Dynamic characteristics of external luminance of highway tunnel in cold area

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Abstract—The external luminance of highway tunnels in cold areas is a key parameter for the lighting design of the tunnel entrance section. Due to the influence of the tunnel portal form, tunnel orientation, solar radiation intensity and solar irradiation angle, the external luminance of the tunnel varies with different seasons and different times. At present, there are relatively few studies on the time-varying characteristics of the external luminance of highway tunnels in cold areas. Relying on the Wunvfeng extra-long tunnel, combined with different tunnel opening orientations, the changes in the luminance of the tunnel exterior with time under several typical weather conditions are analyzed. The dynamic characteristics of the external luminance outside the tunnel in the cold area was obtained, which provide more detailed and reliable data for tunnel design. It has reference value for the lighting design and operation control of the entrance section of the tunnel and the design of light reduction outside the tunnel.

1. INTRODUCTION

As an important indicator reflecting the light environment outside the tunnel, Adaptation Luminance is one of the important benchmark data for tunnel lighting system design. Whether the luminance value outside the tunnel is determined reasonably or not has a great influence on the investment of lighting facilities and the cost of operation and maintenance. For example, a comparative analysis has been conducted in the design of the Tokyo Bay Subsea Tunnel in Japan [1]. Under the same other conditions, the external luminance of the tunnel is respectively set to 4000 cd/m² and 6000 cd/m². Under the external luminance of 6000 cd/m², the equipment cost is 34% higher than that of 4000 cd/m². The annual lighting power consumption is 30% more in the case of 6000 cd/m² [2]. Therefore, on the premise of satisfying the safety and comfort of driving, a reasonable determination of the luminance value outside the tunnel is of great significance to reduce equipment investment and reduce lighting energy consumption. [3] The external luminance of the tunnel is not a fixed value.
a reference [5]. The luminance value of the outside of the tunnel in the "Japanese Tunnel Lighting Standard" is based on Yoshikawa measurement of a typical highway tunnel located in the mountainous area of central Japan for a continuous year, and the average value of the outside luminance of the tunnel is given [6].

In order to obtain the luminance outside the tunnel entrance in different regions, it is necessary to test the luminance outside the tunnel entrance in a large area. For a long time, it is possible to obtain a representative and suitable luminance parameter in a certain area [7]. There was few such a large number of long-term luminance test data of outside tunnels as the basis for formulating standards. In fact, different geographical locations, different light, climate conditions, different materials and reflection properties of the tunnel portal elements, the luminance of surface vary greatly.

There is obvious luminance characteristics of dynamic changes outside the tunnel. The external luminance of the tunnel is affected by many factors such as local light environment, climate conditions and different seasons, and has obvious characteristics of dynamic changes. Relying on the Wunvfeng tunnel, the regularity of the luminance outside the tunnel under different weather condition was analyzed. The research provides references for tunnel designing, operation controlling of highway tunnels in cold areas.

2. PROJECT OVERVIEW

Wunvfeng tunnel is the longest road tunnel in Northeast of China, which is a key project of the Ji'an-Tonghua section of the Ji'an-Shuangliao expressway. It is located on the south side of the southwest section of the Laoling Mountains in the southeast of Jilin province and the northwest of the Yalu River. The tunnel is a two-way four-lane separated super long tunnel with a total length of 7930m in the left tunnel and 7871m in the right tunnel. The designed driving speed is 80km/h. In winter, the vegetation in the area where the tunnel is located almost wither, and there is snow, which causes the reflectivity of the environment outside the tunnel to increase. Especially in the case of exposure to sunlight, the increase in reflectivity is more obvious, as shown in Figure 1.

