Eye Adaptation Effect Based Study on Configuration of Tunnel Entrance Structure

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Abstract. Due to the unique nature of the tunnel as a tubular structure, an approaching motorist experiences an abrupt change in brightness under the black-hole effect. This sharp change in brightness makes the threshold zone prone to traffic accidents. It is therefore necessary to provide a dimming structure in the threshold zone to support the eye adaptation of the motorist to lower lighting levels in the interior of the tunnel. There is currently a lack of research worldwide on specific configuration parameters and types of dimming structure. This paper covers analysis of the entrance structure of a tunnel and comparison of different alternatives in non-sun-tight louver, its height and transmittance, and proposes an optimal scheme to increase traffic safety and comfort.

1. Introduction

At the tunnel entrance, brightness outside the tunnel is markedly higher than inside the tunnel. The eye of an approaching motorist will experience a sharp change in brightness [1] and cannot quickly adapt to lower lighting levels in the interior of the tunnel, i.e. "black-hole effect". This frequently causes traffic accidents. Consequently, bright light the threshold zone should be dimmed to reduce temporary vision error due to abrupt changes in brightness by mitigating the brightness difference between the interior and exterior of the tunnel, so that the motorist can drive a vehicle comfortably.

Currently, main dimming measures for highway tunnel approach are to use dimming structure and vegetation. Though using vegetation for dimming is economical and practical, the survival rate of vegetation is constrained by geological conditions and its dimming effect is limited, so this measure should be auxiliary in medium and long terms. Therefore, dimming structure is frequently used in engineering practice to reduce the brightness at tunnel entrance.

Prior research has been done on dimming structure. Weng Ji [3] at Chongqing University analyzed the type, advantages, disadvantages and applicability of dimming structure for tunnel. Yang Gongxia [4] at Tongji University investigated sunshades with different transmittance based on Dapu Road Tunnel in Shanghai and gave recommended transmittance for sunshades. Ao Minxia [5] studied the light transition effect in the threshold zone of Xincheng Tunnel, compared structural types of sunshades in dimming performance and economy and determined the form of dimming structure at the portal of Xincheng Tunnel.
There is currently a lack of research on specific configuration parameters and types of dimming structure. In response, this paper covers analysis of the entrance structure of an actual tunnel project using optical analysis program DIALux4.13 and comparison of different alternatives in non-sun-tight louver, its height and transmittance, and proposes an optimal scheme to increase traffic safety and comfort.

2. Project Overview
The background project, Shijialing Tunnel of Yangcheng-Manghe Expressway, is located in Yangcheng County, Jincheng City, Shanxi Province. It is one of the provincial highways linking the provinces of Shanxi and Henan. It is connected to Jiyuan-Luoyang Expressway S93 in Henan. Shijialing Tunnel is oriented in north-south direction with its entrance at 112°3′E and 35°N, oblique cut portal and design speed of 80km/h.

Vegetation outside the Shijialing Tunnel is good and beneficial to dimming. A fully closed sunshade does not allow sunlight to directly reach the pavement. Embedding transparent or semitransparent materials can produce good shading effect by making light uniformly distributed on pavement. In addition, it can reduce erosion of pavement and subgrade due to rain or snow by preventing vehicles from sliding on wet pavement. Therefore, sunshade is selected as the dimming structure in this study.

The sunshade is designed to be 60m long, 11.46m wide and 7.55m high, with 200mm wide longitudinal steel joists at a spacing of 3m. The bottom of the sunshade is 1.1m high concrete foundation. The light-proof part is made from stainless steel screen and color steel plate. The transparent part is made from polycarbonate (PC) solid sheets and 10mm thick. The PC solid sheets are highly resistant to ageing [6], adaptable to natural environment and allow easy control of light transmittance.

3. Computational Model
Based on structural parameters of the sunshade, we built a model using optical analysis program DIALux4.13, as shown in Fig. 1-2, to study its non-sun-tight louver location and configuration parameters. Invariables set for each structure in the model are as follows: transmittance is 0% and reflectance is 40% for the light-proof part; the reflectance is 5% for the transparent part. The simulation is based on 8:30-16:30 on summer solstice and winter solstice in sunny and cloudy weather.

