Experimental study on energy-saving of highway tunnel lighting with symmetric lamp distribution

Chao Yang¹*, Shijuan Fan²

¹School of Mechatronics and Vehicle Engineering, East China Jiaotong University, Jiangxi, 330013, China
²School of Transportation and Logistics, East China Jiaotong University, Jiangxi, 330013, China

*Corresponding author’s e-mail: ychydyfsj@163.com

Abstract. In order to study the energy-saving of highway tunnel lighting experimentally with low cost, a similar tunnel model was designed and used for the lighting experiment. Yanlieshan highway tunnel was selected as the study object. On the basis of the tunnel structure sizes (TSS) and the selected LED lamps, the optimized symmetric lamp installation parameters (OSLIPs) for energy-saving were obtained with the lighting parameters optimization model (LPOM) on symmetric lamp distribution (SLD) from reference. Based on the TSS and the OSLIPs, a simulation experiment of the tunnel lighting was accomplished with DIALux. A similar tunnel model was designed and built according to the TSS and similarity theory, and a tunnel model lighting experiment with SLD was carried out. The road-surface-illuminance (RSI) data of the tunnel model lighting experiment were compared with the simulation experiment results. The comparison of horizontal RSI from the two methods coincide well, which proves the LPOM is correct, the lighting experimental study with similar tunnel model is feasible and the experiment method in this study is valid.

1. Introduction

In order to reduce the energy consumption of tunnel lighting, many studies on the highway tunnel lighting energy-saving problems were conducted in such aspects as energy-saving renovation [1], energy-saving control [2-3] and energy-saving parameters optimization [4-6]. However, due to the limitations of actual tunnel lighting experimental conditions, most of the studies were theoretical or emulational, lacking experimental verification.

In this paper, optimized lighting parameters for energy-saving (OLPES) will be obtained by a lighting parameters optimization model (LPOM), according to the actual highway tunnel section sizes, selected LED lamps and tunnel lighting demands. A simulation experiment will be carried out, based on the sizes of the target tunnel and the OLPES. According to the cross-section sizes (CSS) of the target tunnel, a smaller tunnel similar model will be designed and built according to the similarity theory, and a tunnel model lighting experiment will be conducted. A comparison and analysis of the lighting data from the two ways will be conducted to verify the feasibility of the lighting experimental study on energy-saving with tunnel model, and the validity of the experiment method.

In order to facilitate the comparisons between the simulation experiment results and the tunnel model experiment results, the same tunnel structure data and tunnel LED lamps will be used in lighting parameters optimization and lighting simulation, and the tunnel model lighting experiment
will be completed in the tunnel similar model, and same series of LED lamps will be used, and the calculation regional grids will be divided in the same way.

2. Highway Tunnel and Lamp

2.1. Highway Tunnel
The interior zone of Yanlishan tunnel of Jiujing highway is used as the study objective. The tunnel was designed as one-way, double holes and two lanes in each hole. The total length of the tunnel is 3352m, the total width of the tunnel road is 10.25m, the clear height of the tunnel hole is 7.425m, the lanes is 8.5m wide, the cross-section of the tunnel hole is circular arch with radius of 5.4 m. The designed traffic volume is greater than 1200 vehicles per hour and the designed driving speed is 80 km/h. Reflective materials were laid on the tunnel wall area within 2m high, and the rest are cement concrete wall. The ground was paved cement. According to the Guidelines [7], the overall luminance uniformity (OLU) of the tunnel road surface of the tunnel interior zone is set to 0.4, the longitudinal luminance uniformity (LLU) of the tunnel road surface centerline of the tunnel interior zone is set to 0.6, and the maintenance factor of the lamp is set to 0.7, and the conversion relationship between the average illuminance and the average luminance is 10lx/(cd⋅m⁻²).

2.2. Tunnel Lamp
SPARK SPT-B series tunnel LED lamps are selected as lighting lamps, their lateral light-emitting angle is 100°, longitudinal light-emitting angle is 110°, light output ratio $\eta_0$ is 100%, color rendering index (Ra) is 70 or more, color temperature (CT) is 5000K. The light distribution curves (LDC) of the SPT-B LED lamps are shown in figure 1.

