Simulation and Analysis of glare effect of two lane tunnel lighting under symmetrical lighting arrangement

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Abstract: Glare seriously affects the quality of tunnel lighting, and also has a negative impact on drivers' visual recognition in the tunnel. By introducing the calculation method of glare influence level $G$ and relative threshold increment $TI$, the article uses DIALux evo lighting simulation analysis software to simulate and analyze the tunnel lighting glare of different installation spacing and angle combinations under the condition of Symmetrical lighting on both sides in the tunnel. The influence range of glare produced by different installation spacing and angle combinations under symmetrical lighting is obtained. The research results show that: in the symmetrical lighting mode on both sides of the tunnel, when the angle between the driver's sight line and the incident direction of the tunnel lighting is less than 82.38°, the lamps will produce glare to the driver. When the glare influence level of symmetrical bat-wing tunnel lamp is between 1 and 3 at any installation distance and angle under the symmetrical arrangement of lights on both sides, it is a serious glare effect.

1. Introduction

By the end of 2019, there were 19,067 road tunnels in China, with a total length of 18,966,600 meters\textsuperscript{[1]}, at the same time, a variety of long and extra-long tunnels are gradually increasing. The driver recognizes safety and the quality of light environment in tunnels have also aroused people's wide concern. Glare is caused by inappropriate brightness distribution or excessive brightness changes or extreme contrast in space and time, which causes the driver's visual discomfort or reduces the ability to observe important objects\textsuperscript{[2]}. Glare will prolong the time for the driver to recognize the object, and in severe cases, the driver will form "blind vision", which will affect the driver's acquisition and analysis of driving conditions and vehicle information in the tunnel, and bring hidden dangers to driving safety. At present, the research on the elimination of glare in the tunnel entrance section has been more mature, but the correlation research of the light environment quality in the middle section of the tunnel where drivers travel for a long time still needs to be strengthened and improved.

In terms of internal glare research and related specifications, the American physicist Holladay first
proposed the concept of glare. He also pointed out that the main reason for glare to affect visual function is the equivalent light curtain brightness formed by the light emitted by the glare source in human eyes. Ferguson et al. [4] found that short-wave low-color temperature light sources are more likely to produce glare through the analysis of the influence level test of glare on light sources with different wavelengths. Gadegaard and Gamponogara et al. [5] [6] optimized the design of LED lamps to improve lighting performance and reduce glare. According to the regulations of The Ministry of Transport of China [7], lighting fixtures in highway tunnels should take measures to suppress glare and avoid interference to safety and visual comfort. Lamps with the same power or luminous effect should adopt lamps with low surface brightness. Ye Qiang [8] discussed the measures to reduce the lighting glare of the expressway tunnel by adjusting the light transmission angle of the lamp lens. Ding Yi et al. [9] based on the research on the curved lens of LED lamps, proposed an asymmetric single-sided bat-wing light distribution method to control and eliminate glare by optimizing the curved lens; Wang Chao, Ma Fei et al. [10] analyzed the correlation between the luminous flux, light distribution form and glare value of tunnel lamps through simulation experiments, and concluded that the glare value of the two lanes is greater than that of the middle lane in the three-lane tunnel and the symmetrical light distribution mode. Fu Yi et al. [11] analyzed the influence of tunnel lighting glare under three lighting modes, and obtained the influence range and degree of glare. Fan Dechao [12] obtained the correlation between the influencing factors under the state of the glare threshold level by designing the glare experiment, and then obtained the glare threshold under different light environmental conditions, which provided a theoretical basis for the lighting detection and treatment of the anti-glare curve tunnel. From the current existing research, the tunnel glare research under the common way of arrangement lamp is still insufficient, and the current highway tunnel lighting specification [7] only stipulates surface brightness of the luminous intensity of luminaires to prevent glare effect, and the tunnel lighting design details [13] did not mention how to avoid glare. This study is based on the most commonly used two-sided symmetrical lighting method in the tunnel. By adjusting the installation spacing and angle of the lamps in the tunnel, the correlation between them and the glare value in the tunnel is simulated. The glare can be eliminated or minimized to ensure that the average brightness and brightness uniformity of the road surface in the tunnel meet the specification requirements.

