2004-01-1094

Headlamp Illumination and Glare: An Approach to Predicting Peripheral Visibility

John D. Bullough and John Van Derlofske
Transportation Lighting Group, Lighting Research Center, Rensselaer Polytechnic Institute

ABSTRACT

Peripheral visibility is an important aspect of driving but one that is not understood as robustly as on-axis visibility. The present paper summarizes results from a series of field studies investigating the effect of headlamp illumination and of oncoming headlamp glare on the speed and accuracy of response to small targets located in the visual periphery. These experiments used headlamp sets providing differing amounts of illumination on targets of varying reflectance, located throughout the field of view. Reaction times to the onset of targets and the percentage of missed targets were measured. The characteristics and locations of the targets and experimental geometry were similar in each study as were the subject demographic characteristics, so that results were very consistent among each of the studies. The pooled results of these studies make up a set of data from which a model of forward visibility as a function of headlamp illumination, oncoming glare, target reflectance and peripheral angle can be developed. An empirical model is outlined in the present paper with recommendations for future refinements.

INTRODUCTION

Headlamps provide forward illumination for drivers to see by at night. In locations where no roadway lighting is provided, headlamps are the only means of providing visibility about the surrounding environment.

Several models are available to predict visibility under headlamp illumination both with and without the effects of glare [e.g., 1-3]. The models are based on the ability to detect pavement markings, roadway signs or delineators, and pedestrians along the roadway. However, few data and models are available that incorporate the impact of headlamp characteristics and glare on peripheral visibility, although this aspect of vision is undoubtedly important for the driving task [4,5].

METHODOLOGICAL APPROACH

Van Derlofske et al. [6-8] investigated the impact of different headlamp distributions on peripheral visibility without oncoming glare. In three successive field studies, approximately age-matched groups of subjects were asked to respond to small (20 by 20 cm) targets of reflectance (ρ) 0.2 or 0.4 while performing a tracking task located in the center of their field of view. Subjects sat in a stationary vehicle facing the targets. Targets were positioned at angles (θ) from 7.5^o to the left of the tracking task to 17.5^o to the right, 60 m ahead of the subjects' seating position (Figure 1). Upon the presentation of a target, subjects released a hand-held switch that permitted recording the reaction time to a target, and (when no response occurred within 1000 ms) the occurrence of missed target presentations.

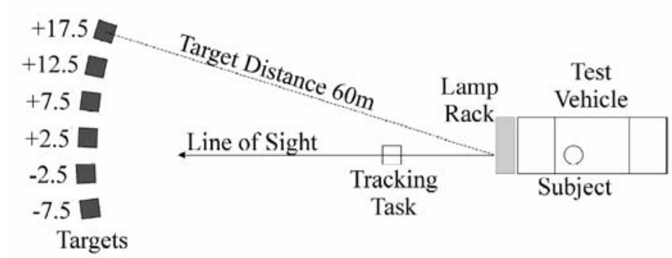

Figure 1. Experimental layout used in field studies of peripheral visibility under headlamp illumination.

All of these studies occurred along an unused, unlighted airport runway. The objectives of the field studies at the time of their implementation were to investigate the impact of high-intensity discharge (HID) headlamps compared to halogen headlamps meeting European [6] and North American [7] forward lighting specifications, and to investigate the impact of spectral power distribution [8] of forward lighting. Despite these different objectives, the similarity of methods and subject demographics, as well as the differences among the illuminance on the targets from each headlamp set that provided forward illumination, suggest that the results can be pooled in a *post hoc* manner to develop a data set that permits a systematic investigation of the impact of headlamp illuminance, target position and target reflectance on peripheral visibility.

In pooling these results it is important to consider the potential confounding effect of spectral power distribution of headlamps on peripheral visibility at the mesopic light levels experienced while driving at night [9]. In this context, spectral effects have been found to impact peripheral visibility from headlamps [8,10], although the difference in spectral power distribution between conventional halogen headlamps and typical HID headlamps found on vehicles does not result in large differences (typically, 5%-10%) in rod-stimulating (scotopic) output that would greatly impact peripheral visibility under mesopic conditions. For this reason, the pooled data include both halogen and HID headlamps [6,7], as well as HID headlamps [8] filtered to mimic the small differences in scotopic output between halogen and HID headlamps. (While the study of spectral power distributions [8] incorporated conditions with much larger differences in scotopic output than found between halogen and HID lamps, these conditions are not investigated further in the present paper.)

