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EVALUATION METHOD OF DISCOMFORT GLARE OF LED TUNNEL INTERIOR LIGHTING

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Abstract

The evaluation method for discomfort glare of tunnel interior lighting was studied by measuring the lighting characteristics and carrying out observations in on-site and in a laboratory.

The results of observations in on-site show no correlation between Tl and discomfort glare and that discomfort glare is correlated to equivalent veiling luminance. The results of observation in the laboratory demonstrate that discomfort glare is correlated to the equivalent veiling luminance of one luminaire and the adaptation luminance. And a prediction equation for discomfort glare was derived by multiple regression analysis of observation results.

The prediction equation and ratings of discomfort glare in the tunnel were compared. The comparison showed that the prediction equation and the ratings are correlated.

By applying the discomfort glare prediction equation to plan tunnel lighting, a tunnel interior lighting facility with suppressed discomfort glare may be built.

Keywords: Tunnel interior lighting, Discomfort glare, LED luminaire

1 Introduction

A glare may be divided roughly into two types: visual function reduction glare that affects visibility and discomfort glare that affects comfort. CIE (CIE 2004) recommends that Tl should be held down to 15 % or under to suppress glare from tunnel interior lightings. But we have found that when LED is used for lighting, drivers may feel discomfort even when the Tl is below the specified value. For this reason, we decided to study the evaluation method for discomfort glare of tunnel interior lightings.

2 Observation on-site

2.1 Experimental installation

Observations were conducted in a some 2 700 m long, one-way expressway tunnel as shown in Figure 1. The road surface is paved with draining asphalt. The carriageway has two 3,5 m lanes and 1,0 m wide hard shoulders are located on both sides of the carriageway. The tunnel wall has white interior boards installed 2,5 m high from the road surface. For the entire length of the tunnel, LED pro-beam lightings (light flux 6 800 lm, colour temperature 5 000 K, general colour rendering index 70) with a 3 level dimmer (50 %, 25 %, 12,5 %) are installed facing each other at a 4,4 m interval.

Figure 1 – Lighting installation

2.2 Conditions

The observers evaluated discomfort glare from an observation vehicle on the carriageway using the de Boer 9 level rating scale (9: Unbearable, 7: Distracting, 5: Just acceptable, 3: Satisfactory, 1: Unnoticeable) (De Boer et al, 1959). Luminaires were arranged opposite each other or in a staggered arrangement, at an interval of 4,4 m to 13,2 m. The output of the lightings was adjusted to 12,5 % to 100 %. The combination of these conditions produced road surface luminance of 0,62 cd/m² to 13,3 cd/m². The 9 observers (age 32 to 50) moved one-fourth of the interval between lightings at a time in the longitudinal direction of the tunnel and rated discomfort glare at four locations. Luminaires arranged facing each other were also evaluated in the opposite direction to the travel direction.

2.3 Results

As shown in Figure 2, because discomfort glare and *TI* had no correlation, an evaluation index other than *TI* was needed to rate the discomfort glare of LED luminaires.

On the other hand, as shown in Figure 3, discomfort glare had a relatively high correlation with equivalent veiling luminance. The observation results shown in Figure 3 were obtained under multiple road surface luminance, and therefore, it can be surmised that differences in the ratings tended to arise for specific equivalent veiling luminance.

Equivalent veiling luminance and road surface luminance could not be set independently for the lightings at the test tunnel. So, to measure their effects on discomfort glare, tests were conducted in a laboratory, which are described later.

Figure 2 – Relationship between *TI* and discomfort glare ratings

Figure 3 – Relationship between equivalent veiling luminance and discomfort glare ratings

3 Observation in the laboratory

3.1 Experimental facility

The equivalent veiling luminance (L_{v-L1} , L_{v-L2} , L_{v-L3}) of luminaires $L1$, $L2$, $L3$, within the visual field of the driver and installed on the driver's side of the carriageway, and the summation (L_{v-s}) of the equivalent veiling luminance of all luminaires within the visual field were calculated through simulations and are as shown in Figure 4. The ratios of the two values (L_{v-L1}/L_{v-s} , L_{v-L2}/L_{v-s} , L_{v-L3}/L_{v-s}) were calculated and are shown in Figure 5. Conditions of the tunnel lighting facilities are shown in Table 1.

The ratio L_{v-L1}/L_{v-s} for LED tunnel lightings tended to be about 50 % or higher than the High frequency fluorescent lamp luminaires which were standard tunnel lightings in Japan before LEDs were employed.

