

# Model predicting discomfort glare caused by LED road lights

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**Abstract:** To model discomfort glare from LED road lighting, the effect of four key variables on perceived glare was explored. These variables were: the average glare source luminance ( $L_g$ ), the background luminance ( $L_b$ ), the solid angle of the glare source from the perspective of the viewer ( $\omega$ ) and the angle between the glare source and the line of sight ( $\theta$ ). Based on these four variables 72 different light conditions were simulated in a scaled experimental set-up. Participants were requested to judge the perceived discomfort glare of these light conditions using the deBoer rating scale. All four variables and some of their interactions had indeed a significant effect on the deBoer rating. Based on these findings, we developed a model, and tested its general applicability in various verification experiments, including laboratory conditions as well as real road conditions. This verification proved the validity of the model with a correlation between measured and predicted values as high as 0.87 and a residual deviation of about 1 unit on the deBoer rating scale. These results filled the gap in estimating discomfort glare of LED road lighting and clarified similarities of and differences in discomfort glare between LED and traditional light sources.

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## 1. Introduction

In recent years, high power LED technology shows rapid developments in improving its lighting properties, such as luminous efficiency, color characteristics and costs. These

developments enable the penetration of LED technology into the general lighting market. However, this kind of new light sources possesses the characteristics of high surface luminance, small emitting size and special spectral power distribution due to its peculiar emitting principle, in outdoor lighting, and especially in road lighting, there is also a rising concern that LED based light sources may cause more glare to drivers and pedestrians [1]. Since glare increases the detection threshold of objects' motion nearby [2] and decreases the luminance contrast between objects and their background, it is considered a severe issue for traffic safety. The method of glare control is becoming a hot topic in the evaluation of the lighting quality again as the widespread applications of the LEDs.

There are two types of glare: disability glare and discomfort glare. Disability glare is mainly based on a physiological response of the human eye, and expresses the loss of visibility as a consequence of a glaring source in the field of view. Discomfort glare does not necessarily hamper visibility on the short term, but reflects the irritating, distracting and even painful sensation of seeing a glaring source somewhere in the visual field [3, 4]. It may, therefore, result on the longer term in mental fatigue, headache and tension, which may reduce attention and safety [5]. Disability glare is more easily addressed [3], since it can be described with known aspects of the physiology of the human visual system [6, 7]. Discomfort glare, on the other hand, has a psychological response, and therefore, is more difficult to address. Hence, to define design guidelines for safe LED-based road lighting, especially discomfort glare resulting from LED light sources needs to be better understood.

The evaluation of discomfort glare was hotly debated in the past decades [8]. Its occurrence was usually assessed by asking observers to rate their discomfort sensation [9–22], and these studies proved that participants could easily give a graded response to the presence of a glare source [23]. The most widely adopted scale used to evaluate discomfort glare was established by deBoer and Schreuder. This so-called deBoer rating scale is a nine-point scale with adjectives near the odd numbers. A larger value on the deBoer rating scale represents less perceived discomfort glare.

Based on the deBoer rating scale many models for discomfort glare in road lighting have been developed, i.e., by deBoer et al. [11], Schmidt-Clausen et al. [12] and Bullough [19, 20, 22]. In general, these models predict the sensation of glare  $G_s$  from a single glare source for various parameters including the luminance of the glare source  $L_s$  (in cd/m<sup>2</sup>), the solid angle subtended at the eye by the glare source  $\omega_s$  (in Sr), the luminance of the background  $L_b$  (in cd/m<sup>2</sup>), and the deviation of the glare source from the line of sight  $p$ , resulting in Eq. (1) [24]. In this equation, the coefficients  $a$ ,  $b$ ,  $c$  and  $d$  have to be fitted to experimental data.

$$G_s = \frac{L_s^a \cdot \omega_s^b}{L_b^c \cdot p^d} \quad (1)$$

These prediction models, existing for outdoor lighting, however, were not established for LED-based light sources. The model of deBoer [9], for example, was developed for incandescent lamps, which are nowadays rarely used for road lighting, and also the model of Bullough [19, 20, 22] was not established for LED-based light sources. The model of Schmidt-Clausen [12] was even developed to predict discomfort glare from headlamps of motor vehicles. As in general, while driving, observation of vehicle headlamps is different from the observation of road lights, it is at least questionable to what extent the existing models can be used to predict perceived discomfort glare from LED-based road lights. Moreover, some models, e.g., the one of Bullough [19, 20, 22], were developed to predict discomfort glare when participants looked directly into the glare source, while that viewing condition is very different from the general behavior of drivers and pedestrians, who usually do not look directly into the road lights. Finally, the model of Bullough [19, 20, 22], for example, expressed glare sensation as a function of the vertical illuminance at the position of an observer's eyes, combining different luminous parts in the visual field ( $E_l$  = light source illuminance,  $E_s$  = surrounding illuminance and  $E_a$  = ambient illuminance) [19], obviously,

these values were influenced by each other, and so, difficult to accurately determine independently. Moreover, these values are of limited practical relevance for designers of road lighting luminaires, since they cannot always estimate all contributions from light sources in the visual field to the vertical illuminance at the position of an observer's eyes in a real environment.

Contrary to the situation for road lighting, models, which predict perceived discomfort glare of LED-based light sources, exist for interior applications. These models mainly focus on the impact of the luminance non-uniformity in the LED-based luminaires on perceived discomfort glare [25–27]. It has been reported that increased non-uniformity in the luminous area, caused by the spatial arrangement of LEDs, the pitch length between the LED chips and the chip density in a fixed area, may influence perceived discomfort glare [28]. Based on these findings, the currently widely adopted Unified Glare Rating (UGR) was modified by introducing a factor for the non-uniformity [29, 30]. This modification has proven its validity for interior lighting applications [29, 30], but in road lighting generally the viewing distance is so large that geometrical features inducing non-uniformity are less perceived, and therefore these models for perceived discomfort glare may be less suitable.