Indeed, a preliminary model was developed [11] that incorporated the results of the first two field studies referenced above [6,7]. That preliminary model [11] did not incorporate any potential effects of oncoming headlamp glare on peripheral visibility.

A subsequent investigation of forward peripheral visibility (in terms of reaction times and missed targets) under similar conditions was conducted in which several conditions of oncoming glare was incorporated [12]. A set of oncoming HID headlamps was located 5^o off-axis at a distance of 50 m, representing a meeting condition along a two-lane highway. The illuminance from the oncoming headlamps ranged from 0.2 to 5 lx (vertical) at the observers' eyes. Just as in the earlier studies, small targets were positioned 60 m from the subjects and located from 2.5^o to the left of the line of sight to 17.5^o to the right. (The location of the oncoming headlamps at 5^o to the left of the line of sight made it impossible to locate a target 7.5^o to the left of the line of sight.) Although the oncoming glare sources were HID headlamps, there is no significant impact of spectral power distribution of a glare source on peripheral or on-axis visibility [12-14].

DEVELOPMENT OF MODEL: NO GLARE

REACTION TIMES - The combined data set showing the impact of headlamp illuminance (E), target reflectance (ρ) and target position (θ) on reaction times (RT) is shown in Figure 2 as a series of plots corresponding to the four peripheral angles from 2.5^o to 17.5^o.

He et al. [9] reviewed literature showing that RT to on-axis and peripheral targets can be modeled by an equation of the form:

$$RT = aL^{-0.33} + n \qquad (1)$$

where RT is in ms, L is the luminance of the target of interest (in cd/m^2) and n (in ms) is a constant corresponding to the nonvisual, motor response time involved in making reaction time judgments, and for the studies described above [6-8], was found to be approximately 400 ms. The exponent -0.33 was shown to be applicable to a wide range of conditions. Since the targets used were diffuse in reflectance, L in Equation 1 can be replaced by the illuminance (E) from the headlamp. Using curve-fitting software (WinCurveFit), the values of the coefficient a were found for each target position (q) and reflectance (r) to provide the best fit to the data in Figure 2 using the modified equation:

$$RT = aE^{-0.33} + 400 \qquad (1b)$$

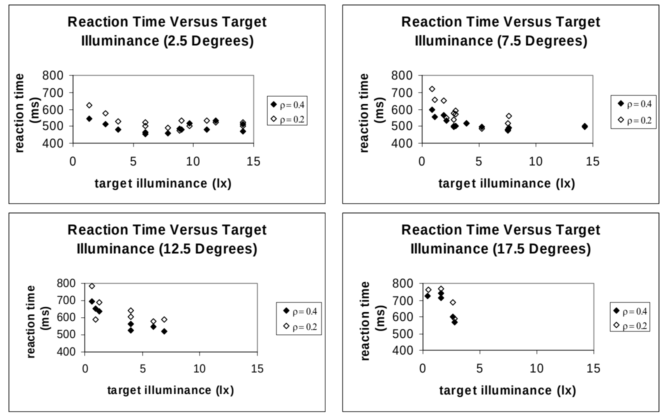

Figure 2. Reaction times to peripheral targets as a function of target illuminance, target reflectance and target position (with no glare present).

The best-fitting values of a increased with increasing position angles and decreased with increasing target reflectance. Interestingly, the value of the coefficient a could be predicted closely using a power function of the form:

$$a = b|\theta|^c + d \qquad (2)$$

where θ is the target position (in degrees; angles to the left of the line of sight are negative and to the right are positive; absolute value is used because the direction of displacement from the line of sight is unimportant) and the coefficients b, c and d are themselves functions based on target reflectance:

$$b = 0.0065\rho^{-2.64} \qquad (3a)$$
$$c = 3.52\rho^{0.35} \qquad (3b)$$
$$d = 143\rho^{-0.28} \qquad (3c)$$

Figure 3 the overall relationship between the observed RT values [6-8] and the values predicted by incorporating Equations 1b, 2 and 3. There is a strong ($r^2 = 0.79$) correlation between the values.

MISSED TARGETS - In similar fashion to Figure 2, Figure 4 shows the impact of headlamp illuminance (E), target reflectance (ρ) and target position (θ) on the percentage of targets that were missed (MT). Noting the monotonic, curvilinear relationship shown in this figure, and taking into account that speed and accuracy of visual performance often follow similar types of trends [15], these data were modeled with a power function of the form:

$$MT = fE^{g} \text{ (or 1 when } fE^{g} > 1) \quad (4)$$

The best-fitting values of the coefficient f increased with increasing position angles and decreased with increasing target reflectance. The best-fitting values of the coefficient g were not systematically related to either target position angle or reflectance; the mean value of g was found to be -0.49.