4. Selection of non-sun-tight louver for the Sunshade
In order to find the optimum non-sun-tight louver location for the sunshade we compare three locations - bottom, central and top, as shown in Fig. 3. Taking into account specific dimensions of the sunshade we select maximum length of the non-sun-tight louver as 2.5m and transmittance as 30%.
4.1. Analysis of road average brightness

We built a numerical model to simulate the road average brightness under the sunshade with different locations of non-sun-tight louvers on summer solstice and winter solstice, and plotted the results, as shown in Fig. 4-7.

As shown in Fig. 4-7:

- Throughout the sunny day of summer solstice the road average brightness with non-sun-tight

louvers at the bottom and central locations changes in an overall U shape, with the minimum value observed at 12:30; the road average brightness with non-sun-tight louvers at the top rises before falling, peaking at 12:30;

- throughout the cloudy day of summer solstice the road average brightness with non-sun-tight louvers at the three locations rises before falling; and at any time in the day, the road average brightness level shows the following pattern: top > central > bottom;
- throughout the sunny day of winter solstice the road average brightness with non-sun-tight louvers at the top rises before falling, peaking at 12:30 when non-sun-tight louvers are at the central and bottom locations and at 12:30 when they are at the top;
- throughout the cloudy day of summer solstice the road average brightness with non-sun-tight louvers at the three locations rises before falling; and at any time in the day, the road average brightness level shows the following pattern: top > central > bottom;
- to display the result of numerical simulation in greater detail, we organized the road average brightness values in all conditions into Table 1.

|                | 8:30 Sunny | 8:30 Cloudy | 10:30 Sunny | 10:30 Cloudy | 12:30 Sunny | 12:30 Cloudy | 14:30 Sunny | 14:30 Cloudy | 16:30 Sunny | 16:30 Cloudy |
|----------------|------------|-------------|-------------|-------------|------------|-------------|------------|-------------|------------|-------------|
| Bottom         | 409        | 65          | 103         | 95          | 89         | 107         | 104        | 96          | 366        | 67          |
| Summer solstice|            |             |             |             |            |             |            |             |            |             |
| Winter solstice| 48         | 17          | 173         | 47          | 76         | 58          | 119        | 47          | 71         | 17          |
| Central        | 625        | 92          | 570         | 134         | 115        | 149         | 570        | 135         | 507        | 94          |
| Summer solstice|            |             |             |             |            |             |            |             |            |             |
| Winter solstice| 34         | 24          | 261         | 66          | 153        | 81          | 183        | 65          | 60         | 24          |
| Top            | 179        | 110         | 805         | 160         | 1109       | 179         | 732        | 162         | 127        | 113         |
| Summer solstice|            |             |             |             |            |             |            |             |            |             |
| Winter solstice| 31         | 29          | 80          | 79          | 228        | 97          | 163        | 79          | 58         | 29          |

In accordance with provisions on the brightness of tunnel threshold zone in the Guidelines for Design of Lighting of Highway Tunnels (JTG-T-D702-01-2014) [7], the part within the length of the sunshade is defined as the tunnel threshold zone 1 (TH1). Its brightness is calculated from $L_{th1} = k \cdot L_{20}(S)$ where $k$ is brightness reduction coefficient for the threshold zone, taken as 0.035 for a 80km/h highway; $L_{20}(S)$ is brightness outside the tunnel, taken as 2500cd/m² for an oblique cut portal. Thus $L_{th1}$ is calculated at 87.5 cd/m², i.e. the lower limit of average brightness for approach 1. This value is the empirical value when sunlight is brightest and should be compared to conditions on the sunny day of summer solstice. The brightness level that allows for comfortable visibility should be within 2-6 times the lower limit, i.e. the range of 175cd/m²-525cd/m², so that the motorist can drive a vehicle safely and comfortably.

