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Ergonomic Glare Evaluation Model on Automobile Headlamp Condition and the Level of Driver's Response

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Abstract

Prolonged exposure to headlights can temporarily affect drivers' visibility, especially at night-time driving environment. The night-time driving environment presents various challenging visual conditions for drivers. Most of the glare studies are subjective and have used the De Boer glare index for evaluation. However, driver's responses are one of the vital parameters need to be considered while studying glare. Hence, this work studied glare effect by considering psychophysiological response of drivers in various environments. The environment include headlamps (LED, HID, Halogen), ambient brightness level, and illuminance level. The psychophysiological responses measured are pupil size, brain activity, and personal satisfaction level. Also, this study proposed discrimination model and prediction model using the De Boer Index and pupil size. With this development it is possible to predict nighttime glare and could reduce accidents at night time driving.

Keywords: De Boer Index, Prediction Model, Glare Effect, Psychophysiological Response

I. INTRODUCTION

Korea has been reducing the investment associated with traffic safety due to rapid economic growth and industrialization. Korea's government implemented a policy that includes traffic safety education, improvement of traffic safety facilities, and application of new technologies for lowering an accident [1]. However, Korea has a relatively high number of traffic accidents, injuries, and deaths compared to advanced countries. The comparison of the mortality rates associated with the traffic accidents in 2010 - 2014, the night-time zone was 0.5% higher (daytime zone was 2.15%, night time zone was 2.65%). In other words, night time accidents can be more deadly for the drivers and the passengers as the traffic environment is dark. Recent advancement in technology provides various lighting, light-signaling devices with different luminous intensity. In the 1990s, most of the automobiles used halogen light as headlights. In recent times, different headlights are used, such as high-intensity discharge (HID), light emitted diode (LED), and laser. However, these lighting cause glare and confusion to the drivers which leads to an accident [2, 3]. High-intensity headlamps emit 2 ~ 3 times higher luminous flux than halogen headlights, also realize functions such as AFLS (adaptive front-lighting system) and ADB (adaptive driving beam). However, on the other hand, drivers are more exposed to glare [4]. Most of the glare studies are subjective and have used the De Boer glare rating scale, i.e., nine-point scale. For example, the rating "1" in the scale referred to as "Unbearable" and "9" referred as "just noticeable." Numerous researchers used the De Boer rating scale to measure the discomfort glare level; however, they were no uniformity in illuminance levels (Table 1).

Bullough and Van [5] reported a high correlation with discomfort glare for the illuminance range of 0.04 to 2.6 lx. The high-intensity discharge (HID) appeared to produce more glare than the halogen headlights. Akashi et al. [6] evaluated the glare of each wavelength using subjective evaluation; the short wavelength of the headlight resulted in more glare. Schmidt and Bindels [7] proposed a mathematical predictive model for the De Boer index under the condition of illuminance (within 20 lx) and ambient brightness (1 ~ 25 cd/m2). Lenhert [8] updated the mathematical model of Most of the discomfort glare studies used the De Boer index or developed a mathematical predictive model for the De Boer index. However, the De Boer index has certain disadvantages; the index not considered carelessness and fatigue of drivers. Van [9] suggested that the method of glare evaluation should be improved from the physiological point of view. Ji and Yang [10] and Lal and Craig [11] suggested that the driver's fatigue can be evaluated by nonintrusive methods such as eye detection, eyelid movement, and face orientation. Coetzer and Hancke [12] reported that glare and fatigue could be interpreted using EEG.