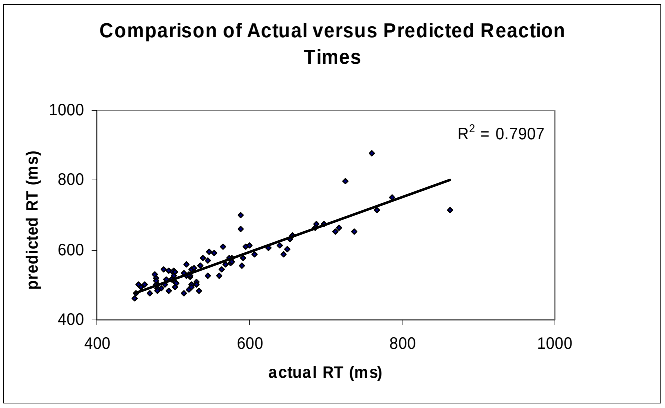

Figure 3. Correlation between actual and predicted reaction times (without glare present).

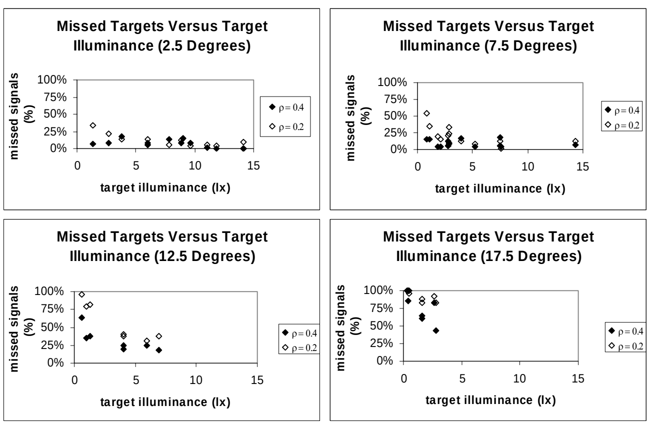

Figure 4. Missed target percentages for peripheral targets as a function of target illuminance, target reflectance and target position (with no glare present).

Using a similar method to derive an expression for f as that used to derive the value of a for the RT predictions, the value of the coefficient f could be modeled as a function of the target position:

$$f = h|\theta|^{j} + k \quad (5)$$

where θ is the target position (in degrees) and h, j, and k are predicted as a function of target reflectance (ρ):

$$h = 0.000064\rho^{-3.11} \quad (6a)$$
$$j = 3.98\rho^{0.63} \quad (6b)$$
$$k = 0.0099\rho^{-2.2} \quad (6c)$$

Figure 5 shows the predicted missed target percentages as a function of the observed percentages [6-8]. A strong correlation ($r^2 = 0.89$) between the values is seen in this figure.

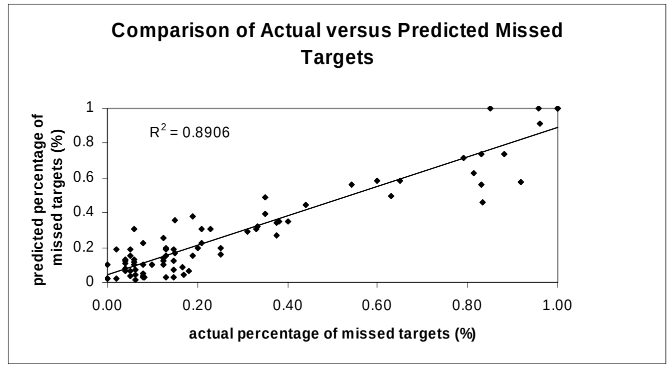

Figure 5. Correlation between actual and predicted missed targets (without glare present).

$\rho = 0.2$			
Angle (θ)	0.2 lx glare	1 lx glare	5 lx glare
-2.5^{o}	∞	∞	∞
$+2.5^{o}$	23 ms	77 ms	193 ms
$+7.5^{o}$	77 ms	151 ms	117 ms
$+12.5^{o}$	24 ms	∞	∞
$+17.5^{o}$	∞	∞	∞
$\rho = 0.4$			
Angle (θ)	0.2 lx glare	1 lx glare	5 lx glare
-2.5^{o}	∞	∞	∞
$+2.5^{o}$	10 ms	15 ms	46 ms
$+7.5^{o}$	22 ms	24 ms	77 ms
$+12.5^{o}$	7 ms	38 ms	56 ms
$+17.5^{o}$	∞	∞	∞

Table 1. Increases in reaction times brought about by exposure to glare.