2. Glare evaluation index in tunnel

Glare is a very important lighting quality evaluation index, which is widely used in indoor and outdoor lighting. Representative indexes include glare reduction (GR) and unified glare reduction (UGR), visual comfort probability (VCP), glare limit system (Brightness Limit Curve), glare index method, etc. For many years, in the field of highway lighting, the threshold increment TI and the glare influence grade G value [14] are mainly used as the lighting quality evaluation indexes.

2.1 Glare influence grade G

Glare influence level G is the evaluation index specified for glare limitation of highway tunnel lighting. It qualitatively evaluates glare discomfort caused by highway lighting facilities to ensure the comfort level of drivers while driving on the highway. The standard calculation of G value is shown in Equation (1).

\[ G = a\lg L_g + b\lg \omega - c\lg L_b \]

Where: a, b, c are constants and have different values according to different populations;
- \( L_g \) is the brightness of the glare source (\( cd / m^2 \));
- \( L_b \) is the background brightness (cd/m²);
- \( \omega \) is for opening angle of dazzling light.

Chinese scholar Pang Yunfan [15] re-determined the glare constant according to the physical condition of Chinese people, and adopted three levels (feeling glare is level I, discomfort is level II, unbearable is level III) as the measurement standard, and obtained the test coefficient of glare parameters through experiments: a=1, b=0.63, c=0.28. The relationship between G value and glare comfort is shown in Table 1.
Table 1 The relationship between G value and glare comfort

| G  | Glare perception degree            | Subjective evaluation |
|----|-----------------------------------|-----------------------|
| 1  | An intolerable glare              | Feel very bad         |
| 3  | Glare with interference           | Feel a little upset   |
| 5  | Just enough glare to allow        | Can accept            |
| 7  | Feel satisfactory                  | Feel good             |
| 9  | The glare was barely perceptible  | Feel so good          |

As can be seen from Table 1: When G value is between 1 and 3, it will have an impact on the normal driving of drivers; If G value is less than 1, it will cause serious glare effect, which is very harmful to the traffic safety in highway tunnel.

2.2 The relative threshold increment of glare TI

Glare is caused by the presence of high brightness or contrast in the field of vision, reducing the body's ability to see and recognize objects. Due to the influence of glare, drivers will be unable to clearly identify obstacles, which will affect driving safety. The ratio of the increased contrast to the effective contrast when the object is just seen in the glare condition is called the relative threshold increment of glare, which is represented by TI. The value of the relative threshold increment should be less than 15%. Under highway lighting conditions, the average illumination of the road generally conforms to the range of $0.05 \text{cd/m}^2 < L_b < 5 \text{cd/m}^2$. The calculation method of relative threshold increment TI is shown in Equation (2):

$$TI = 65 \frac{L_v}{L_{AV}} \times 100\%$$

Where: $TI$ is the relative threshold increment (%); $L_v$ is equivalent light curtain brightness ($\text{cd/m}^2$); $L_{AV}$ is the average road brightness.

The calculation formula of equivalent light curtain brightness $L_v$ is shown in Equation (3):

$$L_v = K\frac{E_\theta}{\theta^2}$$

Where: $L_v$ is equivalent light curtain brightness ($\text{cd/m}^2$); $E_\theta$ is the illumination $\text{lx}$ generated by the dazzling light source on a plane perpendicular to the line of sight of the eye of the observer; $\theta$ is the line of sight with dazzling light source the light incident direction angle; $K$ is constant, when $\theta$ expressed as angle $K$ take 10.

3. Design of highway tunnel lighting simulation model

This research uses the DIAlux evo lighting simulation analysis software to build the two-lane tunnel model. The light distribution curve of the lighting fixture adopts the most commonly used symmetrical bat wing. The tunnel luminaires are installed at a certain interval and angle in the tunnel model. The operation calculation can obtain the average illuminance of the road surface and the equivalent light curtain brightness value, and realize the simulation and quantitative analysis of the influence of artificial light environment glare in highway tunnel lighting.