Eye pupil size decreases when lots of light enters the eyeball. On the other hand, when less light enters the eyeball, pupil size increases [13]. The pupil size of older adults gradually decreases as age increases [14]. Hopkinson [15] suggested that pupil size is more related to the intensity of light than to the feeling of discomfort. Colombo et al. [16] reported that the pupil size changed from 4.8 ~ 7.2 mm with a change in the illumination conditions of 15, 30, 60 lx. Daneault et al. [17] compared participant's pupil size with blue (480 nm) and green (550 nm) lights, the result claimed that the pupil size decreased more in blue light than in green light. Badia et al. [18] performed an EEG spectral analysis with fluorescent light sources using 5,000 lx of bright light and 50 lx of dim light. As a result, Beta waves were activated at night time and showed no difference during day time. Shieh et al. [19] claimed that alpha wave decreased, and theta wave increased as contrast of luminance was decreased. Sakaue et al. [20] reported the decreased alpha wave pattern when light intensity of 40 lx with shorter wavelength (470 nm) than the long-wavelength (630 nm).

Most of the studies mentioned above were considered the intensity and wavelength of light. However, not many studies focused on night traffic environment and driver's responses. Hence, it is necessary to study the glare at night traffic environment, including headlight type, illuminance, and ambient brightness, and driver's response including pupil size, brain activity, and subjective satisfaction. This study is to suggest an ergonomics evaluation model for glare on headlamp type and driver's response. Also, this study aims to develop a practical and easy to use glare prediction model.

Table 1. Range of illuminance on the De Boer glare index

De Boer rating	Schmidt (1974)	Lehnert (2001)	Bullough et al., (2002)	Theeuwes et al., (2002)	Akashi et al., (2005)	Range of illuminance (lx)
1 (Unbearable)	10	6	-	-	-	6 ~ 10
2	5	-	2.6	20	-	2.6 ~ 20
3 (Disturbing)	1.26 ~ 2	2	1.3	10	4	1.26 ~ 10
4	0.4 ~ 0.7	-	-	5	-	0.4 ~ 5
5 (Just admissible)	0.12 ~ 0.27	0.8	-	2.5	2	0.12 ~ 2.5
6	-	-	-	1.26	1	1 ~ 1.26
7 (Acceptable)	-	0.2	-	0.63	-	0.2 ~ 0.63
8	-	-	0.04	0.32	-	0.04 ~ 0.32
9 (Just Noticeable)	-	0.1	-	0.16	-	0.1 ~ 0.16

II. METHOD

II.I. Subject

This study participants were 30 healthy male (10 people of 20 ~ 29 years old, ten people of 30 ~ 39 years old, ten people of 40 ~ 49 years old) licensed drivers who had no ocular diseases and mental illness. The mean age of the participants was 37.2 years (SD 8.37). The mean visual sight, i.e., decimal visual acuity of the participants, was 1.02 (SD 0.16). The participants mean the driving experience was 9.73 years (SD 6.88). Ethical approval for this study was obtained from the Human Subjects Research and Ethics Committee, Hanyang University, Korea. The study purpose was informed to the participants.

II.II. Headlight selection and characteristics

Researchers and automotive manufacturers seek to enhance the driving experience and safety of every generation of automobiles. Till the 1990s, halogen lights were used in headlights mostly. In the late 1990s, automobile manufacturers (example: Bosch company) developed and began to use high-intensity discharge (HID) headlights [21]. In recent times, light-emitting diodes (LED) are being used in headlights [22, 23]. Headlight technology has been developing rapidly in recent years. LED and HID lamps have begun to replace halogen lamps. Caruso et al. [24] surveyed and reported that both HID and LED lighting together going to take 33% of the new vehicle market by 2020, it was 22 % in 2016 [25]. In this study, three headlamps (including halogen, HID, and LED) as a unit (including the bulb, reflector, and lens) were considered.

II.III. Experimental setup

Experiment were performed in a dark room (research laboratory) of 35 meters long and 8 meters wide. The room was designed in such a way to represent typical night time driving conditions. The experimental setup comprised of headlights (halogen, HID, and LED), constant voltage regulator, illuminator, MP150 Biopac system, FaceLab, trigger, and chinrest. The MP150 Biopac system was used to measure brain (EEG) signals from the participants' Frontal lobe and left side occipital lobe regions. Participants' pupil size was measured using eye-tracker, i.e., FaceLab. A computer was installed on the right side of the room to control the data acquisition systems (MP 150 and Eye-tracker), and partition was installed to prevent light. The position of the headlamp, participants, and glare source aperture details reported in [26, 27].

