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Experimental Study on Energy-saving of Highway Tunnel Lighting with Central Lamp Distribution

Shijuan Fan[1] and Chao Yang[2,*]
[1]School of Transportation and Logistics, East China Jiaotong University, Nanchang 330013, China
[2]School of Mechatronics and Vehicle Engineering, East China Jiaotong University, Nanchang 330013, China
*Corresponding author

***Abstract*—At present, most energy-saving studies on tunnel lighting are theoretical or emulational, fewer are experimental studies. Based on optimized tunnel lamp installation parameters, a simulation experiment of tunnel lighting and a tunnel model experiment of lighting were carried out to study the energy-saving of tunnel lighting with low cost. Yanlieshan highway tunnel was selected as object, the optimized central lamp installation parameters (OCLIPs) were obtained with the lighting parameters optimization model (LPOM) on central lamp distribution (CLD) from reference on the basis of tunnel structure sizes (TSS) and selected LED lamps. Simulation experiment of the tunnel lighting was accomplished with DIALux based on the TSS and OCLIPs. A similar tunnel model was designed and built according to the TSS and similarity theory, a lighting experiment was accomplished with the similar tunnel model, and the road-surface-illuminance (RSI) data were obtained and reversely treated, and compared with the simulation experiment results, the statistical results of horizontal RSI of the two ways coincides well, which proves the correctness of the LPOM, the feasibility of the lighting experimental study with tunnel model and validity of the experiment method.**

Keywords—highway tunnel lighting; energy-saving; experimental study; central lamp distribution

I. Introduction

Due to the conservative design of many highway tunnel lighting systems in China, excessive lighting and serious power waste in the operation process have caused heavy cost burden to the tunnel operation management department. How to reduce the energy consumption of tunnel lighting has become an urgent problem to be solved. For this reason, many studies on the highway tunnel lighting problems were conducted in such aspects as energy-saving renovation[1], energy-saving control[2,3] and energy-saving parameters optimization[4-7]. However, due to the limitations of actual tunnel lighting experimental conditions, most of the studies were theoretical or emulational, lacking experimental verification.

According to the actual highway tunnel section sizes, the selected LED lamps and tunnel lighting demands, optimized lighting parameters (OLPs) will be obtained by a lighting parameters optimization model (LPOM). Based on the sizes of the target tunnel and the OLPs, a simulation experiment will be carried out. 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 according to the OLPs. 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 this paper.

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 are used in lighting parameters optimization and lighting simulation, and the tunnel model lighting experiment is completed in a tunnel similar model, and same series of LED lamps are used in the two lighting experiments, and the calculation regional grids are divided in the same way.

II. Highway Tunnel and Lamp

A. 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, and there are 1 m wide maintaining roadway at one roadside and 0.75 m wide maintaining roadway at the other roadside for the demand of traffic safety and maintenance. 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[8], 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}).

B. Tunnel Lamp

SPARK SPT-B series tunnel LED luminaires are selected as lighting lamps, their lateral light-emitting angle is 90°, longitudinal light-emitting angle is 110°, light output ratio, η_0, is 100%, color temperature (CT) is 5000K, color rendering index

(Ra) is 70 or more. The light distribution curves (LDC) of the SPT-B LED lamps are shown in Fig. 1.

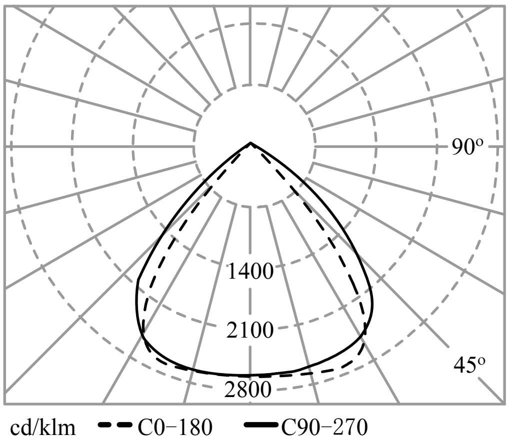

FIGURE I. LIGHT DISTRIBUTION CURVE OF SPT-B LED LAMP

III. Lighting Parameters Optimization of Tunnel

A. Basic Lighting Formula

The lamps arrangement is shown in Fig. 2, in which O_i (i=1,2,3, …) is the projection point of the tunnel lamp A_i (i=1,2,3, …) on the road surface, O is the origin of the coordinate system, that is, the center point of the calculation area $B_1B_2B_3B_4$ of the tunnel road surface, s is the longitudinal spacing of adjacent two lamps.