INCORPORATION OF GLARE

REACTION TIMES - Table 1 lists the increases in reaction time found when glare was present over the predicted reaction times from the model without incorporating glare. Of course, since the study incorporating oncoming glare used only one forward illumination distribution, the values in Table 1 apply only precisely to that particular distribution, but since it is a typical low-beam distribution closely matching those of halogen headlamps sets in other studies [6,7], it provides a useful basis for the preliminary model developed here.

As can be seen, the increase (RT_{inc}) is dependent on the glare illuminance (larger for higher glare illuminances), on the target reflectance (larger for the lower reflectance targets) and on the target location. In particular, targets closest to the oncoming glare source were greatly impacted by the presence of any glare (more so than would be predicted by considering the veiling luminance caused by scattered light in the eye [16]). Those targets furthest from the line of sight were also greatly affected, since presumably they were already closer to threshold as evidenced by their longer reaction times.

This more complex behavior was modeled by power functions of the glare illuminance (E_{gl}), using an exponential type of equation having large increases above and below certain target angles (θ):

$$RT_{inc} = 2[e^{m + n/(\theta + 20) + p \ln(\theta + 20)}]^2 E_{gl}^{0.49} \quad (7)$$

The values of m, n and p are determined by the reflectance (ρ) according to the following equations:

$$m = -345(0.6 - \rho) \quad (8a)$$
$$n = 2095(0.6 - \rho) \quad (8b)$$
$$p = 82.3(0.6 - \rho) \quad (8c)$$

Using the sum of the no-glare reaction times (RT) and the increase (RT_{inc}) in reaction time caused by glare (and substituting 1000 ms for predictions longer than 1000 ms as well as targets missed completely), the actual and predicted reaction times were plotted in Figure 6. There is a relatively high correlation (r^2 = 0.81) between the actual and predicted values.

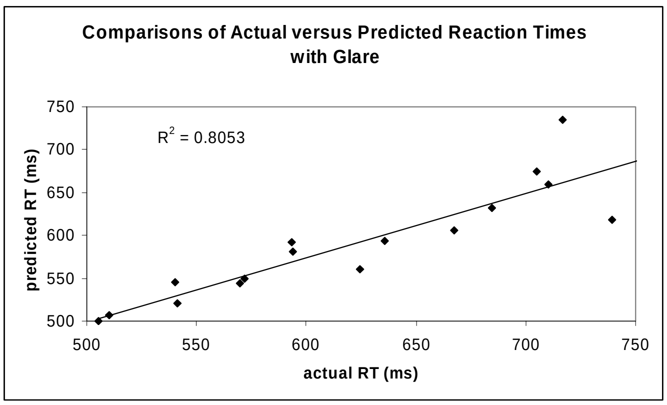

Figure 6. Correlation between actual and predicted reaction times (with glare present).

ρ = 0.2			
Angle (θ)	0.2 lx glare	1 lx glare	5 lx glare
-2.5^o	+77%	+77%	+75%
+2.5^o	+0.9%%	no change	+46%%
+7.5^o	no change	+19%	+54%
+12.5^o	no change	+18%	+30%
+17.5^o	no change	no change	no change
ρ = 0.4			
Angle (θ)	0.2 lx glare	1 lx glare	5 lx glare
-2.5^o	+95%	+95%	+93%
+2.5^o	+15%	+9.9%	+9.9%
+7.5^o	+8.5%	+3.6%	+3.6%
+12.5^o	+27%	+25%	+37%
+17.5^o	no change	no change	no change

Table 2. Increases in missed targets brought about by exposure to glare.

MISSED TARGETS - In similar fashion to the reaction time data, the presence of oncoming glare increased the percentage of missed targets. Table 2 shows these increases over the predictions from the model without glare. As with the reaction time data, the behavior is complex because missed targets increase greatly near the glare source regardless of the glare illuminance. There tends to be little impact of glare near the line of sight, especially for the high reflectance targets located 2.5^o to the right of the sight line. Far from the line of sight, the percentage of missed targets tends to already be high so that large increases are not seen in at these locations, although the presence of glare surely would have a significant impact on visibility.