II.IV. Design

This study was performed to evaluate the subjective satisfaction and psychological response (pupil size, brain wave) using within-subject design (3 (headlight 3 levels) × 5 (illuminance 5 level) × 2 (ambient brightness 2 levels)). The independent variables were 3 level of headlight (Halogen, HID, LED), 5 level of illumination in the eye (0.2lx, 1lx, 5lx, 10lx, 20lx) and 2 level of ambient brightness (0.1 cd/m^2, 2 cd /m^2).

The dependent variables were pupil size, EEG (P300, frequency) and subjective satisfaction. The experimental procedure used the Latin square method to reduce the carryover effect of the participants.

II.V. Procedure and Data Analysis

The experimental procedure explained in Fig. 1. The pupil diameter was analyzed using FaceLAB 5 software. EEG (P300, frequency) were analyzed using BIOPAC acknowledge software. EOG artifacts were removed using independent component analysis to ensure the EEG data accuracy, i.e., a blind signal separation technique. The subjective satisfaction used De Boer index, which is widely used in automotive headlight glare measurement.

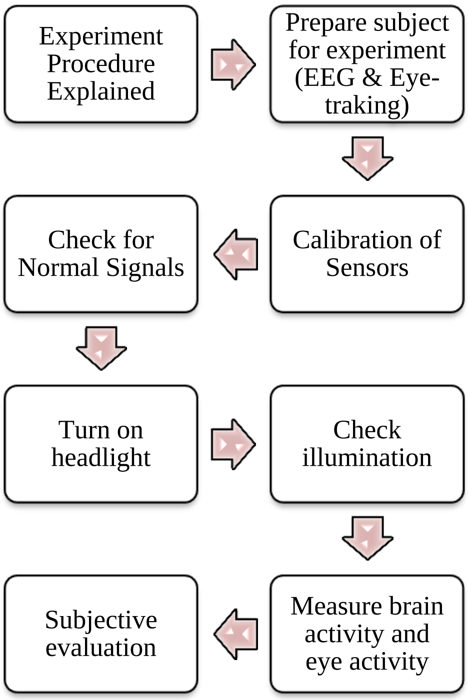

Fig. 1. Experimental procedure. Data collected for 5 second period and 3 min break was given between each measurement.

III. Development of glare prediction and discrimination model

This study aims to develop a practical and easy to use glare prediction and glare discrimination model. The models are based on mathematical and statistical basis by considering human reaction level. The glare discrimination and prediction model was developed as a logistic regression analysis and a special Regression Model, respectively, with the De Boer index and pupil size as dependent variables. The dependent variable of the logistic regression analysis uses a qualitative measure, a binary variable. The special regression model used the indicator variable & dummy variable for the certain headlamp type to analyze the relationship between the dependent variable and the independent variable [28]. For both logistic regression analysis and special regression analysis, the De Boer index and pupil size were set as dependent variables, and, headlamp type, illuminance and ambient brightness were set as independent variables (Table 2). The dependent variables were classified as two groups [29] as shown in Table 2 to develop a discrimination prediction regression model. To distinguish the characteristics of the headlamps, the color temperature was measured 10 times according to headlamp type and illuminance condition, and interval scales were used. The color temperature of the headlights used in the experiments was within the white range of KMVSS (Korea Motor Vehicle Safety Standards). During the logistic regression analysis, a total of 900 data (30 subjects X 3 headlight type X 5 illuminations X 2 ambient brightness levels) were coded based on De Boer index and pupil size. The coding of dependent variables for analysis shown in Table 3. The independent variables were converted into indicator variables as "0" and "1" for each headlamp (Table 4) to develop a prediction model using special regression model. Hence, it is difficult to use as independent variables in the special regression model. The illuminance level was converted to a logarithmic function by applying R^2 of the curve estimation. Multiple regression analysis was performed using the statistical package SPSS.