Based on the above statements, there clearly is still a need to explore a model for predicting perceived discomfort glare from LED-based road lights, since at this stage it is unclear to what extent the existing models for perceived discomfort glare are robust enough to cover the existing mismatches with the new LED-based road lights. Hence, we performed an empirical study to address this lack in the existing knowledge. As such, we measured the effect of four key variables (i.e., the average glare source luminance, the background luminance, the solid angle of the glare source from the perspective of the viewer and the angle between the glare source and the line of sight) on perceived discomfort glare. With these four key variables, we created 72 different light conditions in a laboratory set-up, mimicking as closely as possible a real road situation. Based on the experimental data, we developed a model for perceived discomfort glare and validated its general applicability in both an additional laboratory experiment and in the real field. These results show that the developed model can estimate the perceived discomfort glare of LED road lighting well and it helps to clarify similarities or differences in perceived discomfort glare between LED-based and traditional light sources.

## 2. Method

### 2.1 Equipment

Figure 1 gives a schematic diagram of the experimental set-up. The whole set-up was built in a totally dark room with the walls and floor painted black.

The glare source used in the experiment consisted of a matrix of high power LEDs covered with a diffuser and had a correlated color temperature (CCT) of 3000K, which is common for road lighting. The reason for setting the CCT to 3000K was to make the results more comparable with traditional light sources (i.e., high pressure sodium and metal halide lamps with both a relatively low CCT). Earlier research showed that light sources with a higher CCT may bring more perceived discomfort glare because they have spectral power distributions with a higher percentage of flux in the “blue” region of the spectrum [31–35]. The luminance of the glare source was controlled with a direct current power supply. The LED-based glare source was installed on a fixed support, through which the position of the lamp could be adjusted to generate different viewing angles between the glare source and the line of sight.

A black-painted wall was partly illuminated by a projector mimicking the road background as in a real road situation. The size of the projecting area was  $2.00 \times 1.38\text{m}^2$  to simulate the human visual field in a real situation. In accordance with the color temperature of the light source, the  $u'$  and  $v'$  value of the background was set at 0.19 and 0.49, respectively.

During the experiment, the observer sat at a distance of 2m from the projection screen, fixed by a head rest. Also the line of sight was fixed by requesting the participants to focus at a fixation mark added to the center of the background.

An additional fluorescent lamp 4 meters behind the observer with a CCT of 3000K was used to provide ambient illumination, resembling a real situation. Because of its wide light distribution, this additional lamp generated a relatively uniform luminance distribution in the whole visual field of the participant. When other light sources were switched off, the corresponding vertical illuminance at the participant's eyes produced by the ambient light was 0.2lx.

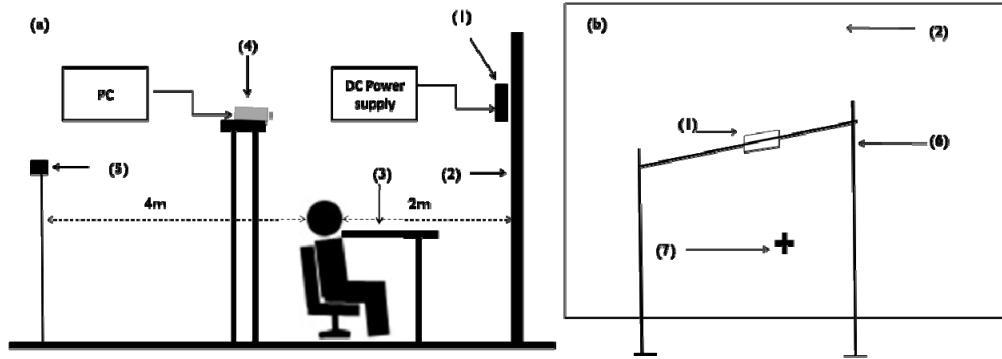


Fig. 1. The schematic of the experimental set-up, in which (a) refers to the side view and (b) to the front view. The number (1) refers to the glare source, (2) to the projection wall, (3) to the head rest used during the experiment, (4) to the projector, (5) to a fluorescent lamp used to generate a low amount of ambient illumination, (6) to a support for the glare source, and (7) to a fixation point used to determine the line of sight.

## 2.2 Experimental conditions

We designed a first experiment to build the glare model. All relevant parameters for this experiment are summarized in Table 1. Of these parameters four independent variables were selected for their presumed effect on discomfort glare: the average glare source luminance, the background luminance, the solid angle from the perspective of the participant, and the viewing angle between the glare source and the line of sight. All other parameters, such as the color temperature, the surrounding luminance, the viewing distance and the tilt angle (i.e., the angle between the surface of the luminaire and the horizontal plane), were fixed at values resembling as much as possible the real condition of driving on an illuminated road. To select the values for the four independent variables we also considered the real road condition, or scaled it down where necessary.

In a real road situation, the typical height of a light post is 10m, the distance between light posts is 30m, and the maximal angle with the line of sight is 20° (because of the shading by the windshield in the car). Assuming these values implies that when the closest road light is shielded by the windshield, the driver can see the next road light at a viewing angle of 10°. The latter road light yields the most disturbing discomfort glare. Hence, the range of viewing angles used in the experiment was chosen between 10 and 20 degrees as road lights appearing in this range cause most glare.

The size of the glare source was scaled proportionally to maintain the same solid angle as on the road. The typical size of LED road lights (i.e., Philips brand) is  $600 \times 250\text{mm}^2$ . Based on these values the scaled size of the glare source could be calculated for the viewing angles used from 10 to 20°. Doing so yielded solid angles of approximately  $1 \times 10^{-5}\text{sr}$  for 10° and  $9 \times 10^{-5}\text{sr}$  for 20° viewing angle.

