Simulation Experiment on Tunnel Lighting Aided by High Diffuse Reflectance Materials

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Abstract. The existing tunnel lighting calculation methods only consider the effect caused by direct light source and ignores the reflection effect of light flux emitted by lamps inside the tunnel closed pipe, which is not conducive to the energy saving and safety of tunnel lighting. In this paper, a tunnel illumination calculation method considering the reflection increment of tunnel sidewall is proposed. This method is based on the diffuse reflection coefficient of tunnel sidewall material which can characterize the reflection characteristic of its surface, so as to calculate the illuminance of road surface. Matlab software was used to simulate the real lighting environment of the tunnel with energy storage luminescent material as the side wall. It was found that the increase of reflection caused by high-quality tunnel interior materials could effectively improve the tunnel lighting.

1. Introduction

By the end of 2019, China had 16,200 road tunnels with a total length of 15,285.0km. With the construction of highway tunnels, the contradiction between safety and comfort in operation and energy saving becomes more and more prominent. Relevant data show that the lighting expenditure of the highway tunnel accounts for about 30% of the total expenditure, which is the largest part in the operation of the highway tunnel.

Compared with the outdoor road environment, the highway tunnel has a special semi-space structure, so it is of great application value to build an efficient lighting environment of the highway tunnel based on its structural characteristics. The ceiling and side wall of the tunnel has certain reflective factor, the light flux from the lamps reflected several times in the semi-space to effected to the road, whichs can improve pavement illuminance and luminance, so some scholars consider using the reflective effect to improve the quality of tunnel lighting: Liang Bo [1,2] put forward the theory of auxiliary lighting on the inner wall of the tunnel, considering the use of coating materials with good reflective properties as the inner wall of the tunnel. The light reflected on the inner wall can improve the lighting level of the tunnel, thereby reducing the energy waste at the beginning of the lighting design. Energy saving in tunnel operation is of practical significance; Pan Guobing [3] used Dialux software for simulation to evaluate the tunnel lighting quality when different materials are used as the inner wall of the tunnel from the aspects of road surface illumination; Based on mathematical statistics, Yang Tao [4] proposed a method.
for calculating the increment of the reflection of the inner wall of the tunnel by introducing the reflection coefficient of the wall surface, pavement and the distribution ratio of light flux.

Accurate lighting calculation method can provide a theoretical basis for the rational use of the reflection increment of the inner wall of the tunnel, and can effectively narrow the gap between the theoretical data and the measured data, help to establish a more accurate and perfect tunnel lighting design standard, and realize the energy saving of the tunnel of great significance. The current calculation method of tunnel lighting in China is a calculation method based on the light distribution curve of lamps proposed in the "Guidelines for Design of Lighting of Highway Tunnels" [5]. Although the standard mentions that "walls within 2m on both sides of the road should be laid with materials with high reflectivity, when the wall reflection-coefficient reaches 0.7, the luminance of the road can be increased by 10%", however, the standard does not give the specific calculation method of the reflective increment.

Based on this, this paper proposes a lighting calculation method that considers the reflective increment of the tunnel side wall. This method, on the one hand, makes up for the deficiencies of the existing tunnel lighting calculation formulas. It is proposed that the illuminance of the road surface comes from the direct generation of lamps and the reflection of the inner wall. On the other hand, it helps people realize that the tunnel sidewall material is not a single decorative function to beautify the internal environment of the tunnel. It can also improve the lighting quality of the tunnel and the safety and energy-saving effects of highway tunnel lighting, thus opening a new study for tunnel lighting research field. This method is different from the previous research that uses mathematical statistics to complete the processing of the reflection increment, but is based on optical theory. The calculation and derivation are traceable. Therefore, in actual use, it is easy to adapt to different calculation scenarios through parameter adjustment.

2. Calculation Method of Tunnel Lighting in Consideration on Reflected Light of Sidewall

2.1. Calculation of Direct Luminance
The cosine formula can be used to calculate the illuminance generated by direct lighting at the calculation point, as shown in formula (1):

$$E_{pi} = \frac{I_{pi} \cos \gamma \times \frac{\phi}{1000}}{H^2} \times M$$

(1)

The illuminance of multiple lamps directly illuminate at the calculation point is shown in formula (2):

$$E_p = \sum_{i=1}^{n} E_{pi}$$

(2)

2.2. Calculation Method of Tunnel Lighting in Consideration on Reflected Light of Sidewall

2.2.1. Tunnel Sidewall Discretization. The tunnel interior material is discretized into a series of units by using the finite element method, and which is regarded as the unit light source in the lighting calculation process. The size of the units depends on the calculation accuracy. The smaller the size is, the higher the calculation accuracy will be.