Table 2. Logistic regression analysis variables setting for discrimination model generation

Variable		**Definition**
Dependent variable	De Boer index	Group 1: De Bore index below 4 (glare) Group 2: De Boer index 4 or more (no glare).
	Pupil size	Group 1: Less than 3 mm pupil size (low vision, glare) Group 2: Pupil size 3 mm or more (normal vision, no glare)
Independent variable	Headlight color temperature	Range : 3,116.6～6,190.2 K(Kelvin)
	Illuminance	0.2, 1, 5, 10, 20 lx
	Ambient brightness	. 0.1～2 cd/m^2

Table 3. Coding dependent variables

Original value	Internal value	Classification standard
1	0	De Boer index 4 or less Pupil size 3 mm or less
2	1	De Boer index 4 or higher Pupil size 3 mm or more

Table 4. Setting the headlight indicator variables

Headlight type	X_1	X_2
Halogen	0	0
High Intensity Discharge	1	0
Light Emitted Diode	0	1

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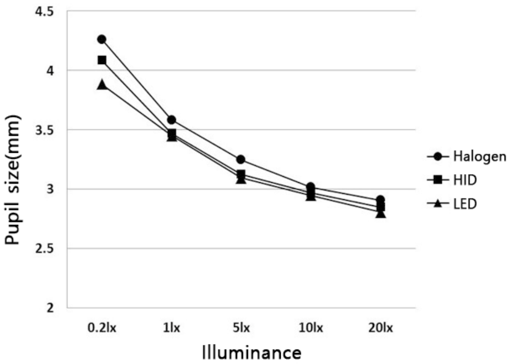
IV. RESULTS

IV. I. Glare

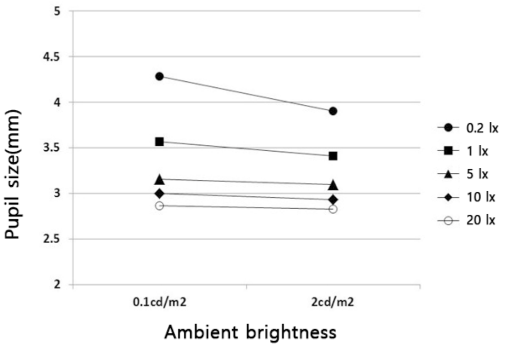
The results of ANOVA (Analysis of variance) for psychophysiological response level (pupil size, EEG (P300, frequency), subjective satisfaction), when testing the main and interaction effects of independent variables are presented in Table 5. A posthoc test was also performed to know which independent variable effect more on dependent variables. In the pupil, the pupil size decreased in the order of halogen, HID, LED headlight. Also, the pupil size decreased as the illuminance increased, and the ambient environment became brighter. The interaction effect of pupil size with independent variables shown in Fig. 2.

Table 5. ANOVA for main effect and interaction effect on pupil size and subjective satisfaction

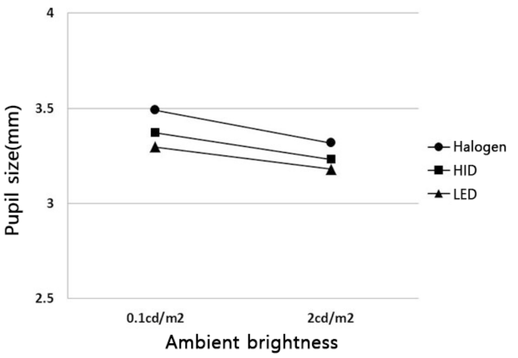
			Headlight	Illuminance	Ambient brightness	Headlight × Illuminance	Headlight × Ambient brightness	Illuminance × Ambient brightness	Headlight × Illuminance × Ambient brightness
pupil	Left	F-value	41.47***	170.84***	97.45***	7.97***	2.60*	38.08***	1.57
	right	F-value	60.26***	204.72***	112.46***	15.45***	1.53	56.75***	0.83
subjective satisfaction		F-value	39.65***	347.10***	54.65***	1.23	1.87	2.35*	0.63
*** p <0.01; ** p <0.05; *p <0.1									



