glare recovery

Many people who have driven at night in the presence of uncomfortably bright oncoming headlights have undoubtedly breathed a sigh of relief after the offending vehicle has passed by, along with its associated disability or DG. Yet the effects of glare are not limited to the period of time when the so-called glare




(a) (b)

**Figure 4** (a) A wet roadway scene showing reflected glare on the road from overhead highway signs. (b) A computer display screen showing a reflected image of a light source, obscuring visibility of the text on the screen.

the eyes have returned to normal functioning when in fact, they may be still in the process of doing so.

### 2.4 Reflected glare

A fourth type of glare is often described, known as reflected glare or veiling glare. It differs from disability glare in that the "veil" is entirely external to the visual system. Reflected glare is created on surfaces that are specular (or glossy) when illuminated from an angle that forms a mirror-angle among a light source, an illuminated surface, and the observer's eyes. Essentially, an image (often a somewhat diffused or distorted image because many surfaces are not purely glossy but have semi-glossy characteristics) of a light source is visibly superimposed over a surface. The brightness of this image, like the veil from scattered light in the case of disability glare, obscures one's ability to see objects on or along the surface. Figure 4 illustrates the phenomenon of reflected glare from overhead highway signs in a wet roadway scene and in a reflective computer display screen.

## 3 What Factors Affect Glare?

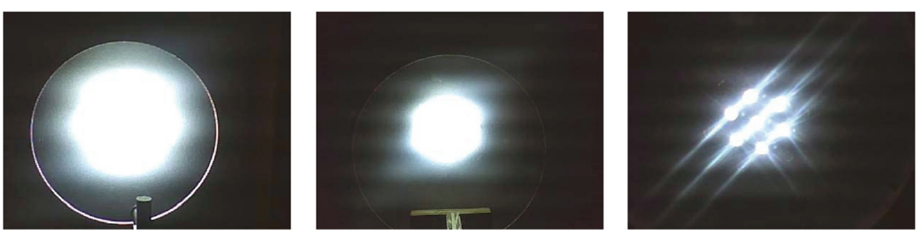
Having described the various types of glare and their definitions in the previous chapter, the present chapter of this Spotlight provides a discussion of the characteristics of a lighting system or a lighting installation that can influence each of these forms of glare.

### 3.1 Light source intensity and illuminance

Formally, the intensity (or luminous intensity) of a light source is characterized in units of candelas (cd) and is specific to a specific direction from the light source. In other words, the intensity of a beam of light from a flashlight is typically much as much as 9:1. Yet these sources all produced a similar degree of disability glare,[28] resulting in similar impacts on target detection times.

With respect to DG, the role of the source's luminance characteristics is somewhat more complex. An important factor that helps to determine whether and the extent to which a light source's luminance might influence visual discomfort is its size. One way to characterize an object's visual size is by the angle it subtends from the observer's viewing location. Returning again to the study of headlight glare illustrated in Fig. 6,[28] the three headlights in that study had diameters of ∼3, 6, and 10 cm, from smallest to largest. At a distance of 50 m, they subtended 0.02 deg, 0.06 deg, and 0.1 deg, respectively. Despite their large differences in luminance (160,000, 480,000 and 1.4 million cd/m$^2$), there were no statistically significant differences among these differently sized headlights when they were rated by observers using the De Boer (DB)[20] rating scale for DG, while they performed the tracking task shown in Fig. 6(a).

In comparison, a different study of DG[34] was carried out using arrays of LED sources (with diameters of 5 cm), where the arrays were either viewed as bare LEDs, or behind circular diffusers located either 7 or 21 cm in front of the arrays. The arrays (Fig. 10) were viewed from a distance of ∼5 m in an otherwise dark room. The maximum luminances of the arrays with the diffusers were 15,000 and 50,000 cd/m$^2$, and the maximum luminance of the array with no diffuser was 1,000,000 cd/m$^2$. All of the arrays produced an illuminance of 2 lx at the eyes of observers in the study, but unlike the headlights in Fig. 6, the light sources in Fig. 10 elicited different ratings of visual comfort. The source with the lowest maximum luminance (15,000 cd/m$^2$) resulted in the highest numerical rating values (the least amount of discomfort) and the source with the highest maximum luminance (1,000,000 cd/m$^2$) elicited the lowest numerical ratings (the greatest amount of discomfort), as illustrated in Fig. 11. An important difference between the sources in each of these studies is their sizes. In the former study,[28] the sources subtended no more than 0.1 deg at the eyes, whereas in the latter study[34] the sources subtended at least 0.6 deg at the eyes. It would seem that the maximum luminance has an influence on DG for light sources that are relatively "large,"