![Figure 1. Light distribution curve of SPT-B LED lamp.](image)

3. Lighting Parameters Optimization of Tunnel

3.1. Basic Lighting Formula
Figure 2 is the schematic diagram of symmetric lamp distribution (SLD), $(A_1, A_2), (A_3, A_4), (A_5, A_6), (A_7, A_8)$ are four pairs of adjacent lamps, they have the same type, same power $p$, same installation height $h$, same longitudinal installation spacing $s$, same crosswise installation spacing $d_i$, and same elevation angle $\xi$. $O_1$-$O_8$ are the corresponding points of lamps $A_1$-$A_8$ on the road surface, respectively; $d_0$ is the width of the traffic lanes, $d'$ is the total width of the tunnel road surface including the width of sidewalks. The area of $B_3B_4B_6B_5$ between the two pairs adjacent lamps $(A_3, A_4)$ and $(A_5, A_6)$ was taken as calculation region. The longitudinal centerline of road surface is the $X$-axis, the crosswise direction is the $Y$-axis, the vertical direction is the $Z$-axis, and the central point $O$ of the area $B_3B_4B_6B_5$ as the origin.
The horizontal illumination produced by lamp \( A_i \) at point \( b \) is

\[
E_{bi} = \left[ h \cdot I(\gamma_i, \theta_i) \cdot (\sin \gamma_i / \cos \xi_i) \cdot (A_i b_i)^{-2} \cdot [X_i^2 + (0.5d_i + y - h \tan \xi_i)^2]^{-1/2} (i = 1, 3, 5, 7) \right]
\]

\[
E_{bi} = \left[ h \cdot I(\gamma_i, \theta_i) \cdot (\sin \gamma_i / \cos \xi_i) \cdot (A_i b_i)^{-2} \cdot [X_i^2 + (0.5d_i - y - h \tan \xi_i)^2]^{-1/2} (i = 2, 4, 6, 8) \right]
\]

(1)

Where \( h \) is the vertical height from the luminous surface center of lamp to road surface, \( A_i b_i \) is the distance from the luminous surface center of lamp \( A_i \) to the point \( b \), \( X_i \) is the component of distance \( O_i b \) in the \( X \) direction, the angles \( \gamma_i \) and \( \theta_i \) are determined by equations (2) and (3), respectively.

\[
\cos \gamma_i = \begin{cases} 
[h \cos \xi_i + (0.5d_i + y) \sin \xi_i] / (A_i b_i) & (i = 1, 3, 5, 7) \\
[h \cos \xi_i + (0.5d_i - y) \sin \xi_i] / (A_i b_i) & (i = 2, 4, 6, 8)
\end{cases}
\]

(2)

\[
\sin \theta_i = X_i / (A_i b \cdot \sin \gamma_i)
\]

(3)

If photometric data of the lamp are available, the luminous intensity of the light-direction deviating \( \gamma_i \) from the optic axis of the lamp is calculated as [4]

\[
I(\gamma_i, \theta_i) = I_{1000}(\gamma_i, \theta_i) \eta_0 \eta M \Phi / 1000
\]

(4)

Where \( I(\gamma_i, \theta_i) \) is the luminous intensity of the lamp in the direction of light \( A_i b_i \); \( \gamma_i \) is the intersection angle of light \( A_i b_i \) and optic axis of the lamp; \( \theta_i \) is the intersection angle between the light distribution profile (LDP) which the light \( A_i b_i \) is in and the LDP CO-180; \( I_{1000}(\gamma_i, \theta_i) \) is the luminous intensity of the lamp from the photometric data corresponding to \( \gamma_i \) and \( \theta_i \); \( \eta_0 \), \( \eta \), \( M \) and \( \Phi \) are light output ratio, utilization factor, maintenance factor and rated luminous flux of the lamp, respectively, \( \Phi = pq \), \( p \) and \( q \) are power, luminous efficiency of the lamp, respectively.

The overall horizontal illuminance of \( n \) lamps at the point \( b \) is calculated as [7]

\[
E_b = \sum_{i=1}^{n} E_{bi}
\]

(5)

### 3.2. Lighting Parameters Optimization Results

It is assumed that SPARK SPT-B40 series of tunnel LED lamps were used in the actual tunnel, \( p = 40W \), \( q = 120.54lm/W \). The factor \( \eta \) is calculated automatically in LPOM according to lighting parameters [8]. The required luminance value of the tunnel interior zone is 3.5cd/m². The Ra and CT of SPT-B40 lamp meet conditions of “half luminance of tunnel road surface for tunnel interior zone” stipulated in the Guidelines, the recommended minimum illuminance \( E_0 \) can be set to 17.5lx, it is the minimum road-surface-illuminance (RSI) after the lamp’s luminance decreases by 30%, so, \( E_0 \) is set to 25lx while optimizing the lighting parameters.

