Influence of tunnel lighting system installation modes and parameters on energy saving

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Abstract. In order to quantitatively analyze the influence of the installation mode as well as the parameters of luminaires on energy saving for tunnel lighting, particularly in regard to the installation angle, a point-by-point method was adopted so as to calculate illuminance and luminance, and a simulation analysis software was developed. The illuminance and luminance obtained by symmetrical, staggered and unilateral modes, as well as pro-beam and anti-beam configurations and different installation parameters, were quantitatively studied to evaluate effects on energy-saving. The obtained results demonstrated that the installation angle of the luminaires directly affected light efficiency when the luminaires were mounted symmetrically on both sides. Moreover, no significant difference in the quality indexes between the staggered arrangement and symmetrical arrangement were present. The illumination of the road surface was only 76% of that of the symmetrical arrangement when the luminaires were installed unilaterally. In addition, the luminance on the road surface was about 33% higher than that of the symmetrical configuration when the anti-beam configuration was adopted. The analytical conclusions attained by this study may encourage lighting designers to pay more attention to the installation parameters of luminaires and carry out on-site installation guidance.

1. Introduction
A road tunnel is a closed tubular structure that has two open portals. It is essential for drivers in overcoming the "black hole" effect when driving into a tunnel as well as the "white hole" effect when driving out of the tunnel during the day, unlike driving at night. In order to remedy "adaptation lag" present in human vision, it is mandatory to equip reasonable electric lighting in road tunnels over a certain length in order to improve driving safety. Hence, for most tunnels, the lighting system provides 24 hours of artificial light sources with a higher amount of electric power consumed during the day [1]. A survey in Europe revealed that the annual electricity consumption was 193.2 kWh·m⁻¹, and although the lighting system accounted for only 14% of the total installed power in tunnels, its energy consumption exceeded 50%[2-3].

Therefore, many areas require improvement in the lighting energy-saving technology, including conducting studies on artificial lighting sources with high luminous efficiency and new materials for paving roads that have a higher reflection coefficient than other ordinary asphalts [1]. For instance, the
EU research project, SURFACE, aims to offer the EU Standard Organization new traceable reference data representative of current road surfaces[4-5]. Additionally, European researchers have adopted a semi-transparent polyester tension structure that can be set just before the entrance to the tunnel to extend the threshold zone out of the tunnel itself to use sunlight as lighting[6-7], and light-pipes were employed in order to distribute sunlight inside tunnels[8]. In China, an intelligent control method for tunnel lighting was also studied based on traffic volume[9]. This study, however, focuses on the influence of tunnel lighting installation modes and parameters on the effects of energy-saving. Although numerous studies have channeled general-purpose software into visualizing LID files, such as DIALux, AGi32 and ProLITE[1, 10-12], this paper adopts a self-developed Computer-aided Design and Optimization Analysis Software for Road Tunnel Lighting System (TLCAD&OA). This software is based on the point-by-point algorithm and quantitatively studies the lighting effect yielded by the luminaire installation mode and parameters, exploring the most energy-saving luminaire installation mode and parameters when utilizing equivalent luminaires.

2. Materials and methods

2.1. Background materials

As a background project, Donggaoling Tunnel in Zhoushan, Zhejiang, China had an electronical upgrade project implemented in 2019 in order to improve its energy-saving performance. The tunnel has two tubes, and each tube has two lanes with a length of 1177m and operation speed limitation of 80km.h⁻¹. The cement concrete pavement was retained so as to shorten the construction time duration, and the tunnel luminaire model MA-31621-EW-W40 was adopted. Here, the input power was 39.8 W, the total luminous flux was 4043 lm, the colour temperature was 4000 K, and the size of the luminaire was 375 mm × 400 mm. In order to improve the electric efficiency, the influence of tunnel lighting installation modes and parameters is conducted.

2.2. Commonly-used algorithms

At present, commonly used calculations can be divided into two categories: the utilization coefficient curve and point-by-point methods. The former is widely used by the majority of design companies in China due to its simple operation, while the latter features a large amount of calculations, which mainly relies on software like Dialux and AGi32.