**Table 1.** Values of the parameters selected in the experiment.

	Parameters	Values
	Adaptation time to the background luminance(min)	5-10
	Illuminance of the surrounding light at the eye position( $E_s$ :lx)	0.2
Constants	Tilt angle(°)	5°
	Colour temperature (K)	3000K
	Observing distance (m)	2
	Viewing mode	binocular
	Average luminance of the LED glare source ( $L_g$ : cd/m <sup>2</sup> )	2500/10000/ 40000/160000
Variables	Background luminance ( $L_b$ : cd/m <sup>2</sup> )	1/5/8
	Solid angle of the glare source ( $\omega$ : sr)	1x10 <sup>-5</sup> /9x10 <sup>-5</sup>
	Viewing angle ( $\theta$ : °)	10/15/20

All combinations of the different values for the four variables were used in the experiment with the aim to collect sufficient data to develop a model. This resulted in 72 different light conditions, which were evaluated on perceived degree of discomfort glare.

### 2.3 Tasks and procedure

The participants performed the experiment one by one. Before the actual start of the experiment, each participant was given a short explanation and training to ensure that he/she was familiar with the process and acquainted with the scale. After having finished the training part of the experiment, he/she remained for 5 minutes in the room with the background and ambient illumination switched on. After this short adaptation period, the actual experiment started. The participant was requested to give a deBoer rating according to the experienced degree of discomfort glare for each of the 72 light conditions. In order to decrease systematic error, the order of the 24 light conditions per viewing angle was randomized differently for each participant. The order, in which the viewing angles were presented to the participant, was based on a Latin Square design. Each light condition was presented by switching the glare source on and off with intervals of 3 seconds. The participant was requested to continuously fixate his/her gaze at the cross mark on the projection wall, in order to avoid that he/she looked directly at the glare source or any other object.

After having given the deBoer rating, the participant was requested to judge whether the light condition was comfortable or not, just with a “yes” or “no” answer. These data were used to obtain the borderline between comfort and discomfort (BCD) with respect to glare perception, defined as the light condition for which 50% of the observers considered it comfortable. In addition, the yes/no responses were used to calculate the visual comfort percentage (VCP) for each light condition. This VCP is an alternative index to indicate the degree of perceived discomfort glare and was adopted to verify the stability of the deBoer

rating scale against different ranges of glare source luminance. As for any rating scale, scores given by the participants on the deBoer rating scale may tend to shift in value depending on the light conditions used in the experiment, even despite of the use of adjectives along the scale [36]. Hence, we compared the deBoer rating with the VCP across all light conditions, to check whether the collected experimental data were reliable.

#### 2.4 Observers

The experiment used a within-subject design with 7 female and 5 male participants, aged between 21 to 29 years. They all had corrected to normal visual acuity (above 1.2) and were not color blind tested by the Pseudo isochromatic Plates. The sample size used was based on a previous pilot study ( $N = 4$ ), indicating that a sample size of 12 would be sufficient to obtain a power larger than 0.95, with one way ANOVA test.

#### 2.5 Verification experiment

In order to validate the model established with the data acquired in the main experiment, a new series of light conditions based on new combinations of the four main variables, but this time also including the CCT, were designed. These light conditions were partly evaluated in the same laboratory as Fig. 1. A supplement verification experiment was carried out in a real road at Fudan University. The participants were seated in a car and were asked to keep looking straight ahead on the road.

The details of these light conditions are listed in Table 2. The whole experimental procedure of the verification experiment was the same as Section 2.3.

**Table 2. Details of the light conditions used in the verification experiment.**

Condition	Sample size	Colour temperature of the glare source											
		3000K				6500K				5000K			
		Laboratory		Laboratory		Real field							
Light condition	12	12	10	10	10	18	18	18	18	18	18	18	18
		$L_g:$ $1 \times 10^4 \text{ cd/m}^2$	$L_b:$ $\text{cd/m}^2$	$\omega:$ $1 \times 10^{-5} \text{ Sr}$	$\theta:$ $^\circ$	$L_g$	$L_b$	$\omega$	$\theta$	$L_g$	$L_b$	$\omega$	$\theta$
1	6	2	5	10	0.08	8	0.8	10	1.1	10	0.8	10	
2	6	2	9	10	3	5	0.8	10	2.6	15	2.6	15	
3	12	2	5	10	3	5	3.1	10	7.2	20	6.1	20	
4	12	2	9	10	3	5	2	10	---	---	---	---	
5	6	2	5	15	5	5	0.8	10	---	---	---	---	
6	6	2	9	15	5	5	3.1	10	---	---	---	---	
7	12	2	5	15	5	5	2	10	---	---	---	---	
8	12	2	9	15	8	1	3.1	10	---	---	---	---	
9	6	2	5	20	---	---	---	---	---	---	---	---	
10	6	2	9	20	---	---	---	---	---	---	---	---	
11	12	2	5	20	---	---	---	---	---	---	---	---	
12	12	2	9	20	---	---	---	---	---	---	---	---	
13	4	1	9	10	---	---	---	---	---	---	---	---	
14	1	5	1	20	---	---	---	---	---	---	---	---	

### 3. Results and discussion

Note that all statistical analyses mentioned further in the paper were performed with SPSS version 16.0. The repeated-measures ANOVA included the main effects of the four independent variables and their 2-way interaction terms. When a post-hoc test was needed, the total error was limited using the Bonferroni method.