According to the LPOM [4], complex method is used to optimize the lighting parameters in Matlab. In the optimization calculation, the light reflectance of wall surface within 2m is set to 0.88, the light
reflectance of the rest wall and vault surfaces is set to 0.23, and the light reflectance of the road surface is set to 0.27. The calculation area is divided into 12 equal parts lengthways and 12 equal parts breadthways as shown in figure 3. The OLPES of SLD with SPT-B40 LED lamps in Yanlieshan tunnel are obtained, \( s=8.89 \text{m}, h=5.5 \text{m}, \xi=5^\circ, d_1=3 \text{m}, p=20\text{W}. \)

\[\text{Figure 3. Distribution diagram of optimizing calculation points.}\]

3.3. Tunnel lighting simulation

According to the CSS of the Yanlieshan tunnel, a simulation model is established in the software DIALux, and a simulation lighting system is established according to the OLPES with SPT-B40 LED lamps. The light reflectance of road surface is set to 0.27, the light reflectance of wall surface within 2m is set to 0.88, and the light reflectance of the rest wall and vault surface is set to 0.23. The calculation area is divided into grid as shown in figure 3.

Parameters are obtained from the simulation experiment data, in the calculation area of the tunnel road surface, the minimum RSI \( E_{\text{min}}=25\text{lx}, \) the maximum RSI \( E_{\text{max}}=42\text{lx} \) and the average RSI \( E_{\text{av}}=34.213\text{lx}. \) On the centerline of the road surface, the minimum RSI \( E_{\text{cmin}}=37\text{lx} \) and the maximum RSI \( E_{\text{cmax}}=42\text{lx}. \) OLU=0.731(>0.4), and LLU=0.881(>0.6). It can be seen that the \( E_{\text{min}}, \) the OLU and the LLU all meet the lighting demands in the Guidelines.

4. Lighting Experiment in Tunnel Model

4.1. Tunnel Lighting Similarity Ratio

Supposing \( C \) is geometric similarity ratio, the tunnel road width of similar model \( D_m, \) model height \( H_m, \) and model vault arc radius \( R_m, \) are \( D_m=D_r/C, \) \( H_m=H_r/C \) and \( R_m=R_r/C, \) respectively, the subscript "m" expresses tunnel model, the subscript "r" expresses real tunnel. In tunnel model, the vertical height from the luminous surface center of lamp to road surface \( h_m=h_r/C, \) the crosswise installation spacing \( d_m=d_r/C, \) and the longitudinal spacing of adjacent two lamps \( s_m=s_r/C, \) where \( h_r, d_r \) and \( s_r, \) are the vertical height from the luminous surface center of lamp to road surface, the crosswise installation spacing and the longitudinal spacing of adjacent two lamps in actual tunnel, respectively.

Supposing the lamp \( A \) and point \( b \) in actual tunnel corresponds with the lamp \( A' \) and point \( b' \) in tunnel model, the similarity ratio of illuminance created by corresponding lamp at corresponding point is

\[ C_e = \frac{E_b}{E_{b'}} \]  

(6)

Where \( E_b \) and \( E_{b'} \) are illuminances of the point \( b \) and the point \( b', \) respectively.

4.2. Tunnel Similar Model

The geometric similarity ratio is set to 7, the CSS of the tunnel similar model are obtained, \( D_m=1.21\text{m}, H_m=1.06\text{m} \) and \( R_m=0.77\text{m}. \) The basic structure of the tunnel model is made of steel tube and steel bar and 10m long. The model framework is covered with gray membrane to simulate the concrete. Ultraviolet reflective cloth is arranged on both sides to simulate the two sides wall of the tunnel. Grid paper with concrete background is laid on the ground as the measuring grid. The grid size is
10cm×10cm.

4.3. Model Lighting Experiment

Digital illuminometer, UT382, is used to measure the ground illuminance. The spectrum of the instrument conforms to CIE standard, and its range is 0~20000Lux.

According to the similarity ratio and the OLPES of SLD with SPT-B40 LED lamps, the lighting parameters of the model lighting experiment of the SLD are obtained, \( h_m=0.786m \), \( s_m=1.27m \), \( d_m=0.429m \), \( \xi_m=5^\circ \), \( p_m=2.86W \).

