Research on Low Altitude Illumination Configuration Technology of Highway Tunnel

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Abstract. In view of the problem of light efficiency utilization in low altitude illumination in tunnels, it is proposed in this paper to improve the lighting benefits by optimizing the light configuration. Combinational analysis of such parameters as light height, elevation angle and spacing in low altitude illumination is performed in this research by Dialux optical simulation software. The average road surface luminance, overall uniformity of road surface luminance and longitudinal uniformity of road surface luminance are taken as key evaluation indicators. The study shows that the optimal height, elevation angle and spacing of low altitude illumination are 3 meters, 40° and 1 meter respectively. The overall uniformity of road surface luminance of low altitude illumination can reach 0.97, the longitudinal uniformity of road surface luminance can reach up to 1.0. The luminous flux per meter is equal in the longitudinal direction of the tunnel. The average road surface luminance is affected by the light arrangement spacing to a very small extent, and the longitudinal uniformity of road surface luminance is affected by the height and elevation angle of the light very slightly.

1. Introduction
Low altitude illumination is widely applied to urban interchange ramps and urban landscape lighting because of its high light efficiency, good visual inducibility, and easy installation and maintenance. When a fire occurs, smoke rises in the air, making it difficult to block lighting in low altitude illumination compared with the traditional high altitude illumination situation [1], so low altitude illumination is also widely used in fire evacuation lighting [2]. Therefore, due to the advantages of low altitude illumination, it has great application prospects in the field of tunnel lighting.

However, the relatively closed space environment in the tunnel is not conducive to the light intensity radiation of the low altitude illumination, and part of the luminous flux is irradiated onto the tunnel wall, thereby reducing the luminous flux projected onto the road surface, that is, reducing the luminous efficiency of the illumination. However, design of light distribution curve and optimization of light parameters are an effective solution to this problem. From the existing related research, there have been related research on glare, stroboscopic, light distribution control and other factors in highway low altitude illumination [3,4], which is of certain reference significance for tunnel lighting.

In the low altitude illumination of the tunnel, Chen Xiaoli [5] considered the optimal height of the light through the test and simulation method from the perspective of convenient installation and fire safety. In terms of light configuration optimization, there are many researches on traditional lighting
configuration [6–8], and are only a few researches on low altitude illumination. Therefore, this paper takes full account of the relevant factors such as height, elevation angle and spacing of low altitude illumination, and optimizes illumination based on numerical simulation.

2. Installation height and stroboscopic effect
Low altitude illumination refers to a way of lighting that is lower in height than traditional illumination. According to the Specifications for Design of Highway Tunnels (JTG 3370.1-2018) [9], the net height in a two-lane road tunnel is generally around 7 meters (height from pavement to arch crown), and the height of the tunnel structure gauge is generally 5 meters (the light height of the high altitude illumination is controlled at 5~7m), the height of overhaul road is generally 20~50cm and a headroom height of 2.5 meters. In order to ensure that the lighting fixture does not invade the tunnel structure gauge, and to prevent the vehicle from scratching the light under special circumstances, the light height of the low altitude illumination is recommended to be set within the range of 3–4 meters. An example of a tunnel cross section is shown in Figure 1.

![Figure 1. Cross-sectional view of tunnel](image)

Luminaire is installed longitudinally on top or both sides of tunnel at equal intervals. Meanwhile, during the driving process in the tunnel, the luminous surface of the luminaire periodically appears and disappears at the edge of the driver's field of vision, causing interference to the driver's vision. Therefore, the number of light spots appearing in the human eye every second is called the flicker frequency (stroboscopic) [10]. The flicker frequency is expressed by \( f \) in Hertz (Hz). It depends mainly on two factors: the luminaire spacing (\( S \)) in meters and the driving speed (\( V \)) in meters per second. The relationship is as follows:

\[
f = \frac{V}{S}
\]  

(1)

When the flicker frequency is between 4 Hz and 11 Hz, and the elapsed time exceeds 20s, discomfort will be caused and the visual recognition ability will be affected. Therefore, combined with the speed of the highway tunnel in China (60~100km/h), the light spacing of 1.51 ~ 6.95 meters at the interior zone illumination should be avoided.

3. Calculation model
The calculation model is a two-lane tunnel. The model has a net pavement width of 8.5 meters, a single lane width of 3.75 meters, an arch crown elevation of 7.14 meters, and a longitudinal length of 200 meters. The sidewalls of the tunnel below 2 meters and the overhaul road are made of cement concrete. Its reflectance is set to 30%. The pavement type is asphalt concrete and the reflection characteristic is R3. The model is shown in Figure 2.
In the calculation model, the lighting fixtures are symmetrically arranged on both sides of the side walls. The spacing of luminaire (L) can be taken as 1 meter, 1.5 meters, 7 meters, 8 meters and 9 meters (with flicker frequency considered). Luminaire designed for low altitude illumination of tunnel is very few on the current market, so a type of LED light, which is now the maturest, is selected in this paper. The light distribution curve of LED light for low altitude illumination is shown in Figure 3. The luminous efficacy of the lights is 85 lm/W, the luminous flux of the model lights can be between 850 lumens and 8000 lumens, and the overall maintenance factor of the lighting system is 0.75.