![Fig. 1 Snow outside the tunnel in winter](image)

3. THE TRAJECTORY OF THE SUN IN DIFFERENT SEASONS

During the year, due to factors such as the earth's revolution and rotation around the sun, the position of the sun in the sky also changes constantly. Which result in the luminance of the environment outside the tunnel changes with the seasons. In summer and autumn, the ambient luminance outside the tunnel is higher, and in spring and winter, the ambient luminance outside the tunnel is lower. Similarly, during the day, the luminance outside the tunnel also changes regularly over time. Therefore, it is necessary to carry out research on the temporal and spatial distribution of environmental luminance outside the tunnel based on the latitude and longitude of the tunnel entrance, the orientation of the tunnel entrance, and the vegetation condition of the tunnel entrance to provide basic information for the dimming structure outside the tunnel.
4. CALCULATION MODEL OF THE LUMINANCE OUTSIDE THE TUNNEL

4.1. Establishment of Calculation Model
During the calculation of the luminance outside the tunnel, the position of the sun is determined according to the latitude, longitude and time of the tunnel entrance. The three-dimensional calculation model is established according to the calculation method of the tunnel lighting specification for the luminance outside the tunnel. Use the geometric information of the tunnel to build a three-dimensional model of the tunnel, and then import the three-dimensional model into the lighting calculation program, and assign the corresponding material to each object. As shown in Figure 3.

![Fig. 3 The calculation model of the luminance outside the tunnel](image)

In the calculation and statistics of the external luminance of the tunnel, the illuminance of the road surface, the mountain and the portal included in the 20° cone of the human eye are respectively counted, and then converted into the luminance according to the surface reflection characteristics of each part of the object, and then weighted to calculate the external luminance.

4.2. Type of sky
Under different weather conditions, the radiation intensity of sunlight is different, and its influence on the luminance of the tunnel is also different. The sky types are divided into sunny, cloudy, and general weather types.

| Weather   | Possibility of direct sunlight | Maximum possible luminance (cd/m²) | Description               |
|-----------|-------------------------------|-----------------------------------|----------------------------|
| Sunny     | Yes                           | 7000                              | No cloud                   |
| Cloudy    | No                            | 1000                              | heavily clouded            |
| Mixed weather | No                           | 3000                              | Between cloudy and sunny   |

![Fig. 2 The track of the sun in the sky in a year](image)
4.3. Calculation conditions
Select the summer solstice and winter solstice periods to establish calculation conditions for the most unfavorable sunny weather for driving, as shown in Table 2. The openings of the tunnel face east, south, west and north respectively.

### TABLE II. CALCULATION CONDITIONS

| Calculation conditions | Parameters                   |
|------------------------|------------------------------|
|                        | Time        | Weather | Tunnel direction |
| A1                     | Summer solstice | Sunny   | East            |
| A2                     | Summer solstice | Sunny   | South           |
| A3                     | Summer solstice | Sunny   | West            |
| A4                     | Summer solstice | Sunny   | North           |
| B1                     | Winter solstice | Sunny   | East            |
| B2                     | Winter solstice | Sunny   | South           |
| B3                     | Winter solstice | Sunny   | West            |
| B4                     | Winter solstice | Sunny   | North           |

5. RESULT ANALYSIS

5.1. The Characteristics of Luminance Variation Outside the Tunnel in Sunny summer solstice
According to calculations in different seasons and different weather conditions, the luminance changes outside the tunnel with different orientations on the summer solstice are obtained. It can be seen from the calculation results that the change trend of the luminance outside the tunnel in different directions is basically the same, but the time to reach the peak is different, and the maximum luminance is also quite different.

The luminance change of the tunnel outside the tunnel entrance facing north is parabolic, reaching the maximum luminance at 12:00 noon, which is 3166 cd/m², as shown in Figure 4. The luminance change of the tunnel outside the tunnel entrance to the south is also roughly parabolic. The solar radiation intensity is the highest at 12:00 noon, and the luminance reaches the maximum luminance, 3471 cd/m², as shown in Figure 5.

![Fig. 4 The luminance of the tunnel entrance facing north in sunny summer solstice](image-url)
The luminance of the road surface outside the tunnel and the luminance of the tunnel entrance are greatly affected by the direction of the tunnel entrance. The luminance of the tunnel with the tunnel entrance facing east is higher in the morning than in the afternoon, and the luminance outside the tunnel is higher in the morning, reaching the maximum luminance at 10:00 in the morning, which is 3785 cd/m², as shown in Figure 6. The west-facing tunnel has a higher luminance value in the afternoon than in the morning, and the maximum luminance outside the cave at 13:00 in the afternoon is 3258 cd/m², as shown in Figure 7.
5.2. The Characteristics of Luminance Variation Outside the Tunnel in Sunny summer solstice