#### 3.1 Plots of the experimental data and variance analysis

Figure 2 illustrates the change in the deBoer rating for the four independent variables used in the experiment. A repeated-measures AVONA on the data demonstrated that the deBoer rating increased (i.e., less glare is perceived) with decreasing glare source luminance ( $F =$

487.9,  $df = 3$ ,  $p < 0.001$ ) and solid angle ( $F = 202.0$ ,  $df = 1$ ,  $p < 0.001$ ) and decreased with decreasing background luminance ( $F = 167.5$ ,  $df = 2$ ,  $p < 0.001$ ), but only slightly decreased with decreasing viewing angle ( $F = 5.916$ ,  $df = 2$ ,  $p = 0.009$ ). The confidence interval of the variance analysis and the following regression analysis was 95%. Figure 2 also shows that the relationship between the deBoer rating and the logarithm of the glare source luminance is close to linear.

Additional post-hoc tests showed that the deBoer rating was significantly different between all levels of glare source luminance (level = 4), solid angle (level = 2) and background luminance (level = 3). With respect to the viewing angle the deBoer rating is only significantly different between the smallest ( $10^\circ$ ) and largest ( $20^\circ$ ) viewing angle. In addition, the interactions of glare source luminance with solid angle ( $F = 26.58$ ,  $df = 3$ ,  $p < 0.001$ ) and of glare source luminance with background luminance ( $F = 4.165$ ,  $df = 6$ ,  $p = 0.001$ ) had a significant effect on the deBoer rating. In general, the difference in the deBoer rating between the two solid angles was smaller at a low luminance of the glare source than at a high one. Similarly, the interaction between luminance of the glare source and background luminance was reflected in the difference in the deBoer rating between a background luminance of 5 and  $8\text{cd/m}^2$  to be larger at a high than at a low luminance of the glare source.

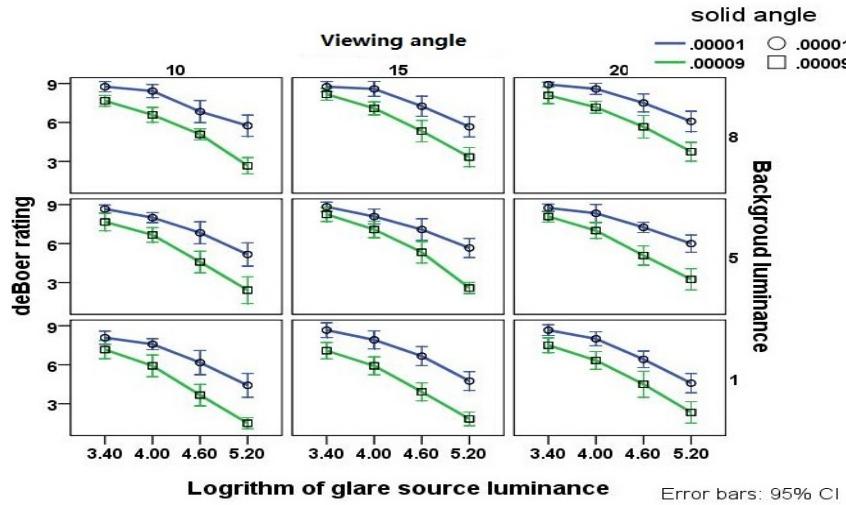


Fig. 2. Change in the deBoer rating for the four independent variables used in the experiment: glare source luminance, solid angle, background luminance and viewing angle.

### 3.2 Alternative variables

According to the model of Bullough [19, 20, 22], the vertical illuminance at the position of the eye produced by the glare source has a significant effect on discomfort glare. With a diffuser in front of the LED glare source, the emitted light is relatively uniform and can be considered as a cosine radiator. So, at a given position of the eye, the relationship between the vertical illuminance at the eye provided by the glare source,  $E_{eye}$ , and the luminance of the glare source,  $L_g$ , is determined by the solid angle  $\omega$  as shown in Eq. (2):

$$E_{eye} \propto L_g \times \omega \quad (2)$$

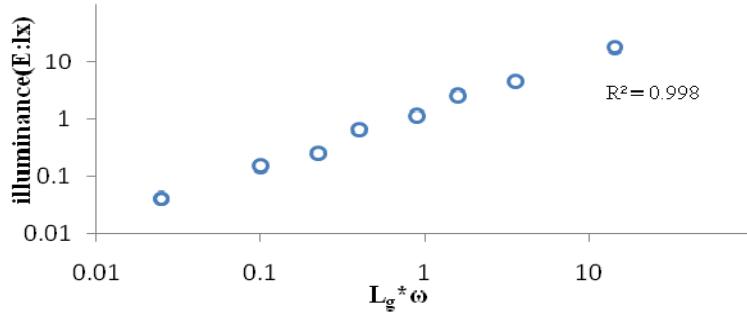


Fig. 3. Relation between the vertical illuminance at the eye produced by the glare source and the product of the glare source luminance and its solid angle (for a viewing angle of 10°).

We measured the illuminance at the eye, excluding the illuminance produced by the background and ambient illumination, for each light condition and compared it to the product of the luminance of the glare source and the solid angle. Taking the conditions for a viewing angle of 10° as an example yielded an almost perfect linear relation, as shown in Fig. 3. Also the relation between the deBoer rating and the logarithm of the product of the glare source luminance and the solid angle was close to linear. Figure 4 shows this relationship again for the light conditions at a viewing angle of 10° and indicates that for each value of the background luminance, the  $R^2 > 0.9$  for the linear fit. Very similar results with  $R^2 > 0.9$  were obtained for the light conditions at a viewing angle of 15° and 20°.