In other words, we can say that one luminaire located closest to the driver has a notable effect on discomfort glare. So, in this experiment, observations were carried out on a hypothesis that one unit of LED tunnel lighting influences discomfort glare.

Figure 4 – Position of driver and luminaires $L1$, $L2$, $L3$

Figure 5 – Ratio of L_{v-L1} , L_{v-L2} , L_{v-L3} to L_{v-s}

Table 1 – Conditions of tunnel lighting facilities

	Light source	Average road surface luminance (cd/m ²)	Arrangement	Spacing (m)
Tunnel A	LED	9,0	Staggered	5,2
Tunnel B		1,6	Staggered	11,5
Tunnel C		9,0	Opposite	11,3
Tunnel D	Hf-fluorescent lamp	9,0	Opposite	6,2

Figure 6 shows the layout of the test facility. To control the adaptation luminance for the observers, a computer graphic (CG) image of the tunnel interior was projected on a screen (H 1,5 m, W 2,0 m). The visual angles of the CG image for the observers were about 26 degree in the vertical direction and about 33 degree in the horizontal direction. The 4 LED luminaires were installed 4,8 m high and at 2,5 m intervals. The output of the LED luminaires was adjusted to between 20 % and 100 %.

Figure 6 – Experimental facility

3.2 Observation test

The road surface luminance (L_{rs}) of the CG image was set at 4 levels (1,1 cd/m^2 to 9,0 cd/m^2). One LED lighting fixture at each lighting location within the observers' field of vision had 9 equivalent veiling luminance (L_{vs}) levels.

The observers adapted to darkness for 5 minutes in the laboratory, then adapted to L_{rs} of the test condition projected on the screen for 3 minutes and then rated the discomfort glare.

The observers evaluated discomfort glare using the de Boer 9 level rating scale (9: intolerable, 7: disturbing, 5: just admissible, 3: satisfactory, 1: unnoticeable).

The observers were 8 lighting engineers, aged 41 to 53.

3.3 Results of laboratory testing

Figure 7 gives an example of regression curves that show the relationship between L_{vs} and discomfort glare ratings obtained in laboratory tests. The difference in the ratings of discomfort glare between observers tended to increase when L_{vs} was comparatively high. The relationship between L_{vs} and discomfort ratings were not notably affected by the position of the LED lightings.

Figure 8 shows the relationship between L_{vs} and L_{rs} as seen by Observer A, as an example. The level of L_{vs} to get a similar discomfort glare rating tended to become high as L_{rs} got higher. Similar tendencies were also seen with other observers.

Figure 7 – Relationship between L_{vs} and discomfort ratings of each observer (L_{rs} : 4,7 cd/m^2)

Figure 8 – Relationship between L_{vs} and L_{rs} (Observer A)

4 Prediction equation for discomfort glare

The preceding tests show that the difference in discomfort glare ratings is comparatively large between observers. Considering this fact, we used equivalent veiling luminance L_{vs}' and L_{rs} that were considered admissible by 6 out of 8 observers to obtain a discomfort glare prediction equation. The calculations using the prediction equation follows.

(1) Deriving discomfort glare prediction equation for each observer

A discomfort glare rating prediction equation was derived for each observer through multiple regression analysis using L_{vs} , L_{rs} , and discomfort glare ratings of each observer. The logarithmic values of L_{vs} and L_{rs} , which are correlated to the rating of discomfort glare, are the explanatory variables of the prediction equation.

$$\text{Discomfort glare ratings of each observer } DG_{TX} = a_X \log(L_{vs}) + b_X \log(L_{rs}) + c_X \quad (1)$$

where

L_{vs} : Equivalent veiling luminance of one lighting fixture (cd/m^2)

L_{rs} : Road surface luminance of CG image (cd/m^2)

a_X , b_X , c_X : Coefficient for prediction equation of each observer

(2) Calculation of L_{vs} to obtain arbitrary DG_{TX} of each observer

Around Rating 1, the upper limit value, and Rating 9, the lower limit value, the ratings do not change by the increase or decrease in the equivalent veiling luminance. Therefore, it is assumed that the logarithmic value of equivalent veiling luminance and rating value are not proportional.

So, L_{vs} to obtain $DG_{TX} = 3$ to 7 was calculated using the prediction equation for each observer obtained in (1)

(3) Calculation of L_{vs}' to obtain 75 % cumulative probability

L_{vs} to obtain $DG_{TX} = 3$ to 7 for each observer calculated in (2) are listed in a descending order and

L_{vs}' (equivalent veiling luminance thought admissible by 6 of the 8 observers) to obtain a cumulative probability of 75 % was calculated. An example is shown in Figure 9.