This behavior is modeled using a third-order polynomial equation as the primary model term. The effects were first modeled as a function of the target angle (θ):

$$MT_{inc} = a\theta^3 + b\theta^2 + c\theta + d \quad (9)$$

where the coefficients a, b, c and d are modeled as linear functions of the glare illuminance (E_{gl}), based on the target reflectances (ρ):

$$a = -\rho E_{gl}/10000 - 0.0012\rho^{0.42} \quad (10a)$$
$$b = (0.007\rho - 0.002)E_{gl} + 0.028\rho^{0.28} \quad (10b)$$
$$c = (-0.078\rho + 0.029)E_{gl} - 0.19\rho^{0.17} \quad (10c)$$
$$d = (-0.3\rho + 0.105)E_{gl} + 0.67\rho^{0.56} \quad (10d)$$

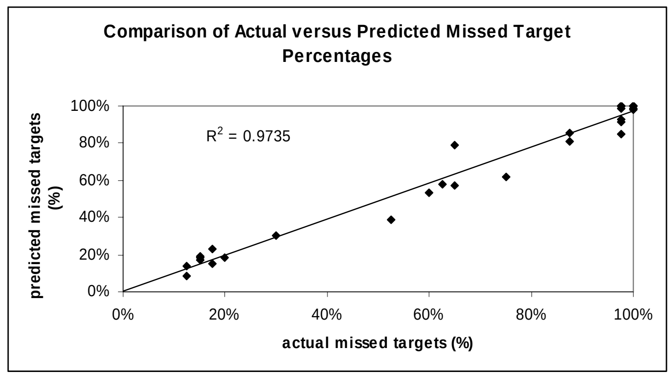

Figure 7. Correlation between actual and predicted missed targets (with glare present).

As with the reaction time/glare model, the predicted percentages of missed targets are determined by adding the missed targets without glare (MT) to the increase in missed targets (MT_{inc}). The actual and predicted values using this model are plotted in Figure 7. The fit between the values is excellent (r^2 = 0.97).

PRACTICAL EXAMPLE

Consider a driving situation with low-beam headlamps, and suppose the visual task is to detect a target located 60 m ahead, having either high (ρ = 0.4) or low (ρ = 0.25) reflectance and located at an angle (θ) either 2.5^o to the left or 10^o to the right of the line of sight. Low-beam headlamps produce a vertical illuminance on the targets (E_t) of 2.8 lx when the targets are 2.5^o to the left, and 1.7 lx when the targets are 10^o to the right. What is the effect of headlamp glare on detection of that target, under oncoming illumination from 50 m having an intensity of 1000 cd or 10,000 cd, corresponding to a glare illuminance (E_{gl}) of 0.4 and 4 lx, respectively?

Using the equations provided above, the overall reaction time (RT_{ov}) and overall missed targets (MT_{ov}) are listed for each condition in Table 3.

ρ	θ	E_t	E_{gl}	RT_{ov} (ms)	MT_{ov}
0.4	2.5° left	2.8 lx	0.4 lx	609	100%
0.25	2.5° left	2.8 lx	0.4 lx	1000+	100%
0.4	2.5° left	2.8 lx	4 lx	772	100%
0.25	2.5° left	2.8 lx	4 lx	1000+	100%
0.4	10° right	1.7 lx	0.4 lx	564	36%
0.25	10° right	1.7 lx	0.4 lx	615	41%
0.4	10° right	1.7 lx	4 lx	582	38%
0.25	10° right	1.7 lx	4 lx	689	69%

Table 3. Impact of different amounts of glare on visibility of targets at two different locations.

Two trends are of note in observing the values in Table 3. First, the presence of any glare at all makes the target located 2.5° to the left of the line of sight virtually invisible in terms of missed targets, demonstrating how difficult it can be to see objects in the oncoming lane when vehicles are also present in that lane. Second, the importance of the target's reflectance can be seen in that the higher glare illuminance only slightly increases the reaction times and missed targets when the reflectance is 0.4. However, the increase in both reaction time and in missed targets is substantial for the target with lower reflectance (0.25), indicating that the impact of disability glare from oncoming headlamps is particularly strong for darker colored objects.

DISCUSSION AND CAVEATS

The simple model of peripheral visibility and the impact of glare on peripheral visibility of targets outlined here is, of course, preliminary. Further refinements to the approach taken here could include the use of additional forward headlamp sets with additional distributions in order to extend the model beyond its present form. Nonetheless, the model closely predicts the results of several studies each conducted using similar experimental methods and can be used to explore the relative impact of forward illumination and oncoming glare on peripheral visibility in order to study the balance between illumination for good forward visibility and potential negative impacts in terms of disability glare.