The tunnel is designed at a speed of 80km/h and a lane width of 3.75m. The inspection lane width, excess width and tunnel structure are all constructed in accordance with the tunnel design specifications. The tunnel pavement is an asphalt concrete pavement, the pavement reflection coefficient is 0.14 and the side wall height is 3m. The clearance height is 5m, and the tunnel cross section is as shown in Figure 1.
Figure 1 Schematic diagram of tunnel cross section

The lighting mode of the simulation experiment is symmetrical lighting on both sides, and the lamps on both sides are 2.45m away from the center line of the tunnel. Figure 2 shows the top view of the tunnel lighting model. The installation height of the luminaire is 5.5m, and the distance between the luminaires is 5, 6, 7, 8, 9, 10m, etc. The above six types of distances are in compliance with the stroboscopic requirements, and the installation angle of the luminaire is 0°, 5°, 10°, 15°, 20°, 25°, 30°, 35°, etc. Figure 3 shows the rendering of the tunnel lighting model.

Figure 2 Top view of tunnel lighting model

Figure 3 Tunnel lighting renderings

The measurement area of average road surface illumination was selected on the road directly in front of the test car, as shown in Figure 4. The equivalent light curtain illumination was selected on the road directly in front of the test vehicle and perpendicular to the road, as shown in Figure 5. The software DIALux evo will automatically generate the illuminance value of the selected area and calculate the relative threshold increment TI value and the glare influence level G, so as to obtain the change of the relative threshold increment TI value and the glare influence level G under different lighting installation
angle and distance, and finally analyze the correlation between them.

![Figure 4 Measurement area of road average illumination](image)

![Figure 5 Measurement area of Equivalent light curtain illumination](image)

4. Simulation and analysis of highway tunnel glare

4.1 The simulation results

The illumination values of the measured area of average road illumination and equivalent light curtain luminance were calculated by using the DIAlux evo lighting simulation software. The simulation results of the combined average road illumination and equivalent light curtain luminance values at different installation angles and intervals were shown in Table 2.

| Lighting installation angle (°) | Luminaire installation spacing (m) | 5  | 6  | 7  | 8  | 9  | 10 |
|-------------------------------|-----------------------------------|----|----|----|----|----|-----|
| 0                             | L_{AV}                            | 61.8 | 51.5 | 44 | 38.6 | 34.3 | 30.8 |
|                               | E_{AV}                            | 56.7 | 27.2 | 27.6 | 25.7 | 15.1 | 22.7 |
| 5                             | L_{AV}                            | 63.8 | 53.1 | 45.4 | 39.8 | 35.4 | 31.8 |
|                               | E_{AV}                            | 38.2 | 28.3 | 28.6 | 26.6 | 15.3 | 23.5 |
| 10                            | L_{AV}                            | 65.1 | 54.2 | 46.4 | 40.6 | 36.1 | 32.5 |
|                               | E_{AV}                            | 39.1 | 29   | 29.7 | 27.6 | 15.8 | 24.5 |
According to Table 2, the expression of relative threshold increment $TI$ under the combination of installation angle and spacing of each kind of lamps can be obtained, as shown in Equation (4):

$$TI = 65 \times 10^{E_{AV} / \left(\theta^2 L_{AV}\right)} \times 100\%$$

If the relative threshold increment $TI$ of glare is less than 15 degrees, then Equation (5) can be written:

$$TI = 650 \times E_{AV} / \left(\theta^2 L_{AV}\right) \times 100\% \leq 15^\circ$$

When formula (5) is established, the driver in the tunnel will not be affected by the glare of the lighting fixture. If the value of the angle between the line of sight and the incident direction of the glare light source does not meet the formula (5), the driver in the tunnel will be affected by glare. From formula (5), the value range $\theta_1$ of $\theta$ can be calculated for different lamp installation spacing and angle combinations, which requires $\theta \leq \theta_1$, as shown in Table 3.

Table 3 Value range of $\theta$ under different lamp installation spacing and angle combinations (°)

| Lighting installation angle (°) | 5   | 6   | 7   | 8   | 9   | 10  |
|-------------------------------|-----|-----|-----|-----|-----|-----|
| 0                             | 76.62 | 70.95 | 76.18 | 77.4 | 62.2 | 79.62 |
| 5                             | 77.18 | 71.49 | 76.52 | 77.79 | 61.82 | 79.98 |
| 10                            | 77.46 | 71.78 | 77.3 | 78.61 | 62.34 | 80.95 |
| 15                            | 78.11 | 72.22 | 77.81 | 79.9 | 62.58 | 81.64 |
| 20                            | 78.69 | 72.46 | 78.25 | 79.83 | 62.97 | 82.19 |
| 25                            | 79.08 | 72.74 | 78.7 | 79.92 | 63.3 | 82.38 |
| 30                            | 79.13 | 73.09 | 78.55 | 79.63 | 63.4 | 81.79 |
| 35                            | 79.08 | 73.09 | 78.41 | 79.02 | 63.48 | 81.14 |
| 40                            | 76.62 | 70.95 | 76.18 | 77.4 | 62.2 | 79.62 |

According to Table 2 and Table 3, the glare influence grade $G$ value under different lamp installation angles and spacing combinations can be obtained, as shown in Table 4.