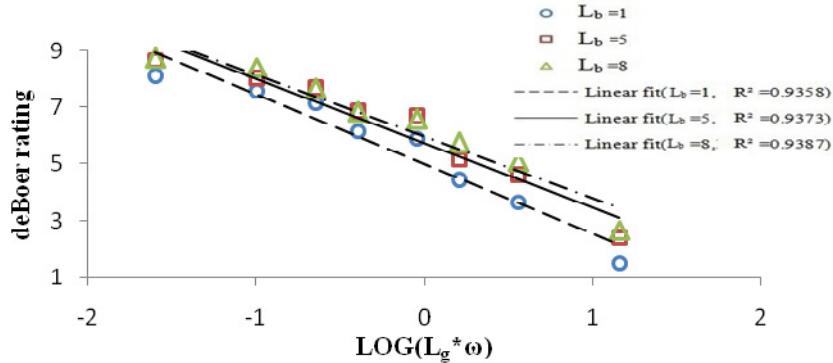


Fig. 4. Linear fit of the deBoer rating as a function of the logarithm of the product of the glare source luminance and solid angle (for a viewing angle of 10°).

As for the interaction between the glare source luminance and background luminance, an assumption could be based on the general expression of glare sensation shown in Eq. (1). Referring to this model, we assumed that the deBoer rating  $R_{deBoer}$  was related to the logarithm of a combined variable containing the glare source luminance ( $L_g$ ) and the background luminance ( $L_b$ ) as shown in Eq. (3):

$$R_{deBoer} \propto \log_{10}(L_g / L_b) \quad (3)$$

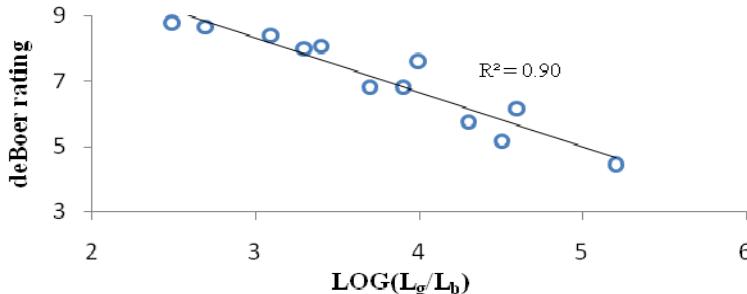


Fig. 5. Linear fit of the deBoer rating as a function of the logarithm of the ratio of the glare source luminance and background luminance (for a solid angle of  $1 \times 10^{-5}$  and a viewing angle of  $10^\circ$ ).

This ratio of the luminance of the glare source and background luminance is actually the luminance contrast in the visual field, which is indeed a main factor that determines the degree of discomfort glare in road lighting. That the logarithm of this ratio almost linearly affects the deBoer rating is confirmed with the data plotted in Fig. 5 (again, for a viewing angle of  $10^\circ$ , and for a solid angle of  $1 \times 10^{-5}$ ). Including also the other viewing angles and solid angle values resulted in fits that in all cases had a  $R^2 > 0.84$ .

The above findings suggest that alternative variables can be used: i.e.,  $\log_{10}(L_g \times \omega)$  and  $\log_{10}(L_g/L_b)$ . These two variables, however, are not independent, and so, including them both in an ANOVA model implies that we induce non-linearity. As an alternative, we can introduce the variable  $\log_{10}(L_g \times \omega/L_b)$ , which actually already combines three of the original four variables. We can now repeat the repeated-measures ANOVA with the new variables, being  $\log_{10}(L_g \times \omega/L_b)$  and the viewing angle, including their 2-way interaction. The result shows that (as expected) both independent variables have a significant effect on the de Boer rating, i.e., for  $\log_{10}(L_g \times \omega/L_b)$  ( $F = 144.9$ ,  $df = 23$ ,  $p < 0.001$ ) and for the viewing angle ( $F = 5.92$ ,  $df = 2$ ,  $p = 0.009$ ). There is no significant interaction between  $\log_{10}(L_g \times \omega/L_b)$  and viewing angle, implying that the change of the deBoer rating with  $\log_{10}(L_g \times \omega/L_b)$  is similar at all viewing angles.

### 3.3 Regression analysis

According to the ANOVA analysis described in section 3.2, the most logical model to relate the deBoer rating to the various independent variables has the following shape shown in Eq. (4):

$$R_{\text{deBoer}} = \text{cte} + \alpha \times \log_{10}\left(\frac{L_g \times \omega}{L_b}\right) + \beta \times \theta \quad (4)$$

However, this model differs fundamentally from the Schmidt-Clausen model [10] and the general expression for glare put forward by Boyce [24](see Eq. (1)) in two aspects: (1) in our model the components  $E_{\text{eye}}$  (or  $L_g \times \omega$ ) and  $L_b$  have the same exponent, while the exponent differs in the models existing in literature, and (2) in our model the viewing angle  $\theta$  is linearly summed, while it is included in the log-term in the models existing in literature. These observations justify the comparison of our model given above with an alternative model of the form shown in Eq. (5):

$$R_{\text{deBoer}} \propto \log_{10}\left(\frac{(L_g \times \omega)^\alpha}{L_b^\beta \times \theta^\gamma}\right) \quad (5)$$

which is equivalent to what shown in Eq. (6):

$$R_{\text{deBoer}} \propto \alpha \times \log_{10}(L_g \times \omega) - \beta \times \log_{10}(L_b) - \gamma \times \log_{10}(\theta) \quad (6)$$

We used SPSS to fit this model to our data, and found the following equation shown in Eq. (7):

$$R_{\text{deBoer}} = 3.45 - 2.21 \times \log_{10}(L_g \times \omega) + 1.02 \times \log_{10}(L_b) + 1.62 \times \log_{10}(\theta) \quad (7)$$

which is equivalent to (hereafter referred to as the Lin-Liu model) what shown in Eq. (8):

$$R_{\text{deBoer}} = 3.45 - \log_{10}\left(\frac{(L_g \times \omega)^{2.21}}{L_b^{1.02} \times \theta^{1.62}}\right) \quad (8)$$

The standardized coefficients of  $\log_{10}(L_g \times \omega)$ ,  $\log_{10}(L_b)$  and  $\log_{10}(\theta)$  are  $-0.835$ ,  $0.180$  and  $0.091$ , respectively, which indicates that eye illuminance is the most dominant factor influencing discomfort glare. This model resulted in an adjusted  $R^2$ -value of  $0.929$  and the comparison between the experimental data and the predicted values is shown in Fig. 6 (taking the viewing angle of  $10^\circ$  for example). In addition, this model is fully in line with the general model proposed by Boyce [24] and looks very similar to the model proposed by Schmidt-Clausen [10]. So, we can conclude that for a LED road light with a uniform emitting surface, perceived discomfort glare is similarly affected by the key parameters of the light source as a traditional light source. The difference between the two types of light sources is not in how the key parameters affect perceived glare, but just in the weighting coefficients of these parameters.