Of interest, the precision of the model appears to be greater for missed targets than for reaction times. This seems reasonable, given the experimental protocol under which reaction time measurements were made. Because reaction times longer than 1000 ms were excluded from the final data set for reaction times, a number of conditions with glare had very few reaction time values from which to make predictions. The missed target data therefore provided a more precise and perhaps more accurate measure of visual performance under the conditions tested.

It should also be recalled that the visual targets used in the studies forming the basis of the model were small, square shapes approximately 20 cm across. Undoubtedly, responses to larger targets would be improved [15] but the model in present form is probably a sensitive predictor of when visual conditions are likely to begin deteriorating.

ACKNOWLEDGMENTS

The field studies described in this paper were conducted with the assistance of Claudia Hunter, Yukio Akashi, Peping Dee and Jie Chen of the Lighting Research Center. The studies of forward visibility in the absence of glare were supported by Philips Automotive Lighting under the direction of Josef Schug. The study of forward visibility in the presence of glare was supported and by the National Highway Traffic Safety Administration under the direction of Michael Perel.

REFERENCES

1. Farber, E. and C. Matle. 1989. PCDETECT: A revised version of the DETECT seeing distance model. *Transp. Res. Rec.* (1213): 11-20.
2. Aktan, F. and T. Schnell. 2002. A web-based legibility threshold and road sign luminance contrast calculator for nighttime driving conditions. *16th TRB Visibility Symp.*, Iowa City, IA.
3. Uding, K. 2002. Using the ERGO modeling program to optimize in-field sign retroreflectivity. *16th TRB Visibility Symp.*, Iowa City, IA.
4. Schieber, F. 1995. Effects of visual aging upon driving performance. *3rd Intl. Symp. Ltg. Aging Vis. Health*, Orlando, FL.
5. Owsley, C., K. Ball, M. E. Sloane, D. L. Roenker and J. R. Bruni. 1991. Visual/cognitive correlates of vehicle accidents in older drivers. *Psychol. Aging* 6: 403-415.
6. Van Derlofske, J., J. D. Bullough and C. M. Hunter. 2001. Evaluation of high-intensity discharge automotive forward lighting (2001-01-0298). *SAE World Cong.*, Detroit, MI.
7. Van Derlofske, J., J. D. Bullough and C. M. Hunter. 2002. Visual benefits of high-intensity discharge forward lighting (2002-01-0259). *SAE World Cong.*, Detroit, MI.
8. Van Derlofske, J. and J. D. Bullough. 2003. Spectral effects of high-intensity discharge forward lighting on visual performance (2003-01-0559). *SAE World Cong.*, Detroit, MI.
9. He, Y., M. S. Rea, A. Bierman and J. Bullough. 1997. Evaluating light source efficacy under mesopic conditions using reaction times. *J. Illum. Eng. Soc.* 26(1): 125-138.
10. Van Derlofske, J., D. Dyer and J. D. Bullough. 2003. Visual benefits of blue-coated lamps for automotive forward lighting (2003-01-0930). *SAE World Cong.*, Detroit, MI.
11. Bullough, J. D. 2002. Modeling peripheral visibility under headlamp illumination. *16th TRB Visibility Symp.*, Iowa City, IA.

12. Bullough, J. D., J. Van Derlofske, P. Dee, Jr., J. Chen and Y. Akashi. 2003. Impact of headlight glare on peripheral visibility. *PAL Symp.*, Darmstadt, Germany.
13. Flannagan, M. J. 1999. *Subjective and Objective Aspects of Headlamp Glare: Effects of Size and Spectral Power Distribution.* Ann Arbor, MI: University of Michigan.
14. Bullough, J. D., Z. Fu and J. Van Derlofske. 2002. Discomfort and disability glare from halogen and HID headlamp systems (2002-01-0010). *SAE World Cong.,* Detroit, MI.
15. Rea, M. S. and M. J. Ouellette. 1991. Relative visual performance: A basis for application. *Lighting Res. Technol.* 23(3): 135-144.
16. Fry, G. A. 1954. Evaluating disability effects of approaching automobile headlights. *Highway Res. Bull.* (89): 38-42.

CONTACT

John D. Bullough, Lighting Scientist and Adjunct Assistant Professor, Lighting Research Center, School of Architecture, Rensselaer Polytechnic Institute, 21 Union Street, Troy, NY, 12180, USA. Telephone: +1.518.687.7100; facsimile: +1.518.687.7120; email: bulloj@rpi.edu; web: www.lrc.rpi.edu.