(a) (b) (c)

**Figure 10** (a) View of an LED array diffused to a maximum luminance of 15,000 cd/m$^2$. (b) View of an LED array diffused to a maximum luminance of 50,000 cd/m$^2$. (c) View of an LED array without a diffuser; the maximum luminance is 1,000,000 cd/m$^2$.

stimuli ranging in illuminance at the eyes from 0.5 to 8 lx and having durations of 0.125 to 2 s. In addition to finding the expected relationship between DG and the light source's illuminance (see Section 3.1), they found that duration also exerted an effect on DG, with the longer-duration stimuli being reported as more uncomfortable. Overall, ratings of discomfort were found to be correlated with the "dose" of light exposure, defined by the product of illuminance (lx) and duration (s) and having units of lx·s. However, in a study by Van Derlofske et al.[33] in which DG ratings to stimuli varying in illuminance (from 1 to 4 lx at observers' eyes) and in duration (from 2.5 to 5 s) were assessed, the duration of exposure did not impact the DG ratings. Possibly, the duration matters in terms of DG up to a duration of about 2 to 2.5 s after which it no longer impacts visual discomfort, but this would require further testing to verify.

Glare recovery is the response that appears to have the strongest relationship with the duration of exposure to a light source. Irikura et al.,[37] Van Derlofske et al.,[33] and Skinner and Bullough[25] all found that recovery times following glare exposure were strongly correlated with the dose as defined in the preceding paragraph (i.e., illuminance × duration). Interestingly, this relationship with the glare dose also seems to interact with the recovery task (on- or off-axis) and the spectral distribution of the glare source[51] as described in Section 3.5. Figure 24 shows recovery times following exposure to sources with different CCTs (3000 and 6500 K), and it illustrates the relationship between recovery and the glare dose, albeit a different one for each glare source CCT.

Like disability glare, reflected glare is a physical phenomenon, and further takes place entirely within the realm of physics, occurring outside the eye. Consequently, reflected glare is present for the same duration that the offending light source is present.

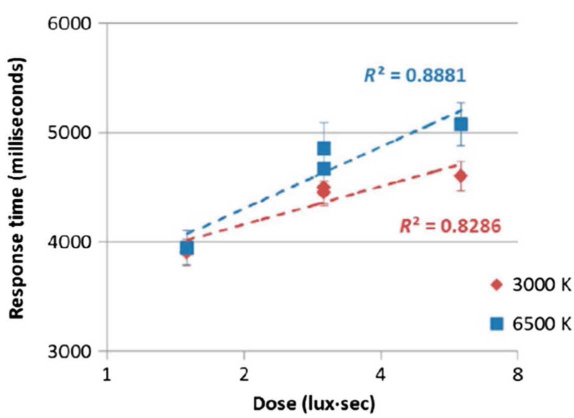



**Figure 24** Glare recovery times for an off-axis visual task as a function of the glare dose for two glare source CCT values.[51]

The perceived aesthetics of a glare source can also influence the degree to which observers might experience DG. The degree of visual discomfort from windows with different view characteristics was investigated.[79] Controlling for the light levels produced by the windows, they either were diffused to eliminate the view through them completely, had a mundane view of a concrete block wall, or had a view of a natural park scene. The visual interest of these scenes were rated in a separate experiment to increase from no view, to the view of the wall, to the natural view. People's responses to the views showed that they experienced less DG when there was an attractive natural view, and they experienced the most DG when the view was obscured by the diffusers, even if all of the windows produced the same light levels at observers' eyes.[79] This demonstrates that people are more able to tolerate DG if the environment is more attractive or interesting.