Table 4 Influence grade $G$ of glare under combination of installation angle and spacing of various lamps

| Lighting installation angle (°) | 5   | 6   | 7   | 8   | 9   | 10  |
|-------------------------------|-----|-----|-----|-----|-----|-----|
| 0                             | 1.77 | 1.76 | 1.7 | 1.66 | 1.67 | 1.58 |
| 5                             | 1.77 | 1.77 | 1.7 | 1.66 | 1.66 | 1.58 |
| 10                            | 1.78 | 1.77 | 1.7 | 1.66 | 1.67 | 1.57 |
| 15                            | 1.77 | 1.77 | 1.7 | 1.64 | 1.68 | 1.56 |
4.2 Analysis of simulation results

According to the value range of $\theta$ under different lamp installation spacing and angle combinations in Table 2, the variation rule of $\theta_1$ can be obtained, as shown in Figure 6. As can be seen under the selected tunnel lamps, the range of $\theta$ value under symmetrical arrangement of lamps on both sides is greater than 61.82° and less than 82.38°. The change of installation angle under different installation spacing does not make the $\theta$ value fluctuate greatly, but under different installation spacing the $\theta$ value will appear larger fluctuation. When the arrangement lamp spacing is 9 m, the value of $\theta$ is the minimum, which is most beneficial to the driver in the tunnel not to be affected by glare. The range of glare influence angle $\theta$ is shown in Figure 7.

![Figure 6 Range of the angle $\theta$ between the line of sight and the incident direction of the glare light source](image)

![Figure 7 Analysis diagram of the range of glare influence angle $\theta$](image)

It can also be seen from Figure 7 that, if tunnel lighting adopts the light-matching type, the glare influence of tunnel lighting on drivers can be reduced to a great extent. The analysis diagram of glare angle is shown in Figure 8.
Figure 8 Glare angle analysis diagram of tunnel lamps

According to the G value of the glare influence level under the combination of installation angles and spacing of various lamps in Table 4, under the condition of symmetrical arrangement of both sides of the tunnel lights used in this paper, the glare influence level is between 1.54 and 1.78, and the glare perception degree is between the glare with interference and the unbearable glare.

5. Conclusion

Based on the analysis of the lighting glare from different installation angles and spacing under the symmetrical lighting arrangement on both sides of the tunnel, the following conclusions are drawn:

(1) When the two-sided symmetrical lighting method is adopted in the tunnel, and the angle between the line of sight and the incident direction of the actual tunnel lighting source is less than 82.38°, the driver will be affected by the glare generated by the lamps in the tunnel. When the distance between the lamps is 9m, the driver is least likely to be affected by glare.

(2) Through the comprehensive analysis of the simulation results, the symmetrical bat-wing tunnel lamp has a glare effect between 1 and 3 at any installation distance and angle under the symmetrical arrangement of lights on both sides, which is a serious glare effect and needs to be appropriately reduced the surface brightness of the lamp.

The analysis conclusions obtained in this paper further clarify the formation of glare in the middle section of the tunnel. Although the traditional symmetrical bat-wing tunnel lamp can better meet the uniformity of the road surface brightness, the glare cannot be ignored. Using light-matching lamp is better to eliminate the effect of glare. At the same time, attention should be paid to the installation distance and angle of the lamps. It should be pointed out that the simulation experiment in this article is based on a specific symmetrical bat-wing light distribution lamp. Even if the power of different lamps is the same, the light distribution curve of the lamp is different, and the quality of the tunnel lighting environment after installation is also different. It is recommended specific design analysis should be carried out for specific tunnels and lighting fixtures to provide more accurate tunnel anti-glare design.

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