As shown in Table 1, the minimum road brightness on the sunny day of summer solstice with non-sun-tight louvers at each of the three locations meets required $L_{th1}$ prescribed in Guidelines. When non-sun-tight louvers are located at the bottom, the maximum road average brightness is in the range of brightness that provides comfortable visibility. Road average brightness at 8:30-10:30 and 14:30-16:30 when non-sun-tight louvers are at the central location and at 10:30-14:30 when they are at the top exceeds to varying degrees the range of brightness that provides comfortable visibility. Therefore, non-sun-tight louvers at central and top cannot effectively control and reduce road average brightness.
4.2. Analysis of pseudocolor image

Because the location of non-sun-tight louvers selected influences both where sunlight arrives on the pavement and whether the motorist can drive a vehicle safely and comfortably, we select some time points at which wide “zebra stripes” appear on the pavement with non-sun-tight louvers at different locations for further comparison. When non-sun-tight louvers are at the top, we select 12:30 and 14:30 on the sunny day of summer solstice. When non-sun-tight louvers are at the central location, we select 10:30 and 14:30 on the sunny day of summer solstice. When non-sun-tight louvers are at the bottom, we select 8:30 and 10:30 on the sunny day of summer solstice. The pseudocolor images are given in Fig. 8-13.

![Figure 8](image1)
Title: Pseudocolor image on sunny day of summer solstice with non-sun-tight louvers at central location (10:30)

![Figure 9](image2)
Title: Pseudocolor image on sunny day of summer solstice with non-sun-tight louvers at central location (14:30)

![Figure 10](image3)
Title: Pseudocolor image on sunny day of summer solstice with non-sun-tight louvers at the top (12:30)

![Figure 11](image4)
Title: Pseudocolor image on sunny day of summer solstice with non-sun-tight louvers at the top (14:30)

![Figure 12](image5)
Title: Pseudocolor image on sunny day of summer solstice with non-sun-tight louvers at the bottom (8:30)

![Figure 13](image6)
Title: Pseudocolor image on sunny day of summer solstice with non-sun-tight louvers at the bottom (10:30)

As shown from the above pseudocolor images, non-sun-tight louvers will generate longitudinal light strips on the carriageway whether they are located at the central or top (especially so when they are at the top). The uniformly-spaced steel joints will project wide “zebra” strips in sharp contrast in brightness to surrounding pavement onto the pavement. This makes the motorist driving a vehicle uncomfortable and prone to glare. In the pseudocolor image with non-sun-tight louvers at the bottom (8:30), the longitudinal light strip is relatively wide and projected to the carriageway but has little...
impact on the motorist's visual comfort because of the low road average brightness at this time point. In the pseudocolor image with non-sun-tight louvers at the bottom (10:30), the longitudinal light strip is on the inspection walkway on one side of the sunshade and off the carriageway, hence having little impact on vehicle operation.

4.3. Analysis of pseudocolor image
From analyses of road average brightness and pseudocolor images with non-sun-tight louvers at three different locations, the following conclusions can be drawn: within the simulated periods of time the road average brightness with non-sun-tight louvers at the bottom meets the Guidelines' requirements and within the brightness range that provides visual comfort; the pseudocolor image with non-sun-tight louvers at the bottom shows a "zebra" strip on the inspection walkway beside the road, having little impact on motorists driving on the carriageway. Thus non-sun-tight louvers should be located at the bottom.

5. Selection of Configuration Parameters for Non-sun-tight louvers of the Sunshade

5.1. Determining the length of non-sun-tight louver
In order to determine the suitable length of non-sun-tight louvers when they are located at the bottom, we selected three alternatives - 1.5m, 2m and 2.5m - and built a model for analysis, still using 30% transmittance.

In this simulation we analyze the road average brightness with the three length options on a sunny day of summer solstice so as to facilitate comparison with the road average brightness specified in the Guidelines for Design of Lighting of Highway Tunnels (JTG-T-D702-01-2014). The road average brightness curves are shown in Fig. 14 and Table 2.