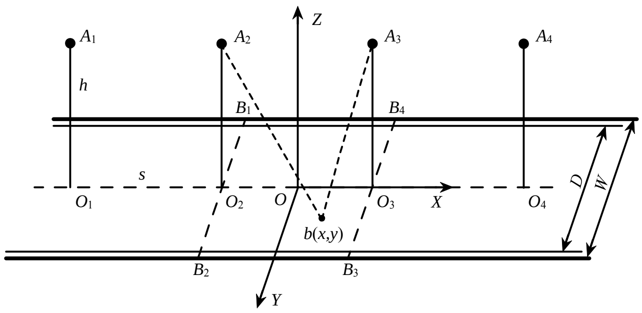

FIGURE II. SCHEMATIC DIAGRAM OF CLD

The horizontal illumination produced by lamp A_i at point b is

$$E_{bi} = h \cdot I_i(\gamma,\theta) \cdot (A_i b)^{-3} . \quad (1)$$

The angles, γ and θ, are determined by Eq. 2 and Eq.3, respectively

$$\cos\gamma = h \cdot (A_i b)^{-1} . \quad (2)$$

$$\sin\theta = X_i \cdot (A_i b \cdot \sin\gamma)^{-1} . \quad (3)$$

Where, h is the vertical height from the luminous surface center of lamp to road surface, A_ib is the distance from the luminous surface center of lamp, A_i to the point b, X_i is the component of distance O_ib in the X direction.

If photomatric data of the lamp are available, the luminous intensity of the light-direction deviating γ from the optic axis of the lamp is calculated as[6]

$$I(\gamma,\theta) = \frac{I_{1000}(\gamma,\theta)\eta_0\eta M\Phi}{1000} . \quad (4)$$

Where, I(γ, θ) is the luminous intensity of the lamp in the direction of light Ab; γ is the intersection angle of light Ab and optic axis of the lamp; θ is the intersection angle between the light distribution profile (LDP) which the light Ab is in and the LDP C0-180; $I_{1000}(\gamma, \theta)$ is the luminous intensity of the lamp from the photomatric data corresponding to γ and θ; η_0 , η, M and Φ are light output ratio, utilization factor, maintenance factor and rated luminous flux of the lamp, respectively, Φ=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[8]

$$E_b = \sum_{i=1}^{n} E_{bi} . \quad (5)$$

B. 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 η is calculated automatically in LPOM according to lighting parameters[9]. The required luminance value of the tunnel interior zone is 3.5cd/m^2. 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 17.5 lx, it is the minimum road-surface-illuminance (RSI) after the lamp's luminance decreases by 30%, so, E_0 is set to 25 lx while optimizing the lighting parameters.

According to the LPOM[6], 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 13 equal parts lengthways and 12 equal parts breadthways as shown in Fig. 3. The OLPs of CLD with SPT-B40 LED lamps in Yanlieshan tunnel are obtained, as shown in Table 1.

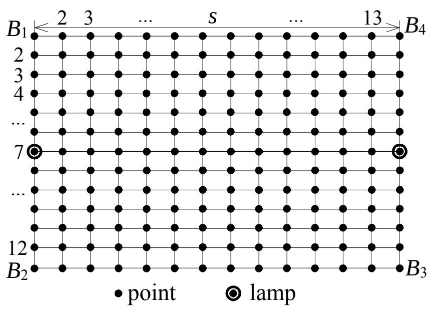

FIGURE III. DISTRIBUTION DIAGRAM OF OPTIMIZING CALCULATION POINTS

TABLE I. OLPS OF CLD

Parameter	*s* [m]	*h* [m]	*p*[W]
Parameter value	9.5	6.7	44

C. Tunnel Lighting Simulation

According to the CSS of the Yanlieshan tunnel, a simulation model is established in the DIALux software, and a simulation lighting system is established according to the OLPs in Table 1 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 Fig.3.

Parameters are obtained from the simulation experiment data, in the calculation area of the tunnel road surface, the minimum RSI, E_{min}=25lx, the maximum RSI, E_{max}=44lx and the average RSI, E_{av}=35.967lx. On the centerline of the road surface, the minimum RSI, E_{cmin}=39lx and the maximum RSI, E_{cmax}=44lx. OLU=0.695(>0.4), and LLU=0.886(>0.6). It can be seen that the E_{min}, the OLU and the LLU all meet the lighting demands in the Guidelines.

IV. LIGHTING EXPERIMENT IN TUNNEL MODEL

A. Tunnel Lighting Similarity Ratio

1) Geometric 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, $h_m=h_r/C$, and the longitudinal spacing of adjacent two lamps, $s_m=s_r/C$, where hr and s_r, are the vertical height from the luminous surface center of lamp to road surface and the longitudinal spacing of adjacent two lamps in actual tunnel, respectively.

2) Illuminance similarity ratio. 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

$$C_E = E_b / E_{b'} . \quad (6)$$

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

B. Tunnel Similar Model

The geometric similarity ratio is set to 7, the CSS of the tunnel similar model is shown in Table 2. 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.

TABLE II. CSS OF TUNNEL MODEL

Parameter	Total width[m]	Road width[m]	Height [m]	Vault arc radius[m]
Parameter value	1.46	1.214	1.07	0.77

C. 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.

1) Lighting parameters of model lighting experiment. According to the similarity ratio and the parameters in Table 1, the lighting parameters of the model lighting experiment of the CLD are obtained, h_m=0.957m, s_m=1.36m, p_m=6.286W.