2.2.1. Utilization coefficient curve method. The average horizontal illuminance of road pavement can be calculated according to equation (1) when the utilization coefficient curve method is used.

$$E_{av} = \frac{\eta \cdot \varphi \cdot M \cdot N}{W \cdot S}$$ (1)

In equation (1), $N$ is the luminaire layout coefficient, where 2 represents the symmetrical installation mode while 1 signifies the staggered and central-line layout. $M$ is the utilization factor, which is checked by the utilization coefficient curve of the luminaire, while $W$ (m) is the tunnel pavement width and $S$ (m) is the luminaire spacing.

The weak point of this method is its low calculation accuracy. Although scholars have put forward various improvements in this regard, it is still unable to comprehensively evaluate the lighting effect and quality, such as calculating the illumination quality indicators such as luminance, overall uniformity and longitudinal uniformity.

2.2.2. Point-by-point method. The calculation principle of the point-by-point method is shown in Figure 1, which was carried out according to the following steps:

(1) First, a calculation area was defined in terms of road width and longitudinal spacing between any two luminaires of the basic lighting circuit, in which a calculation grid with $m$ rows and $n$ columns was established.
Second, luminaires within the influence area, which usually consist of the calculation area and two neighboring zones on both sides, were channeled into calculating the illuminance value of the calculation area point-by-point and luminaire-by-luminaire, as illustrated in equation (2).

Last, the illuminance value on each grid point was summarized, obtaining the average illuminance, luminance, luminance uniformity and other lighting quality indicators. 

\[
E_{\mu} = \frac{I_{c\gamma}}{H^2} \times \cos^2 r \times \frac{\phi}{1000} \times M
\]  

In equation (2), \(E_{\mu}\) (lx) refers to the horizontal illuminance value of a certain calculation point \(P\) contributed by a certain luminaire in the affected area. \(\gamma\) (°) is the vertical angle, namely, the light incident angle of the luminaire corresponding to point \(P\). \(I_{c\gamma}\) (cd) is the light intensity value extracted from the luminous intensity distribution data file (the IES file), namely, the luminous intensity table (\(I\) table) according to the horizontal angle \(c\) (°) and vertical angle \(\gamma\) (°). \(M\) is the maintenance factor of the light fixture, which is usually from 0.6 to 0.7. \(\phi\) (lm) is the rated luminous flux of the luminaire, and \(H\) (m) is the height of the luminaire light source center to the road surface. The luminous intensity distribution data file of each luminaire type was within the influence area, which is usually measured using an illuminance meter, goniometer, colorimeter or photometer and high dynamic range mapping technique, which was necessary in utilizing this method. The luminous intensity distribution data file exhibited the spatial radiation characteristics of a light source.

### 2.3. Development of the analysis program

As previously mentioned, calculation workloads performed according to the point-by-point method is very heavy, and manual calculation is not feasible. One solution involves using a currently widely-used software like Dialux and AGi32. However, such general-purpose software do not provide special tunnel lighting modeling or analysis modules, inhibiting engineers from conducting analyses for tunnel lighting. Alternatively, the present authors have developed a lighting analysis software for road tunnels (TLCAD&OA) according to the point-by-point method. Figure 2 demonstrates the software function flow chart with Figure 3 being the main interface. Accordingly, four modules were provided: the luminance and length calculation of each section, luminaire circuit and calculation parameter setting, lighting calculation and report output, and annual power consumption estimation. The output function included the luminaire layout, point-by-point calculation results, and the Surfer and Origin data exchange file. The simulation of the entire process, from lighting quality check, dimming control to energy-saving evaluation, was then realized, which avoided errors in manual calculation and is convenient for various simulation calculations and analyses.

### 3. Energy-saving effect under different installation methods and parameters

There are four main types of lighting fixture modes commonly used in road tunnel lighting systems, such as symmetrical modes on both sides, staggering mode on both sides, unilateral mode, and central-line mode, as shown in Figure 4. Different installation modes exert different effects on maintenance. In addition, the light efficiency of the luminaire is different. Taking advantage of TLCAD&OA, the parameter influence analysis of several common installation methods is conducted systematically by adjusting various lighting design parameters in order to optimize lighting system design.