4. Simulation analysis of light configuration

4.1. Analysis of elevation angle and height of light arrangement

Because of the interaction between the height of the light and the elevation angle, it is necessary to consider both of them in the research on the best lighting benefits. Considering the problem of tunnel structure gauge (H>2.5m), the height of the light can be 3 meters, 3.5 meters and 4 meters, and the elevation angle can be 20°, 30°, 40° and 50°. The light spacing control variable (L) takes 1 meter, and the single-light luminous flux takes 850 lumens. The simulation calculation results are shown in Table 1.
Table 1 (a). Calculation of the average road surface luminance (cd/m²)

| Light arrangement height (m) | Elevation angle (°) | 3   | 3.5  | 4   |
|-----------------------------|--------------------|-----|------|-----|
|                             | 20                 | 4.07| 4.42 | 4.65|
|                             | 30                 | 4.86| 5.11 | 5.10|
|                             | 40                 | 5.15| 4.69 | 4.13|
|                             | 50                 | 3.67| 3.35 | 3.07|

Table 1 (b). Calculation of the overall uniformity of road surface luminance (cd/m²)

| Light arrangement height (m) | Elevation angle (°) | 3   | 3.5  | 4   |
|-----------------------------|--------------------|-----|------|-----|
|                             | 20                 | 0.2 | 0.71 | 0.78|
|                             | 30                 | 0.76| 0.88 | 0.81|
|                             | 40                 | 0.97| 0.93 | 0.95|
|                             | 50                 | 0.9 | 0.91 | 0.93|

Table 1 (c). Calculation of the longitudinal uniformity of road surface luminance (cd/m²)

| Light arrangement height (m) | Elevation angle (°) | 3   | 3.5  | 4   |
|-----------------------------|--------------------|-----|------|-----|
|                             | 20                 | 0.97| 0.98 | 0.99|
|                             | 30                 | 0.99| 0.99 | 0.99|
|                             | 40                 | 1.0 | 0.99 | 1.0 |
|                             | 50                 | 1.0 | 0.99 | 1.0 |

The overall calculation results in Table 1 show that the elevation angles of the optimal illumination quality for different light heights are different. The calculation results of overall uniformity of road surface luminance in Table 1 (b) show that the overall uniformity of road surface luminance is the best, being 0.97, 0.93 and 0.95 respectively, when the elevation angles are all 40° if the installation height of the lights is 3 meters, 3.5 meters and 4 meters. The calculation results of longitudinal uniformity of road surface luminance in Table 1(c) show that for low altitude illumination, the longitudinal uniformity of road surface luminance is very good, with the lowest value being 0.97, the highest being 1.0, thus almost no brightness gradient, and that the influence of height and elevation angle is small. Table 1 (a) average road surface luminance fitting curve is shown in Figure 4.

It can be seen from the curve variation relationship in Fig. 4 that the optimum elevation angle at a height of 3 meters is 40°, and that the optimum elevation angle at a height of 3.5 meters and 4 meters is 30°. The overall comparison shows that the optimum height and elevation angle of the low altitude illumination are 3 meters and 40° respectively, and the average road surface luminance can reach a maximum of 5.15cd/m² under the low altitude illumination conditions of 1m spacing and 850 lm luminous flux.
4.2. Analysis of light arrangement spacing

The light arrangement spacing also has an important influence on the road surface luminance and road uniformity. In this simulation, the tunnel has a design speed of 80km/s and a unidirectional traffic volume of 1200veh/(h·ln) [11], so the luminance is generally required to be 3.5cd/m². So the spacing of luminaire can be 1 meter, 1.5 meters, 7 meters, 8 meters and 9 meters in accordance with the design parameters, stroboscopic control, and experience in engineering examples. According to the calculation in the previous section, the light height and elevation angle variables are controlled to be 3 meters and 40°. At the same time, in order to be more comparable, the luminous flux per meter in the longitudinal direction of the road is set equal, and the value is 850 W/m. The simulation results of the light spacing are shown in Table 2.

| Light arrangement spacing (m) | Road surface luminance (cd/m²) | Overall uniformity of road surface luminance | Longitudinal uniformity of road surface luminance |
|------------------------------|--------------------------------|---------------------------------------------|--------------------------------------------------|
| 1                            | 5.15                           | 0.97                                        | 1.0                                              |
| 1.5                          | 5.15                           | 0.97                                        | 1.0                                              |
| 7                            | 5.14                           | 0.82                                        | 0.87                                             |
| 8                            | 5.14                           | 0.78                                        | 0.74                                             |
| 9                            | 5.14                           | 0.75                                        | 0.65                                             |

From the calculation results in Table 2, under the same luminous flux (850 lm/w) per meter in the longitudinal direction, the average road surface luminance simulated by different spacing of luminaire is almost the same, but the road surface uniformity is very different. The road uniformity calculation curve at different spacings of lights is shown in Fig. 5.

As shown in Fig. 5, the relationship between the spacing of lights and the road surface uniformity is nonlinear, but it is apparent that the uniformity is decreasing as the spacing increases. It is shown by the calculated value that when the arrangement distance of the lights is less than 1.5 meters, the road uniformity is very good, with the overall uniformity of road surface luminance being above 0.95 and the longitudinal uniformity of road surface luminance being up to 1.0.
5. Conclusions

(1) Simulation analysis of the light height and elevation angle of the low altitude illumination shows that the optimum elevation angles at the light arrangement heights of 3 meters, 3.5 meters and 4 meters are 40°, 30° and 30° respectively, and that the optimum height and elevation combination of the low altitude illumination is 3 meters and 40°, where the road surface luminance and road surface uniformity are the best.

(2) According to the simulation analysis of the light arrangement spacing of low altitude illumination, when the spacing is less than 1.5 meters, the road uniformity is the best, the overall uniformity of road surface luminance is up to 0.97, and the longitudinal uniformity of road surface luminance is up to 1.0.

(3) According to the comprehensive analysis, under the condition that the luminous flux per meter in the longitudinal direction of the road is equal, the average road surface luminance is affected by the light arrangement spacing to a very small extent. Similarly, the longitudinal uniformity of road surface luminance is also affected by the height and elevation angle of the light very slightly.

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