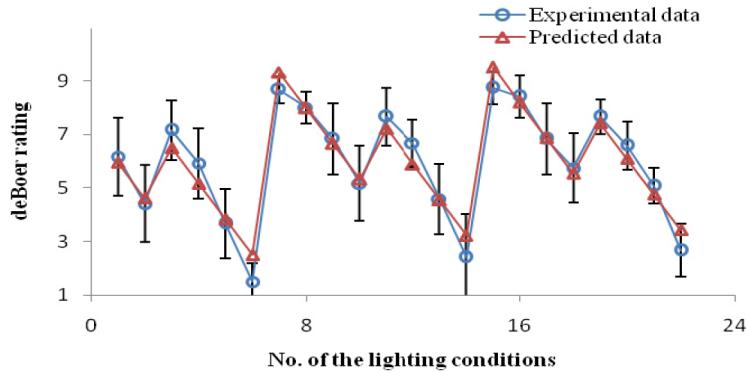


Fig. 6. Comparison between the predicted values calculated by Eq. (8) and the experimental data (for a viewing angle of  $10^\circ$ ).

Still when performing a repeated-measures ANOVA with the deBoer rating as dependent variable, the  $\log_{10}(L_g \times \omega)$ ,  $\log_{10}(L_b)$  and  $\log_{10}(\theta)$  as independent variables and including their 2-way interactions, we found a significant interaction between  $\log_{10}(L_g \times \omega)$  and  $\log_{10}(L_b)$  ( $F = 2.217$ ,  $df = 14$ ,  $p = 0.006$ ). The interactions between  $\log_{10}(L_g \times \omega)$  and  $\log_{10}(\theta)$  and between  $\log_{10}(L_b)$  and  $\log_{10}(\theta)$  were not significant ( $p = 0.812$  and  $p = 0.976$ , respectively). The significant interaction suggests that the regression model should be expanded with a term  $\log_{10}(L_g \times \omega) \times \log_{10}(L_b)$ , resulting in the model shown in Eq. (9):

$$R_{\text{deBoer}} \propto \alpha \times \log_{10}(L_g \times \omega) - \beta \times \log_{10}(L_b) - \gamma \times \log_{10}(\theta) + \delta \times \log_{10}(L_g \times \omega) \times \log_{10}(L_b) \quad (9)$$

Regression analysis in SPSS indicated that the term  $\log_{10}(L_g \times \omega) \times \log_{10}(L_b)$  had indeed a significant contribution, but with a weighting coefficient about 25% smaller than the other weighting coefficients. In addition, the  $R^2$ -value only improved marginally to a value of

0.931. Therefore, we concluded that the simpler model, excluding the term  $\log_{10}(L_g \times \omega) \times \log_{10}(L_b)$  is practically more relevant.

### 3.4 Verification of the model

As mentioned in section 2.5 we used additional light conditions (i.e., new combinations of values of the four key variables) to test the validity of the model against new data. The comparison between the mean rating over 12 participants for each of the 14 light conditions obtained in the verification experiment at 3000K (see Table 2) and the values predicted from the regression model expressed by Eq. (8) is shown in Fig. 7.

The Pearson correlation coefficient between the measured and predicted values was 0.87, which suggested that the trend in measured deBoer ratings was sufficiently accurately predicted by the model. The actual deviation between the verification data and the predicted values can be expressed in the residual deviation (RES), calculated as Eq. (10), where  $R_{pi}$  is the predicted value calculated by the regression model for each light condition,  $R_{vi}$  is the average deBoer rating obtained for each light condition of the verification experiment, and  $n$  is the number of light conditions.

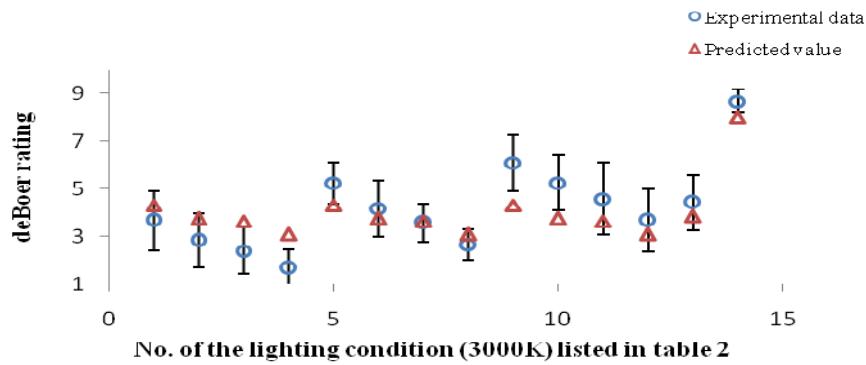


Fig. 7. Comparison between the verification data and the predicted values calculated from Eq. (8) for light conditions with a CCT of 3000K.