Four SPT-B40 LED lamps are used instead because of lacking 6.286W SPT-B series of LED lamp, the lamps are installed according to \( h_m \), \( d_m \), \( \xi_m \) and \( s_m \), and a lighting experiment is conducted, as shown in figure 4. The area between the two middle lamps is taken as the experiment measuring area, and the measuring area is divided just like the simulation experiment.

![Figure 4. Lighting experiment photo of SLD.](image)

The illuminance data of measuring points produced by SPT-B40 LED lamps should be converted into data can be compared with simulation results. The parameters \( h_m \), \( d_m \), \( \xi_m \) and \( s_m \) are defined in accordance with the geometric similarity ratio, so the dimension ratio of grid is equal to the geometric similarity ratio. The angles \( \gamma \) and \( \theta \) of the light ray from the corresponding lamp to the corresponding point on ground do not change in actual tunnel and in tunnel model according to equations (2) and (3). The same series of LED tunnel lamps have the same LDC, \( q \), \( \eta_0 \), \( \eta \) and \( M \), so, the illuminance data of actual tunnel road surface can be calculated as equation (7).

\[
E_{br} = E_{bm} \cdot C^{-2} \cdot \left( \frac{p_r}{p_m} \right)
\]

Where \( E_{br} \) is the illuminance of calculation point of the actual tunnel road surface, \( E_{bm} \) is the illuminance of measuring point of the model lighting experiment, \( p_r \) is the optimized lamp power of the actual tunnel; \( p_m \) is the lamp power of the model experiment.

Since the same series of lamps are used in the simulation experiment and the model tunnel lighting experiment, \( E_{br} \) can be get from equation (7), \( E_{br}=E_{bm}\times20/(49\times40)=E_{bm}/98 \). The illuminance data of the real tunnel road surface with SLD can be obtained only by dividing the model experiment data by 98, which indicates that it is not necessary to convert the experiment data to those of 2.86W LED, and can be compared directly with the lighting data of the tunnel lighting system with the OLPES.

According to the experimental illuminance data, in the measuring area of the tunnel road surface, \( E_{min}=2456lx \), \( E_{max}=3972lx \), \( E_{av}=3292.32lx \). On the centerline of the road surface, \( E_{cmin}=3716lx \) and \( E_{cmax}=3972lx \), OLU=0.746(>0.4), LLU=0.936(>0.6). After conversion of tunnel model lighting experiment data, \( E_{min}=25.061lx \), \( E_{max}=40.531lx \), \( E_{av}=33.595lx \). On the centerline of the road surface, \( E_{cmin}=37.918lx \), \( E_{cmax}=40.531lx \). It can be seen that the \( E_{min} \), the OLU and the LLU meet the lighting demands in the Guidelines.

4.4. Results and Analysis

From the statistical results of illumination data obtained by simulation experiment and tunnel model
lighting experiment, it can be seen that the LPOM from reference [4] is correct and can be used to optimize the lighting parameters of tunnel lighting or design energy-saving tunnel lighting system, the energy-saving study with the tunnel model lighting experiment is feasible and the experiment method and data processing method in this paper is valid.

The causes of errors: (1) There is deviation between the actual shape and sizes of the tunnel model and the theoretical similar tunnel model, and there is deviation in the installation of lamps. (2) In the model lighting experiment, the reflectivity of ultraviolet reflective cloth and gray membrane are different from that of reflective paint and concrete of the tunnel wall in the lighting simulation. (3) In the simulation experiment, the grid size of the calculation area is 74.08cm×70.83cm, the grid sizes of the measurement area of the tunnel model experiment should be 10.58cm×10.12cm, but the actual grid sizes of the tunnel model experiment are 10cm×10cm. (4) The illuminance value measured by the illuminometer is the average illuminance on an area, not the illuminance value of a grid point. (5) The tunnel model shrinks in sizes, but the sizes of lamp are not scaled down.

5. Conclusions
In this paper, a tunnel similar model was designed and constructed according to the CSS of a actual highway tunnel. According to the traffic demands of the highway tunnel lighting system and the selected LED lamps, OLPES were obtained by the LPOM for the SLD from reference. Based on the CSS and the OLPES, a simulation experiment was carried out by using DIALux. A lighting experiment system was constructed and a tunnel model lighting experiment was carried out. Comparisons between the simulation results and the tunnel model experiment results were conducted, the statistical results of illuminance from the two methods coincide well, which proves the LPOM for the SLD to save energy is correct, the tunnel model lighting experiment is feasible, the experimental study and data processing method in this paper is valid.

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