Figure 9 – Cumulative probability of L_{vs} which gives DG_{TX} 5 to 6 of 8 observers (L_{rs} : 4,7 cd/m^2)

(4) Deriving prediction equation for discomfort glare by multiple regression analysis

The prediction equation was derived through multiple regression analysis using model Equation (2), applying the logarithmic value of L_{vs}' which obtains 75 % cumulative probability of $DGI_T = 3$ to 7 calculated in (3) and logarithmic value of L_{rs} as the explanatory variables.

$$\text{Discomfort glare rating value } DGI_T = a \log_{10}(L_{vs}') + b \log_{10}(L_{rs}) + c \quad (2)$$

where

L_{vs}' : Equivalent veiling luminance thought admissible by 6 out of 8 observers (cd/m^2)

L_{rs} : Road surface luminance of CG image (cd/m^2)

a, b, c : coefficient

The prediction equation for discomfort glare obtained following the above mentioned procedure is shown in Equation (3).

$$\begin{aligned} DGI_T &= 6,2 \log_{10}(L_{vs}) - 4,1 \log_{10}(L_{rs}) + 11 \\ &= \log_{10}(L_{vs}^{6,2} / L_{rs}^{4,1}) + 11 \end{aligned} \quad (3)$$

where

L_{vs} : Equivalent veiling luminance of one lighting fixture (cd/m^2)

L_{rs} : Road surface luminance of CG image (cd/m^2)

In application, L_{rs} = average road surface luminance

5 Examination

5.1 Verification of hypothesis

In this test, it was assumed that, of the lightings within the visual field of the driver, the equivalent veiling luminance generated from one lighting fixture located closest to the driver is the main cause of discomfort glare. To verify this hypothesis, the same experiment was carried out under the following conditions with multiple lightings lit simultaneously. Four LED lightings were lit under the same condition. The ratio of each lighting's equivalent veiling luminance to the equivalent veiling luminance when all lightings within the visual field were lit was as follows: Lighting position 1,5 %; lighting position 2,3 %; lighting position 3,2 %; and lighting position 4,5 %.

Test conditions

L_{rs} : 2.2 cd/m^2

L_{vs} : $0,19 \text{ cd/m}^2, 0,26 \text{ cd/m}^2, 0,43 \text{ cd/m}^2, 0,56 \text{ cd/m}^2, 0,74 \text{ cd/m}^2$

Observers: 2 of the observers who participated in the laboratory test

Figure 10 shows the relationship between ratings of discomfort glare marked by above mentioned observers when all 4 LED lightings were lit and the ratings calculated by the prediction equation applying L_{rs} and L_{vs} at each lighting position.

The discomfort glare rating calculated by the prediction equation using conditions of lighting position 1, which is closest to the observing position, generally matched the discomfort glare rating when all 4 lightings were lit. Discomfort glare tended to be influenced mainly by the lighting closest to the observing position, and the hypothesis suggested for the test was proved to be appropriate.

Figure 10 – Relationship between ratings when all 4 luminaires are lit and ratings for one lighting calculated by prediction equation.

5.2 Comparison with field tests

Figure 11 shows the relationship between DGI_T , calculated using the discomfort glare prediction equation suggested in this study, and rating values to obtain a cumulative probability of 75 % when the discomfort glare ratings of all observers, marked under each field-test conditions described in paragraph 2, are lined up in a descending order.

Figure 11 shows that rating value gained in the field tests and DGI_T have a positive correlation. This shows that DGI_T is better suited as an evaluation index for discomfort glare than TI .

Figure 11 – Relationship between DGI_T and field test ratings

6 Conclusion

(1) Observation tests showed that discomfort glare is correlated to equivalent veiling luminance and average road surface luminance.

(2) A discomfort glare prediction equation, using equivalent veiling luminance of one lighting fixture located closest to the driver and average road surface luminance as explanatory variables, was derived in this study.

(3) The suggested discomfort glare prediction equation and discomfort glare observed in the field were shown to be correlated.

(4) Tunnel interior lighting facilities with suppressed discomfort glare may be built by planning tunnel lighting using the discomfort glare prediction equation derived in this study.

References

- CIE 2010. CIE 115 2nd:2010. *Lighting of Roads for Motor and Pedestrian Traffic*. Vienna: CIE.
- De BOER J. B. et al 1959. Appraisal of the quality of public lighting based on road surface luminance and glare. Proceedings for the 14th Session of CIE, 529–538.

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