Using Eq. (10) the RES was 0.97 for the light conditions at 3000K, indicating that the residual deviation was within one unit on the deBoer rating scale. Studies have shown that a difference of 1 unit in glare index is a just noticeable difference (JND) [37], and so, we showed to be able to predict perceived discomfort glare for LED-based road lights within a JND.

$$RES = \sqrt{\frac{\sum_{i=1}^n (R_{pi} - R_{vi})^2}{n}} \quad (10)$$

For the verification data based on glare sources with another color temperature (i.e. 5000K in the real field condition and 6500K in the laboratory condition) the Pearson correlation coefficient between the measured glare ratings and the predicted values was also equal to or higher than 0.95, as illustrated by the fit in Fig. 8 and Fig. 9, respectively. Hence, this result indicated that the variation of perceived discomfort glare with eye illuminance, background luminance and viewing angle was similar for different CCT of the glare source. But the residual deviation between the measured data and the predicted values was substantially higher (i.e., 2.18) than what we found for the verification data with light conditions at a CCT of 3000K. Obviously from Fig. 8, the higher color temperature resulted in more discomfort glare, which is consistent with past studies, which found that the spectral power distribution of the light source indeed influences the degree of discomfort glare [31–35]. This might be the reason that LED with higher CCT is complained to be more glaring in

application. Actually, the effect of CCT or the spectral power distribution on the deBoer rating scale could be roughly described as a constant off-set, where the off-set was such that the deBoer rating decreased (so, worse perceived glare) when the CCT increased. When considering the average difference (over all light conditions) between the experimental data points and the values predicted by the model as the off-set with which we had to correct the model, all model values should be decreased with a value of 2.1. If we applied this correction, the remaining RES between the measured values and the corrected model values was 0.58, which showed a severe improvement in the model predictions.

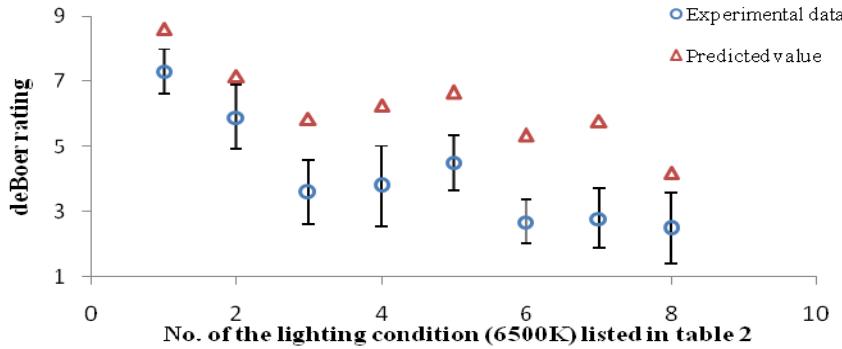


Fig. 8. Comparison between the verification data and the predicted values calculated from Eq. (8) for light conditions with a CCT of 6500K.

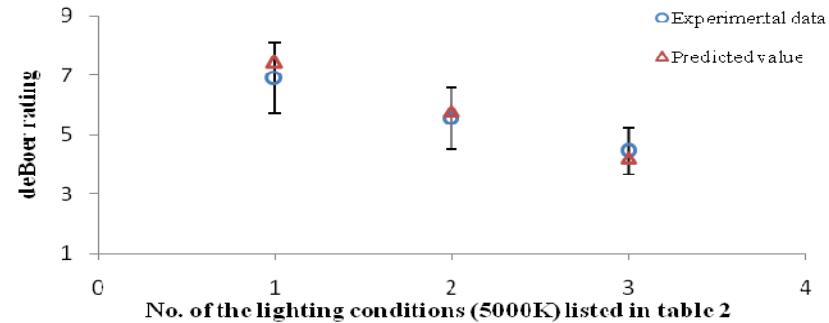


Fig. 9. Comparison between the verification data and the predicted values calculated from Eq. (8) for light conditions with a CCT of 5000K, measured in the real field.

If, however, we corrected the data of the verification in the real situation with a color temperature of 5000K of the glare source, assuming a linear off-set for the difference in CCT (off-set for 5000K =  $((6500-5000)/(6500-3000)) \times$  offset in the deBoer rating from 6500K to 3000K), we found a RES between the measured and predicted values of 0.68. Basically, we also found that the spread in the predicted glare scores was bigger than the spread in the actually measured values. This mismatch might be due to the difference in glare source luminance between the field test and the laboratory experiment. All in all, however, the model predictions were sufficiently close to the experimental data obtained in a real road condition, showing that the model has practical relevance.

In general, the verification experiments all showed a high Pearson correlation between the verification data and the values predicted from Eq. (8), which confirmed the general validity of the regression model. By adjusting the constant in Eq. (8), the model may predict discomfort glare of LED road lights with other color temperatures as well. However, how to

adjust the constant according to different spectral power distribution of the glare source exactly needs further exploration, including developing new metric instead of CCT to evaluate brightness and hence glare [38, 39].

### 3.5 Visual comfort percentage and its correlation with the deBoer rating

Figure 10 shows the mean deBoer rating given by the 12 observers for each light condition on the horizontal axis and the percentage of people indicating that that light condition was comfortable on the vertical axis. Curve fitting shows that the relationship between them was close to a cumulative Gaussian distribution, with an  $R^2$  of 0.96. When 50% of the observers found the light condition comfortable, the corresponding deBoer rating was defined as the borderline between comfort and discomfort. In this experiment, the corresponding deBoer rating was 4.7 at the borderline between comfort and discomfort, being close to the label “5-just admissible” in the deBoer rating scale. Semantically a score of 5 indeed refers to a transition between acceptable and non-acceptable. In addition, by consensus, discomfort glare is believed not to be a problem in lighting installations if the VCP is 70% or more [22]. The corresponding discomfort glare score based on the deBoer rating was slightly above 5, and so admissible. As such, we can conclude that the two methods for measuring discomfort glare show consistent results.