![Figure 14. Road average brightness curves on sunny day of summer solstice](image)

As shown in Fig. 14 and Table 2, the longer the non-sun-tight louver, the higher the road average brightness level; the minimum value of road average brightness with each of the three lengths occurs at 12:30; only when the length of non-sun-tight louver is 2.5m can the brightness satisfy the 87.5cd/m² brightness specified by the Guidelines for Design of Lighting of Highway Tunnels (JTG-T-D702-01-2014).
When the length is 2.5m the road average brightness is maximum at 8:30 but still within the range of brightness that provides visual comfort for human eye. To demonstrate more clearly changes in road brightness on lane cross-section at 12:30 with different lengths of non-sun-tight louver, we select a lane cross-section in the middle of the sunshade for analysis, as shown in Fig. 15.

As shown in Fig. 15, the brightness levels are the highest at all locations when the length of non-sun-tight louver is 2.5m and close to the brightness value specified in the Guidelines. At the lane centerline, the brightness levels are too low when the length of non-sun-tight louver is 1.5m and 2m. Comprehensive comparison suggests the length of non-sun-tight louver should be 2.5m.

5.2. Determining transmittance

In order to determine the suitable transmittance when the non-sun-tight louver is located at the bottom and 2.5m long, we selected three alternatives - 30%, 40% and 50% - and built a model for analysis. We analyze the road average brightness with the three transmittance options on a sunny day of summer solstice so as to facilitate comparison with the lower limit of the road average brightness specified in the Guidelines for Design of Lighting of Highway Tunnels (JTG-T-D702-01-2014). The road average brightness curves are shown in Fig. 16. Meanwhile, in order to consider brightness levels under adverse sunlight conditions we simulated road average brightness with the three options on a cloudy day of winter solstice, as shown in Fig. 17.

As shown in Fig. 16 and 17, As transmittance increases the road average brightness in each of the three options rises; on a cloudy day of summer solstice the minimum road average brightness in each
of the three options appears at 12:30; on a cloudy day of winter solstice the maximum road average brightness in each of the three options appears at 12:30.

To clearly reflect detail values of brightness we prepared a table that displays road average brightness values at each time point simulated on a sunny day of summer solstice and on a cloudy day of winter solstice, as shown in Table 3. As shown, the road average brightness with each of the three transmittance values at each time point on the sunny day of summer solstice satisfies the lower limit of 87.5cd/m$^2$ specified in the Guidelines for Design of Lighting of Highway Tunnels (JTG-T-D702-01-2014); and the maximum road average brightness is within the range that provides visual comfort. On the cloudy day of winter solstice the road average brightness at each time point simulated at 50% transmittance transitions relatively smoothly to the luminance level in the transition zone. Therefore, the transmittance should be 50%.

Table 3. Road average brightness at different times of sunny day of summer solstice and cloudy day of winter solstice with three transmittance values (unit: cd/m$^2$)

| Time     | Sunny day of summer solstice | Cloudy day of winter solstice |
|----------|-----------------------------|-------------------------------|
|          | 8:30                         | 10:30                         |
|太阳日     | 30%                          | 409                           |
| 30%      | 409                          | 17                            |
| 40%      | 507                          | 19                            |
| 50%      | 610                          | 23                            |

5.3. Summary
From analyses of road average brightness with different length and transmittance values of non-sun-tight louvers on sunny day of summer solstice and cloudy day of winter solstice we conclude the road average brightness is suitable when the length of a non-sun-tight louver is 2.5m and the transmittance is 50%. These are optimum configuration parameters of non-sun-tight louvers for sunshade.

6. Conclusions
In this paper we used the optical analysis program DIALux4.13 to investigate dimming structure at the entrance to Shijialing Tunnel by comparing different options of non-sun-tight louver location, length and transmittance. Based on these comparisons we proposed an optimum scheme: when non-sun-tight louvers are located at the bottom, 2.5m long and of 50% transmittance, the road average brightness under the sunshade is suitable, supports eye adaptation and assures the visual comfort and safety of approaching motorists.

Providing a dimming structure can eliminate the need for enhanced lighting in the transition zone and hence reduce energy consumption by tunnel operation and accomplish zero carbon emissions for tunnel lighting in line with the philosophy of sustainable, green tunnel development. The proposed solution is economical and suitable for wider application.

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