## 4 Modeling and Predicting Glare

In the present chapter of this Spotlight, a few models of glare are briefly described. These models can be used by lighting specifiers and optical engineers to help make predictions of various aspects of glare that might be experienced by individuals in different lighting applications. Not all glare aspects have been extensively modeled.

### 4.1 Disability glare modeling

There have been several equations published to characterize the properties of the scattered light in the eye that acts like a luminous veil with a particular equivalent luminance. The primary factors that influence disability glare are the illuminance it produces at observers' eyes and the angular distance between the source of glare and the observer's line of sight. As described in the previous chapter, some formulae that can be used to calculate the equivalent veiling luminance produced by scattered light in the eye include factors such as the age of the observer and the observer's eye color.[73] However, the inherent variability among individuals makes those formulae less useful from a practical standpoint. A simple equation for the equivalent veiling luminance ($L_v$, in cd/m$^2$) from by a light source that produces a particular illuminance ($E$, in lx) at the eyes, and which is located at a particular angular distance (θ, in degrees) from the line of sight is as follows:

$$L_v = 9.2E/[\theta(\theta + 1.5)]. \tag{5}$$

Equation (5) should be used for each potential source of glare in the lighted environment; the equivalent veiling luminances from each source can be added together to estimate the overall equivalent veiling luminance that would be experienced. The equivalent veiling luminance is added to the luminances of both the object to be seen and to the immediate background to adjust its contrast so it can be evaluated in terms of visibility.

### 4.3 Glare recovery modeling

Although fundamental work to establish dark adaptation curves like the one shown in Fig. 3 (Section 2.3) has been undertaken, and strong correlational relationships between measured recovery times and glare exposure doses (in terms of lx·s) have been established for specific visual tasks (and for different locations in the field of view), modeling and predicting glare recovery times would be very challenging because of the strong influence of the task one is performing that is used to define recovery. For a very easy task like detecting a large, very bright object, recovery could be almost instantaneous even following a very intense exposure to light for a long duration. If the task is small and/or low-contrast and occurs at a very low light level close to total darkness, recovery times can be very long. Comparisons of two glare source exposures under otherwise identical conditions (location in the field of view, background light level, size and contrast of the visual task) can be made by comparing the exposure doses of the two glare conditions.

### 4.4 Reflected glare modeling

In a study of various interior lighting conditions that included a wide variety of computer display types,[85] a simple model of subjective acceptability of reflections in the screens was made for three types of computer display screens:

- Positive-polarity (white background), glossy-finish screens
- Positive-polarity, diffuse-finish screens
- Negative-polarity (dark background), diffuse-finish screens

Negative-polarity, glossy-finish display screens were not included because these almost always exhibit unacceptable and very conspicuous screen reflections. Observers rated the acceptability of images of ceiling luminaires reflected in the screens on a seven-point rating scale where 1 = never acceptable, 4 = sometimes acceptable, and 7 = always acceptable. Ratings of acceptability ($R$) for each type of screen were related to the luminous intensity ($I$, in cd) from the luminaire in the direction of the display[85]; for positive-polarity, glossy-finish screens were predicted as follows:

$$R = 5.595 - 0.329I^{0.4}. \tag{8a}$$

For positive-polarity, diffuse-finish screens, ratings of acceptability ($R$) were predicted by the following equation:

$$R = 7.392 - 0.139I^{0.4}. \tag{8b}$$

For negative-polarity, diffuse-finish screens, ratings of acceptability ($R$) were predicted as follows:

$$R = 6.107 - 0.307I^{0.4}. \tag{8c}$$

These predictive models were developed around the turn of the millennium.[85] As display finishes have improved in recent years to provide reduced glossiness while maintaining image sharpness, and as they have increased in screen luminance, the formulae in Eq. (8) could be considered conservative because brighter or less glossy screens than those used to develop the model would be expected to be more acceptable than the model equations would predict.