According to the calculation of the sunny weather conditions in winter solstice, the luminance of the outside of the tunnel with different openings facing the tunnel on the winter solstice is calculated. According to the results, the changing trend of the external luminance of the tunnel with different openings is basically the same, but the time to reach the peak is different, and the maximum luminance is different. For the tunnels with the entrance to the north and south, the luminance change trend of the outside of the tunnel is relatively close, and both reach the maximum at 12:00. The tunnel with the entrance to the north is 1729 cd/m², and the tunnel with the entrance to the south is 3143 cd/m², as shown in Figure 8 and Figure 9. Affected by solar radiation, the luminance of the tunnel opening towards the south is higher.

![Fig. 8 The luminance of the tunnel entrance facing north in sunny winter solstice](image)

The luminance calculation result of the tunnel entrance facing east was obviously higher outside the tunnel in the morning, reaching the maximum value at 11:00 in the morning, which is 2051 cd/m². The west-facing tunnel has a higher luminance outside the tunnel in the afternoon, reaching the maximum value at 13:00 in the afternoon, which is 2103 cd/m², as shown in Figure 10 and Figure 11.

![Fig. 9 The luminance of the tunnel entrance facing south in sunny winter solstice](image)
6. CONCLUSIONS

6.1. The Characteristics of Luminance Variation Outside the Tunnel in Sunny summer solstice
The luminance outside the tunnel has a certain impact on the traffic safety and lighting energy consumption of the tunnel. Through numerical calculations, this paper analyzes the luminance changes of tunnels with different openings in certain seasons. The following conclusions can be drawn:

- The luminance outside the tunnel varies with time, and the time of reaching the maximum value is also different. The measured value at a certain time cannot be used to replace the external luminance of a period.
- In terms of different seasons, the maximum luminance outside the tunnel in summer solstice is 3471 cd /m², and which in winter solstice is 3143 cd /m². At other times, the luminance outside the tunnel is less than that in the summer solstice. Therefore, the main consideration is the luminance outside the tunnel in summer solstice when designing tunnel lighting and dimming outside the tunnel.
- As for the direction of the entrance, at the exit of the tunnel facing east in the morning and tunnel facing west in the afternoon, the sunlight is strong, which is extremely detrimental to driving safety. Therefore, the influencing factors such as vehicle speed and the luminance level outside the tunnel should be considered comprehensively, and appropriate light reduction measures should be taken into account, in the tunnel design stage.
In other weather conditions such as mixed and cloudy days, the luminance outside the tunnel is less affected by the orientation of the tunnel.

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REFERENCES
[1] J. B. Hu, C. Jiang, and X. J. Gao, “Analysis of tunnel lighting brightness in high altitude area based on driving workload,” Tunnel Construction, vol. 40, pp. 1–9, May 2020.
[2] Z. Li and Q. X. Zhang, “The optimization research of tunnel lighting design in high altitude area,” Shanxi Architecture, vol. 43, pp. 101–102, Dec 2017.
[3] Y. Tu, S. F. Wang and L. Hou, “Research on access zone luminance L20(S) of road tunnel in southwest mountainous areas of Zhejiang Province,” ZHAOMING GONGCHENG XUEBAO, vol. 22, pp. 34–41, Oct 2011.
[4] C. H. Sun, C. Y. Yang, and Z. L. Chen, “Research on environment luminance at tunnel portal based on theory of luminous climate,” ZHAOMING GONGCHENG XUEBAO, vol. 22, pp. 9–17, Jun 2011.
[5] C. C. Wang and M. F. Wan, “Study on luminance L20(S) outside of tunnels of expressway in Liaoning Province,” Highway Tunnel, vol. 10, pp. 27–29, Mar 2013.
[6] J. Weng and T. Zhang, “Method of determining typical elements’ luminance at tunnel portals according to the data of luminous climate,” Journal of Civil, Architectural and Environmental Engineering, vol. 37, pp. 120–127, Dec 2015.
[7] M. Deng and F. Zhang, “Method obtaining scenery luminance outside tunnel portals with in-situ testing,” Journal of Civil, Architectural and Environmental Engineering, vol. 38, pp. 118–122, Jun 2016.