2) Model lighting experiment. 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 and s_m, and a lighting experiment is conducted, as shown in Fig. 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.

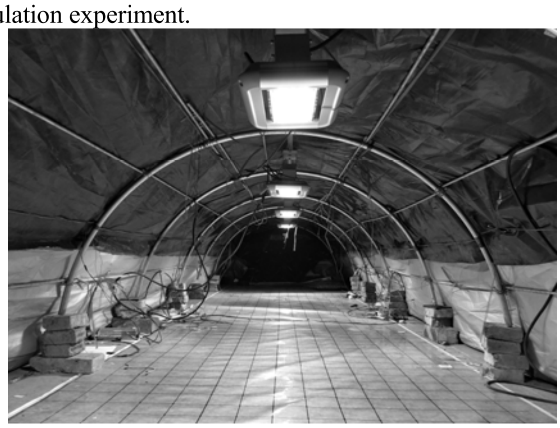

FIGURE IV. LIGHTING EXPERIMENT PHOTO OF CLD

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 and s_m are defined in accordance with geometric similarity ratio, so the dimension ratio of grid is equal to the geometric similarity ratio.

The angles γ and θ 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 Eq.2 and Eq.3. The same series of LED tunnel lamps have the same LDC, q, η_0, η and M, so, the illuminance data of actual tunnel road surface can be calculated as Eq.7.

$$E_{br} = E_{bm} \cdot \frac{p_r}{C^2 p_m}. \tag{7}$$

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, from Eq.7, $E_{br}=E_{bm}\times44/(49\times40)=E_{bm}/44.55$. The illuminance data of the real tunnel road surface with CLD can be obtained only by dividing the model experiment data by 44.55, which indicates that it is not necessary to convert the experiment data to those of 6.286W LED, and can be compared directly with the lighting data of the tunnel lighting system with OLPs.

According to the experimental illuminance data, in the measuring area of the tunnel road surface, E_{min}=1204lx, E_{max}=1915lx, E_{av}=1569.22lx. On the centerline of the road surface, E_{cmin}=1739lx and E_{cmax}=1915lx, OLU=0.767(>0.4), LLU=0.908(>0.6). After the conversion of tunnel model lighting experiment data, E_{min}=27.03lx, E_{max} =42.99lx, E_{av}=35.22lx. On the centerline of the road surface, E_{cmin}=39.04lx, E_{cmax}=42.991lx. It can be seen that the E_{min}, the OLU and the LLU meet the lighting demands in the Guidelines.

V. Results Comparison and Analysis

From the statistical results of illuminance data obtained by simulation experiment and tunnel model lighting experiment, it can be seen that the LPOM from reference[9] 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 grey film 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 10.44cm×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.

VI. Summary

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, OLPs were obtained by the LPOM of the CLD from reference. Based on the CSS and the OLPs, a simulation experiment was carried out by using DIALux. A lighting experiment system was constructed and a tunnel model lighting experiment was carried out, the experimental data were similarly converted. Comparisons between the simulation results and the tunnel model experiment results were conducted, the statistical results of illuminance from the two ways coincide well, which proved the LPOM of the CLD is correct, the tunnel model lighting experiment is feasible, the experimental study and data processing method in this paper is valid.

Acknowledgments

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References

[1] Zhang Naibin, Zhao Weibin, Ma Fei, Research on application of energy-saving reconstruction technology for lighting in highway tunnels, Technology of Highway and Transport, 2016, 32(2): 138-142.

[2] Yu Tiantian, Study on energy-saving control in the lighting system of highway tunnel, Xi'an University of Architecture and Technology, Xi'an, 2013.

[3] Yang Chao, Cheng Cui, Xu Yihang, Tunnel lighting energy-saving control based on parameter optimization of luminaire distribution, Journal of East China Jiaotong University, 2017, 34(2):128-133.

[4] Ji Jiajun, The research on parameter optimization of energy-saving illumination in three-lane highway tunnel, Chongqing Jiaotong University, Chong Qing, 2012.

[5] Huang Chuanmao, Study on luminaire installation parameters optimization of highway tunnel lighting system, East China Jiaotong University, Nanchang, 2016.

[6] Fan Shijuan, Study on parameters optimization of highway tunnel central lamp distribution, Journal of East China Jiaotong University, 2016, 33(4):67-72.

[7] Xiao Yu. Study on luminaire installation parameters optimization of threshold zone and transition zone of highway tunnel, East China Jiaotong University, Nanchang, 2018.

[8] Ministry of Transport of the People's Republic of China, JTGJ D70/2-01-2014.Guidelines for design of lighting of highway tunnels, China Communications Press, Beijing, 2014.

[9] Yang Chao, Cheng Cui, Study of utilization factor of highway tunnel luminaire, China Illuminating Engineering Journal, 2017, 28(1): 97-101.