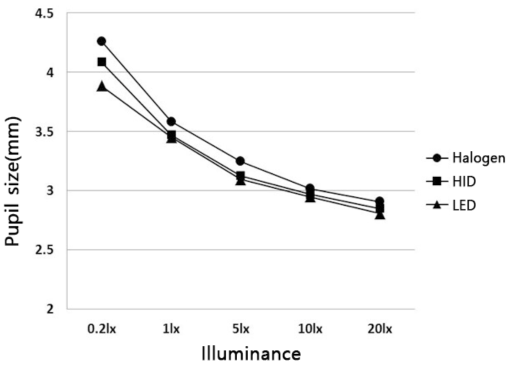
(A) Pupil Right - Headlight × Illuminance



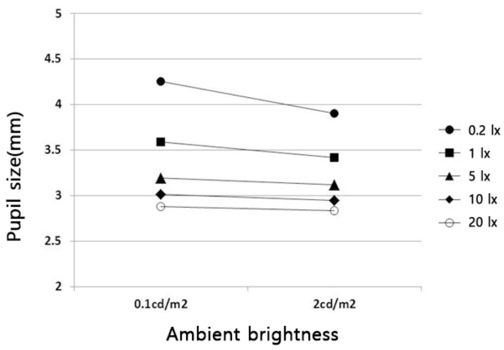
(C) Pupil Right - Illuminance × Ambient brightness



(B) Pupil Right - Headlight × Ambient brightness



(D) Pupil Left - Headlight × Illuminance



(E) Pupil Left - Illuminance × Ambient brightness

Fig. 2. Interaction effect of independent variables on pupil size (A) right pupil – headlight X illumninance (B) right pupil – headlight X ambient brightness (C) right pupil – Illuminance X Ambient brightness (D) left pupil – headlight X illuminance and (E) left pupil – Illuminance X ambient brightness.

IV. II. De Bore index discrimination prediction model using logistic regression analysis

To predict the group in which you belong, the Eqn. 1 can be used where input needs to be your independent variable. The probability of belonging to group 1 (De Boer index 4 or less; glare) is given as P and can be expressed as Eqn. 1.

$$\frac{P}{1-P} = e^{\beta_0+\beta_1 X_1+\cdots+\beta_1 X_k} \quad (1)$$

The results of De Bore index discrimination model using logistic regression analysis shown in Table 6, and the same represented as a model in Eqn. 2. The results showed that all the independent variables are significant ($p<0.01$). The positive (+Ve) sign in regression coefficient (B) classified as a group without glare, and the negative (-Ve) sign classified as a group with a glare. The higher the headlight color temperature and illuminance, the more likely it will be classified as group 1 (glare), and the higher the ambient brightness, the more likely it will be classified as group 2 (no glare).

$$P = \frac{e^{4.297-0.578X_1-3.4X_2+0.284X_3}}{1+e^{4.297-0.578X_1-3.4X_2+0.284X_3}} \quad (2)$$

IV. III. Pupil size discrimination prediction model using logistic regression analysis

Table 7 shows the parameters included in the regression model equation of the pupil size discrimination prediction model, and the same represented as a model in Eqn. 3. All the independent variables (headlight color temperature, illuminance, ambient brightness) were significant ($p<0.01$). In pupil size discrimination prediction model, it is highly likely that the headlamp color temperature and illuminance are high and the surrounding area is brightly classified into group 1(decreased visual acuity and glare). The lower the color temperature of the headlight, the illuminance, and the ambient brightness, the more likely it is classified as group 2(no visual loss). The illuminance becomes $e^{-3.199} = 0.041$. As the illuminance increases, the probability of being classified in group 1 increases by 0.041 times.