2.2.2. Unit Light Intensity Calculation. First, calculate the illuminance of a luminaire illuminate on a unit. Based on the optical theoretical between illuminance, luminance and light intensity, the light intensity of unit can be deduced by combining the reflective property of tunnel side wall materials, as shown in formula (4):
\[ I_{fb} = \frac{E_{ab} \cdot \rho \cdot S \cdot C}{\pi} = \sum_{a=1}^{n} \frac{I(c_{ab}, \gamma_{ab}) \cdot \cos \beta_{ab}^3 \cdot \cos \theta_{ab} \cdot \phi \cdot M \cdot \rho \cdot S \cdot C}{H_{ab}^2 \cdot 1000 \cdot \pi} \] (3)

Which \( E_{ab} \) is illuminance (lx) on the unit b which is caused by lamp a, \( I(c_{ab}, \gamma_{ab}) \) is light intensity (cd) on the unit b which is caused by lamp a, according to the luminous intensity distribution curve. \( \beta_{ab} \) is incident angle (°) unit b corresponding to the lamp a, \( \theta_{ab} \) is the angle between the connection line of the lamp a and the cell b and the normal line of the cell b. \( H_{ab} \) is the vertical distance of the lamp a to the cell b. \( \phi \) is luminous flux of lamp a, \( M \) is the coefficient of maintenance of the lamp. \( \rho \) is the diffuse-reflection factor of the sidewall, which is connected with the characteristics of luminescence of the sidewall. \( S \) is the area of the unit. \( C \) is cleanness factor. \( n \) is the number of lamps.

2.2.3. Sidewall Reflection Effect on Illuminance of the Calculation Point. The illuminance increment generated by reflected light at the calculation point is shown in formula (4).

\[ E_u = \sum_{k=1}^{m} \frac{I_{fb} \cdot \cos \omega_b \cdot \cos \tau_b^3}{H_{ab}^2} \] (4)

Where \( I_{fb} \) is the illuminance(lx) of the calculate point, \( m \) is the number of the units. \( \omega_b \) is the angle between the line of the unit and the calculate point and the normal line of the unit. \( \tau_b \) is the angle between the line of the unit and the calculate point and the road’s normal line. \( H_b \) is the vertical distance of the unit to the calculate point.

2.2.4. The Illuminance of the Calculation Point Considering the Reflection Increment of the Sidewall

\[ E = E_p + E_u \] (5)

Where \( E \) is the illuminance (lx) of the pavement calculation point.

3. Simulation Experiment Based on Improved Calculation method

3.1. Calculation Conditions
The computational simulation process is based on the following tunnel geometry.

![Figure 1. Section geometry of tunnel](image-url)
The elevation angle of the lamp is 30°, and the lamps is distributed according to the symmetrical form on both sides. The spacing of the lighting is 3 meters.

According to the “Measurement methods for lighting” (GB/T 5700-2008)[5], the calculation points of tunnel pavement were arranged. Based on the general situation of the tunnel and lamps, the 3d spatial relation diagram between the LED lights in the tunnel and the pavement calculation points is drawn, as shown in the figure.

![Diagram](image)

**Figure 2.** Three-dimensional spatial relationship between LED lights and pavement calculation points in tunnel

The ceiling material of the tunnel adopts plain concrete with diffuse reflectance of 0.05. Since the ceiling of the tunnel is seriously polluted by vehicle exhaust for a long time, its reflective effect is not considered.

The side wall material uses energy storage luminescent material, which has a high diffuse reflection coefficient, and its diffuse reflection coefficient is 0.7. As a control, another set of simulation experiments is set, and the material of the tunnel side wall is set as a cement mortar material with a diffuse reflectance of 0.05

### 3.2. Calculation Results

Using Matlab modeling calculation, the illuminance of the pavement calculation point when the tunnel side wall material is cement mortar and energy storage luminescent material is obtained, which is shown in the figure below.

![Graphs](image)

**Figure 3.** The illuminance of the different material.
When using energy-storage luminescent materials, the illuminance at the calculation point of the road surface is increased by 9.68lx-28.49lx, and the increase ratio is 10.20% -31.22%. The average increase is 15.90lx, and the increase rate is 16.85%. The study found that when the energy storage luminescent material is used as the material of the inner wall of the tunnel, the lighting quality of the tunnel is significantly improved compared to the cement mortar material.

4. Conclusion
This paper proposes a tunnel lighting calculation method that considers the reflection increase of the tunnel side wall material, and based on this, software modeling is used to conduct simulation experiments. It was found that the use of materials with high diffuse reflectance as the inner wall of the tunnel can significantly increase the illumination of the road surface in the tunnel. If the reflection increment is taken into consideration in the design stage, the energy consumption of the tunnel lighting fixtures can be reduced to a certain extent, so as to achieve the purpose of energy saving in tunnel lighting.

At the same time, in practical application, the characteristics of the highly diffuse reflective material in tunnel fire prevention, durability, cleaning, etc. should be considered, and whether the material is suitable for use in tunnels should be comprehensively considered. With the development of technology, a large number of interior materials with low glare and high diffuse reflectance have been expected to be used in auxiliary tunnel lighting on a large scale.

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