#### 3.1. Optimization analysis on the installation angle of the symmetrical mode

The symmetrical mode is the most commonly used mode in road tunnels. However, in most cases, the installation angle of the luminaire is not clearly stated in the design documents. Therefore, during the actual installation process, the randomness of construction personnel is very large, resulting in the actual lighting efficiency of the luminaire not being maximized.

Figure 5 demonstrates the luminous intensity distribution data file of luminaire type of MA-31621-EW-W40 in the polar coordinate system, where the circumferential angle coordinate represents the horizontal angle of the light intensity value with the radial radius coordinate being the vertical angle.
In the interior section, the symmetrical mode was adopted, and the left and right sides were respectively set into separate circuits with a longitudinal spacing of 10m. Using TLCAD&OA, the average illuminance, average luminance and uniformity values of the different installation angles from 0 ° to 45 ° were accurately analysed (Table 1). Therefore, the installation angle directly affected the utilization efficiency of the luminaires. With the increase in installation angle, the average illuminance and luminance increased accordingly, reaching a maximum value when the installation angle was 35 °, signifying that the best lighting effect can be obtained at this time. If the installation angle was not well-controlled, such as when the installation angle was 0 °, the light efficiency loss reached 35% compared to the optimal installation angle. Moreover, the installation angle had little effect on the total uniformity and longitudinal uniformity, and the uniformity value required by the specification was achieved under various installation angles.

3.2. Comparison of staggered and unilateral modes

If the staggered mode is adopted, the sensitivity of the installation angle can also be analysed. Accordingly, when the installation angle was between 30 ° and 35 °, the average illumination and luminance were almost the same, reaching their maximum value (Figure 7). The average illuminance, average luminance, overall uniformity and longitudinal uniformity values were 68.58lx, 5.24cd·m⁻², 0.69 and 0.94, respectively. Evidently, compared to the symmetrical mode, the average illumination and luminance slightly decreased while the overall uniformity and longitudinal uniformity slightly improved, though the change range was very small at under 5%.

In recent years, for the sake of convenient maintenance, a unilateral installation mode was proposed, that is, the luminaires are mounted on one side outside the tunnel centre line, with a height of about 6m, so that they can be replaced without the interruption of traffic. In this case, the installation height was 6m and the spacing was 5m (take the half of symmetrical or staggered mode), which was 2m away from the tunnel centre line. The illuminance value and luminance value under the installation angle from 10 ° to 30 ° were then analysed. The calculation results are shown in Figures 8 and 9 below. Here, the optimal installation angle was observed to be 20 ° while the corresponding illumination and
luminance were 52.17lx and 3.99 cd·m$^{-2}$, respectively, which are only 76% of the symmetrical mode. This may have been due to the installation height of luminaires being higher than that of the symmetrical or staggered modes, leading to a decrease in the proportion of total luminous flux received by the road surface. At the same time, the overall uniformity and longitudinal uniformity were found to be 0.43 and 0.92, respectively, lower than those of the symmetrical or staggered modes, especially the total uniformity value. Therefore, in addition to convenience in operation and maintenance, the unilateral installation mode has no advantages in energy saving, though it possesses obvious disadvantages.

Figure 3. Main interface of TLCAD&OA.

Figure 4. Commonly used luminaire installation modes in the interior section.
Figure 5. Photometric figure of MA-31621-EW-W40.

Table 1. Lighting impact caused by installation angles under opposite configuration.

| Installation angle (°) | 0  | 5  | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 |
|------------------------|----|----|----|----|----|----|----|----|----|----|
| $E_{av}$ (lx)          | 42.96 | 49.33 | 54.90 | 59.81 | 63.86 | 66.87 | 68.78 | **69.41** | 68.76 | 66.86 |
| $L_{av}$ (cd·m$^{-2}$) | 3.43 | 3.90 | 4.32 | 4.68 | 4.97 | 5.17 | 5.29 | **5.30** | 5.23 | 5.06 |
| $U_o$                  | 0.73 | 0.68 | 0.65 | 0.65 | 0.66 | 0.65 | 0.65 | **0.67** | 0.71 | 0.77 |
| $U_l$                  | 0.88 | 0.93 | 0.94 | 0.91 | 0.91 | 0.91 | 0.91 | **0.91** | 0.91 | 0.92 |

Figure 6. Average luminance and installation under the symmetric mode.