$$P = \frac{e^{3.678-0.146X_1-3.199X_2+0.264X_3}}{1+e^{3.678-0.146X_1-3.199X_2+0.264X_3}} \quad (3)$$

IV. IV. De Boer index prediction model using special regression model

The results of De Boer index prediction model using special regression model shown in Table 8, where the R^2 value is 0.628, i.e., the dependent variable is affected 62.8% by the independent variables. The results of the non-standardization coefficient shown in Table 9, where (+Ve) sign of "B" predicts that the De Boer index, which does not feel glare, however, (-Ve) sign predicts that unbearable glare. The prediction model for De Boer index based on special analysis shown in Eqn. 4.

$$Y_{(De\ Bore\ Index)} = 7.719 - 0.543X_1 - 0.017X_2 - 0.223X_3 - 1.997X_4 + 0.045X_3X_4 + 0.003X_3^2 \quad (4)$$

IV. V. Pupil size prediction model using special regression model

The results of pupil size prediction model using special regression model shown in Table 10, where the R^2 value is 0.645, i.e., the dependent variable is affected 64.5% by the independent variables. The results of the non-standardization coefficient shown in Table 11, where (+Ve) sign of "B" predicts that the pupil size would increase, the (-Ve) sign predicts that the pupil size would decrease. The higher the illuminance and the brighter the surroundings, the smaller the pupil size. The prediction model for pupil size based on special analysis shown in Eqn. 5.

$$Y_{(Pupil\ size)} = 0.514 - 0.013X_1 - 0.021X_2 - 0.029X_3 - 0.084X_4 + 0.031X_3X_4 \quad (5)$$

IV. VI. Subjective Evaluation

The results of subjective evaluation (Fig. 3 and Fig. 4) showed that the subjects felt discomfort in shorter wavelengths, i.e., LED headlamps having shorter wavelength; hence, subject felt discomfort compared to Hid and halogen headlights. The illuminance level of subjective feelings also evaluated. The satisfaction level decreased with increased illuminance levels. And the stratification level decreased when ambient brightness was low. Subjective satisfaction research has been performed a lot by de Boer (de Boer). In general, subjective satisfaction was lower in the shorter the wavelength headlamps, the higher the illuminance and the darker the ambient brightness [7, 9, 30, 31]. Koreans feel reduced glare about 1.5 to 2 De Boer's index compared to the different results presented in other studies. Because it could infer the melanin pigment in the iris. It is recommended that 3 mm diameter or more pupil size is needed in night-time traffic environment to avoid accidents.