## 5 Hints for Designing to Control Glare

The preceding chapters of this Spotlight describe some of the technical details and predictive models that can be employed by the designer of a lighting system or by an optical engineer to reduce the negative impacts of glare. The present chapter will not provide an exhaustive treatment of detailed methods for glare control, but rather will briefly summarize a few approaches that might reduce the negative impacts of disability glare, DG, glare recovery, and reflected glare.

### 5.1 Disability glare control

Methods for limiting the impacts of disability glare include:

- Locate luminaires away from the line of sight (e.g., for outdoor lighting, mount luminaires on poles as high as possible while maintaining appropriate illumination on the roads/sidewalks) to reduce the veiling luminance as shown in Fig. 14.
- Select “cutoff” types of outdoor luminaires[86] or luminaires that produce the lowest amount of high-angle light. The Illuminating Engineering Society (IES) has published a rating system for outdoor luminaires[87] that characterizes the distribution from luminaires by the acronym BUG, where “B” refers to light behind the luminaire (where it might illuminate adjacent properties rather than the road), “U” refers to uplight that can contribute to sky glow, and “G” refers to the high-angle light that can contribute to glare.[87] Select luminaires with the lowest “G” rating value.
- Increase overall light levels making visual tasks easier to perform, so that contrast reductions from scattered light will have a smaller effect on visual performance. When feasible, use high-contrast, large visual tasks (e.g., contrasting tape colors on the edges of stairs to make them more conspicuous).

### 5.2 Discomfort glare control

Methods for reducing the negative impacts of DG include:

## 5.4 Reflected glare control

Consider the following methods for controlling reflected glare:

- Position the light source to avoid reflections in the visual task.
- Use printed materials with matte rather than glossy surfaces.
- If glossy computer screens with white backgrounds are present, limit the luminous intensity of luminaires in the direction of the screens to 180 cd to ensure an average acceptability rating value of at least 3 (see Section 4.4).[85] If diffuse screens with dark backgrounds are present, limit the luminous intensity of the luminaires in those directions to 320 cd. If diffuse screens with white background are present, limit the luminous intensity in those directions to 5500 cd. (Luminous intensities of luminaires as high as 5500 cd may result in discomfort or disability glare!)

# 6 Future Outlook

Hopefully, this Spotlight has provided a brief and basic introduction to the principles underlying glare, its causes, and its effects on performance and comfort in varied lighting applications. Recognizing the limitations primarily with respect to brevity, this chapter provides several thoughts on the current state of research to characterize glare, and methods for its prediction and control.

Presently, research investigations of glare are almost always segregated by specific applications. In this Spotlight, much of the primary focus has been on lighting applications that take place outdoors, such as vehicle headlighting and streetlighting, and on glare when using visual displays. As described earlier, these are the applications where glare, especially disability glare, DG, and glare recovery are most critical. It is likely that for these applications, where the basic effects of factors, such as light source intensity, luminance, and (when relevant) location are understood, that future work and development of lighting systems to control glare may focus on time as a critical factor.

Adaptive lighting control schemes for vehicle headlights include automatic switching systems between high beam headlights and low beam headlights, and more recently, adaptive driving beam (ADB) headlighting systems;[88] see Fig. 28. ADB headlights allow a driver to have their high beam headlights on at almost all times, but use sensors and cameras to identify the locations of oncoming headlights and preceding taillights. With the angular locations of these lights, the intensity from the ADB headlights can be reduced specifically in those locations to reduce disability and DG for drivers located there.

Adaptive streetlighting strategies have also begun to be used, mainly for the purpose of reducing energy use and light pollution. In adaptive streetlighting control, reducing the output of streetlights would also help reduce glare. At the time this Spotlight was produced, the temporal effects of lighting on glare were only beginning to be investigated.[89]

## John D. Bullough

John D. Bullough, Ph.D., FIES is a Program Director, Population Health Science and Policy, at the Light and Health Research Center, part of the Icahn School of Medicine at Mount Sinai. He manages the center's research programs in transportation lighting, safety and human factors. He earned his doctorate in Multidisciplinary Science from Rensselaer Polytechnic Institute and has written or co-written more than 500 articles and technical publications on lighting.