Figure 7. Isogram of illuminance under the opposite and staggered configurations (unit: lx).
3.3. Analysis of pro-beam and anti-beam configurations

The threshold section is the accident-prone area, hence, it is very important to enhance lighting in order to improve visual adaptability. The usual way of accomplishing this is to mount additional high-power luminaires in the section to enhance daytime lighting. Currently, three setting modes, symmetrical lighting, pro-beam and anti-beam modes are commonly utilized. Although controversies exist regarding the functions, advantages and disadvantages between the pro-beam and anti-beam modes, this study focused on their corresponding energy consumptions. However, the luminaires of the two basic circuits were observed to remain symmetrically arranged, and the enhanced lighting Circuit C (Type 15557 with power of 200W) was also symmetrically arranged on both sides with a spacing of 2m and an installation angle of 35°. In order to simulate the pro-beam and anti-beam configurations, the luminaires of Circuit D (Type 15557 with power of 200W) were installed on the centre-line cable tray, and the lighting quality index under each installation angle was then calculated from -45° to +45°. The obtained results are provided in Table 2, demonstrating that the installation angle of the Circuit D luminaire has considerable influence on average illumination and luminance. In this case, when the installation angle of anti-beam was -30°, the average luminance value reached 133% of the symmetrical configuration. However, when the illumination of the road surface increased, the luminance did not change much.

Table 2. Lighting impact caused by the installation angles of luminaires mounted above the centre-line.

| Installation angle (°) | -50 | -40 | -30 | -20 | -10 | 0  | 10 | 20 | 30 | 40 | 50 | 60 |
|------------------------|-----|-----|-----|-----|-----|----|----|----|----|----|----|----|
| \( E_{av}(lx) \)       | 3525.65 | 3333.39 | 2930.41 | 872761.01 | 2616.58 | 2753.50 | 3050.05 | 3313.54 | 3476.32 | 3513.35 | 3478.36 |
| \( L_{av}(cd/m^2) \)  | 229.35 | 240.12 | 257.67 | 254.56 | 230.43 | 193.83 | 183.41 | 188.22 | 192.58 | 193.07 | 189.94 | 186.00 |
| \( U_o \)             | 0.52  | 0.51  | 0.48  | 0.46  | 0.46  | 0.47  | 0.53  | 0.55  | 0.56  | 0.56  | 0.57  | 0.58  |
| \( U_I \)             | 0.65  | 0.63  | 0.61  | 0.62  | 0.71  | 0.89  | 0.9   | 0.84  | 0.78  | 0.72  | 0.69  | 0.66  |

4. Conclusion

This study adopted the point-by-point method as the core algorithm, using the self-developed software to accurately evaluate the influence of the installation mode as well as the angles of the luminaires in the road tunnel. Accordingly, the present study indicated that:
(1) The installation angle of luminaires directly influences the utilization efficiency and energy saving of luminaires. By taking the luminaires as well as the installation parameters adopted in this paper as an example, the best energy efficiency was achieved when the installation angle was 35° and the light efficiency loss rate was as high as 35% at an installation angle of 0°.

(2) Compared to the symmetrical mode, the illuminance, luminance and uniformity of the staggered modes had no significant differences under the same spacing and installation angle.

(3) The illuminance of the unilateral installation mode was only 76% of that of the symmetrical mode, and the overall uniformity index was also significantly reduced. Therefore, this mode only demonstrated advantages in maintenance, but had no disadvantages in energy saving.

(4) The luminance of the anti-beam configuration was about 33% higher than that of the symmetrical lighting and pro-beam configurations, which may significantly improve energy saving and driving safety.

The conclusions drawn from this study may provide further insight regarding the installation parameters of luminaires for lighting engineers, guiding them in field construction. Notably, the quantitative installation parameters proposed in this paper were based on specific luminaires. It is known that even if the power of different luminaires is the same, their luminous intensity distribution features are not. Therefore, further analyses should be carried out for specific projects in order to provide more accurate design results. Furthermore, this study mainly utilized the exhaustive trial calculation method, obtaining the best installation angle by computing various installation angles. In future investigations, optimization analyses like mode search should be used to further improve efficiency.

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