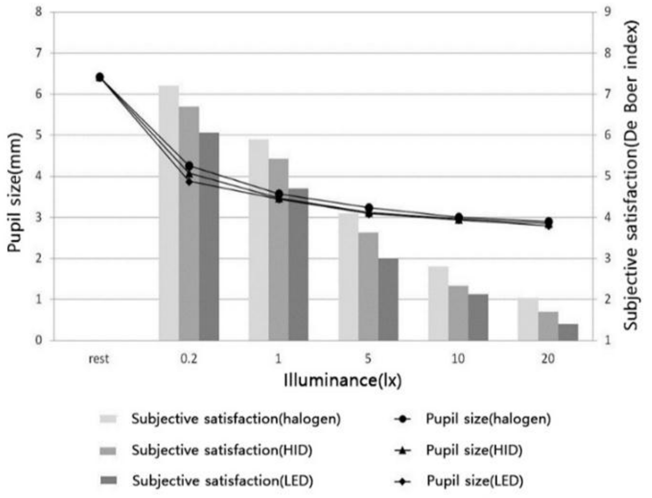


Fig. 3. Subjective evaluation comparison

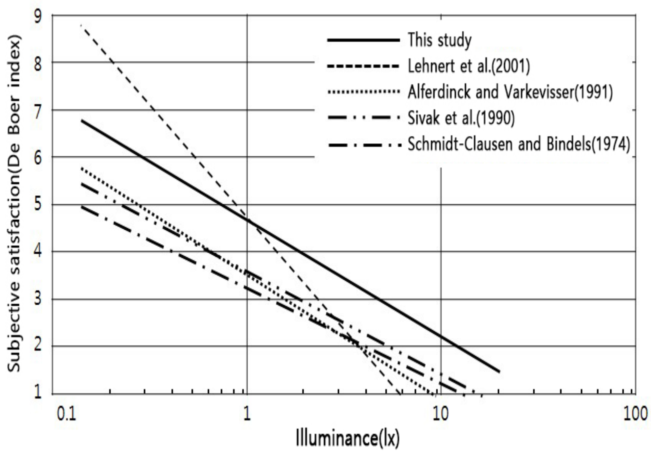


Fig. 4. Illuminance (lx) vs De Boer index comparison between studies.

V. DISCUSSION

There is changes in pupil size between headlamps; however, the pupil size was comparatively small when headlamp with shorter wavelength and higher intensity. The pupil size reduced by LED, HID, and followed by halogen headlamps. Surrounding brightness also one of the contributing factors for the changes in the pupil size, the pupil size was reduced when surrounding brightness was high. These can be correlated with pupil size in the optical characteristics of the headlamps. Halogen, LED and HID headlamps have different optical characteristics including color temperatures and wavelength due to variations in light sources [32]. LEDs showed the closest sensitivity to headlight wavelengths followed by HID and halogen headlights. Kankipati et al. [33] and Münch et al. [34] reported with measured pupil size in general lighting conditions. It is similar to the result of this study that the pupil size is further reduced in shorter wavelengths. When light enters the pupil, the retina (muscle) control a pupil size by the amount of light [35]. Previous studies show that pupil size decreases with an increase in illuminance and ambient brightness [15, 16, 36, 37]. This study also obtained similar results as compared to previous studies.

Also this study analyzed the relationship between pupil size and subjective satisfaction. Schieber and Harms [38] reported that "Discomfort" occurs when the De Boer index is below 4. The pupil size and the illuminances were 5lx and 3mm, respectively when subjective satisfaction (De Boer index) was less than 4. Pupil size is 3-4 mm in day time and 6-8 mm in night time. In this study, the maximum pupil size was 7.65 mm, the minimum pupil size was 2.35 mm, and the rest pupil size was 6.75 ± 0.55 mm. If the light enters the eye during night time, the pupil size decreases. However, the maximum visual acuity is maintained at 3mm. Also when the pupil size is less than 3 mm, the diffraction phenomenon occurs and the visual acuity decreases [39]. When the diffraction phenomenon occurs, the airy disc expands to the retina and the sensitivity of the eyes decreases. As a result, it can be seen that the pupil size of 3 mm or more does not cause any diffraction phenomenon (no glare, maintains normal vision).

In this study, two glare evaluation models are presented. First, logistic regression analysis is used to predict the degree of glare or visual impairment by predicting the De Boer index and pupil size. Second, special regression model for predicting De Boer index and pupil size. The discrimination prediction models and prediction models were proposed and verified by K = 9 cross-validation and jack-knife method. The verification confirms that generalization is possible. The model using logistic regression analysis and special regression model can be applied to real cars and are easy to use since the existing De Boer index does not reflect physiological characteristics of humans. The model presented in this study reflects the psychophysiological characteristics of humans and is highly reliable through validation. With this development it is possible to predict nighttime glare and could reduce accidents at night time driving.