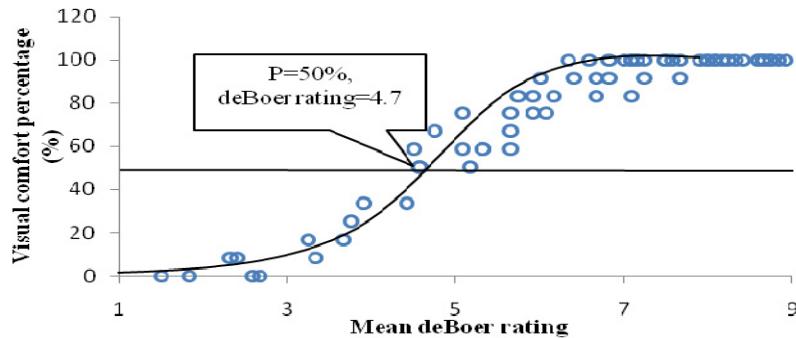


Fig. 10. Curve fitting of the mean deBoer rating vs. the percentage of people indicating that the light setting was comfortable (note that each data point represents a light condition).

### 3.6 Comparison of our model to previous research

Since glare models already exist in literature, we here compare our new model with existing models that used the deBoer rating scale to measure discomfort glare. Considering comparability in light conditions, variable selection as well as measurement method, we limit the comparison here to the model established by Schmidt-Clausen and Bindels [10]. Note that this model was developed for discomfort glare resulting from HID-based headlights of cars, but used the same variables as evaluated in our study. The model is described as Eq. (11), where  $E_i$  is the average level of illumination from the headlamps directed towards the observer's eye,  $\theta_{\max}$  is the glare angle between the observer's line of sight and the direction in which the headlamps emit the maximum illumination and  $L_a$  is the adaptation luminance.

$$R_{\text{deBoer}} = 5.0 - 2.0 \times \log_{10} \frac{E_i}{0.03 \times (1 + \sqrt{\frac{L_a}{0.04}}) \times \theta_{\max}^{0.46}} \quad (11)$$

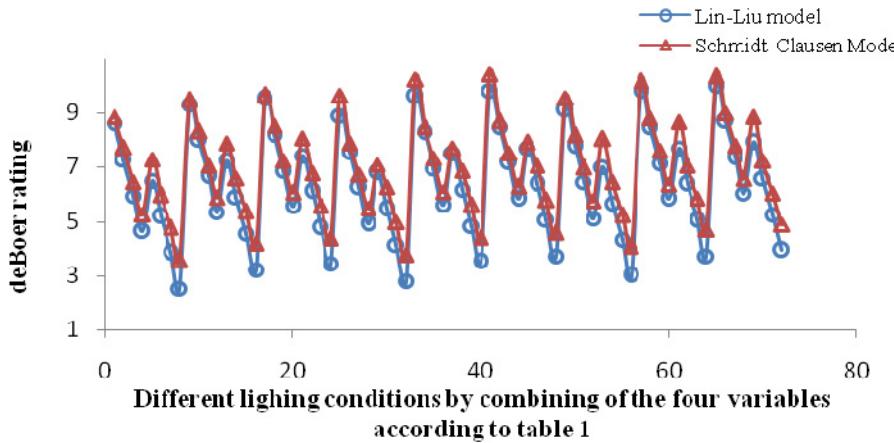


Fig. 11. Comparison between our model for discomfort glare and the one of Schmidt-Clausen for the 72 light conditions used in the main experiment.

The comparison of our model (referred to as Lin-Liu and described by Eq. (8)) to the Schmidt-Clausen model is presented as a scatter plot in Fig. 11, and shows that both models are very similar in predicted discomfort glare. The correlation between both models is as high as 0.995. The deviation between the two models for each of the light conditions tested is maximally in the order of 1 unit on the deBoer rating scale, and so within its JND [37]. Moreover, the deviation is of the same size as the accuracy we obtained in our verification experiments. Although Schmidt-Clausen developed the model for perceived glare from HID headlamps of cars, this same model is also sufficiently accurate to describe perceived discomfort glare from LED road lights with a CCT of 3000K. These results demonstrate that the causes of discomfort glare are very similar for the two models despite of the difference in light source (i.e., HID headlamp vs. LED-based road light).

#### 4. Conclusions

The model developed in this paper based on our experimental data has a similar form as models presented in literature. Perceived discomfort glare expressed by means of a deBoer rating ( $R_{\text{deBoer}}$ ) is related to the illuminance at the eye ( $L_g \times \omega$ ), the background luminance ( $L_b$ ) and the angle between the glare source and the line of sight ( $\theta$ ), as shown in Eq. (12):

$$R_{\text{deBoer}} = 3.45 - \log_{10} \left( \frac{(L_g \times \omega)^{2.21}}{L_b^{1.02} \times \theta^{1.62}} \right) \quad (12)$$

As such, perceived discomfort glare increases with increasing eye illuminance, decreasing background luminance and angle with the line of sight. The most dominant factor for perceived discomfort glare (taking into account normalization of the various contributions) is the eye illuminance, followed by the background luminance and the angle with the line of sight.

As the model was developed with an experimental set-up in a lab environment, it was subsequently validated against new experimental lab data with intermediate values in the four independent variables, as well as with data using a different color temperature of the light and with field data. The model is consistent in predicting the trends in perceived discomfort glare. The absolute value of the model predictions is estimated to be accurate with  $\pm 0.5$  units on the deBoer rating scale. A similar deviation is found between our newly developed model, and the most appropriate model in literature (being referred to as the Schmidt-Clausen model). As our model shows general applicability and validity, it can guide practical designs for LED-based road lighting. These designs should consider controlling the illuminance from the LED

road lights falling onto the drivers' eyes and the luminance contrast between the light source and the background as well as the installed position of the road lights.

### **Acknowledgments**

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