VI. CONCLUSION

Most of the glare studies considered the intensity and wavelength of light. However, not many studies focused on night-time traffic environment and driver responses. This work studied glare effect at night-time traffic environment by considering various headlight types, illuminance levels, and ambient brightness. To study glare effect, drivers' pupil size and brain activity and subjective satisfaction were measured. Also, this study proposed glare discrimination model by considering De Boer Index and Pupil size using logistic regression model. Besides, the study proposed prediction model by considering De Boer Index and Pupil size using special regression model. The model presented in this study reflects the psychophysiological characteristics of humans and is highly reliable through validation. With this development it is possible to predict night-time glare and could reduce accidents at night time driving.

In this study, two glare evaluation models are presented. First, logistic regression analysis is used to predict the degree of glare or visual impairment by predicting De Boer index and pupil size. Second, special regression model for predicting De Boer index and pupil size. The discrimination prediction models and prediction models were proposed and verified by K = 9 cross-validation and jack-knife method. The verification confirms that generalization is possible. The model using logistic regression analysis and special regression model can be applied to real cars and are easy to use. Since the existing De Boer index does not reflect physiological characteristics of humans. The model presented in this study reflects the psychophysiological characteristics of humans and is highly reliable through validation. With this development it is possible to predict nighttime glare and could reduce accidents at night time driving.

Table 6. Variables included in the De Boer index discrimination and prediction model equation

	B	S.E.	Wals	df	p-value	Exp(B)
Headlight color temperature	-0.578	0.091	40.617	1	0.000***	0.561
Illuminance	-3.400	0.223	232.995	1	0.000***	0.033
Ambient brightness	0.284	0.104	7.385	1	0.007***	1.328
Constant	4.297	0.477	81.091	1	0.000***	73.480
***p<0.01						

Table 7. Variables included in pupil size discrimination and prediction model equation

	B	S.E.	Wals	df	p-value	Exp(B)
Headlight color temperature	-0.146	0.076	3.662	1	0.056*	0.865
Illuminance	-3.199	0.237	182.339	1	0.000***	0.041
Ambient brightness	-0.264	0.095	7.659	1	0.006***	0.768
constant	3.678	0.432	72.460	1	0.000***	39.568
*p<0.1, **p<0.05, ***p<0.01						

Table 8. De Boer prediction model using special regression

R	R^2	Adjusted R^2	Standard error of estimated value
0.792	0.628	0.625	1.44706

Table 9. De Boer index prediction model non-standardization coefficient

	non-standardization coefficient		standardization coefficient	t	p-value
	B	Standard error	beta		
Constant	7.719	0.132	-	58.672	0.000***
Indicator variable 1	-0.543	0.118	-0.108	-4.599	0.000***
Indicator variable 2	-0.017	0.118	-0.203	-8.605	0.000***
Illumunance	-0.223	0.026	-0.685	-8.571	0.000***
Ambient brightness	-1.997	0.072	-0.803	-27.854	0.000***
Illumunance × Ambient brightness	0.045	0.007	0.234	6.404	0.000***
Illumunance × Illumunance	0.003	0.001	0.194	2.528	0.012**
***p<0.01; **p<0.05					

Table 10. Pupil size prediction model using special regression

R	R^2	Modified R^2	Standard error of estimate
0.803	0.645	0.642	0.0419378

Table 11. Pupil size prediction model non-standardization coefficient

	non-standardization coefficient		standardization coefficient	t	p-value
	B	Standard error	beta		
Constant	0.514	0.003	-	188.441	0.000***
Indicator variable 1	-0.013	0.003	-0.090	-3.890	0.000***
Indicator variable 2	-0.021	0.003	-0.143	-6.191	0.000***
Illumunance	-0.029	0.002	-0.297	-13.122	0.000***
Ambient brightness	-0.084	0.003	-0.779	-32.931	0.000***
Illumunance × Ambient brightness	0.031	0.003	0.272	10.474	0.000***
***p<0.01					

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