Study on Luminance in the Threshold Zone of Highway Tunnel

Wenwei Chang¹, Zihao Wang⁎², Bingyin Jing¹ and Fei Ma³

¹Yangcheng-Manghe Expressway Co., Ltd. of Shanxi Road & Bridge Construction Group, Yangcheng, Shanxi, 030006, China
²College of Civil Engineering, Chongqing Jiaotong University, Chongqing, 400074, China
³China Merchants Chongqing Communications Technology Research & Design Institute Co., Ltd., Chongqing, 400067, China
⁎Corresponding author’s e-mail: 2518140585@qq.com

Abstract. Currently, highway tunnel development is on the upswing. As an important guarantee for traffic safety in highway tunnel, tunnel lighting has a short history of research. Since the 1960s when tunnel lighting began to become a subject of research, it was gradually and profoundly realized that lighting at the tunnel threshold zone was the focus of the entire tunnel lighting. This paper provides a review on past research into tunnel lighting and findings, and then introduces the latest theory and calculation methods regarding the luminance in the threshold zone of highway tunnel with a view to giving some valuable reference for engineering practice.

1. Introduction
Tunnel construction has a long history, but highway tunnels have not appeared on a large scale until the 1960s [1]. Prior to the mid-1950s, insufficient attention was given to tunnel lighting because of low traffic volume and low travel speed in highway tunnels. Since the mid-1950s, the traffic volume of highway tunnels has increased gradually and travel speeds have also increased accordingly, thus leading to more and more traffic accidents. Until then it was actually realized how important tunnel lighting is to traffic safety and that the problem cannot be solved just by providing some lighting fixtures at will.

In 1957, Waldram [2] described the "black-hole phenomenon" in the threshold zone of a tunnel and studied its hazard and severity. It is more clearly realized that the threshold zone is the key for tunnel lighting. Therefore, determination of the luminance in the threshold zone has been the focus of research. In the 1960s, people made a preliminary exploration around the steady-state vision adaptation theory. Based on the experimental results, human eye vision-oriented methods for determining the brightness of the entrance section were gradually developed, mainly including the L20 method and perceived contrast method based on equivalent veiling theory.

2. Preliminary Exploration Based on Steady-State Visual Adaptation Theory
In 1964, Schreuder published a paper entitled The Lighting of Vehicular Traffic Tunnels, which for the first time provided a systematic description of lighting in the threshold zone of a tunnel [3]. To solve the lighting problem in the threshold zone he carried out theoretical exploration and basic experiments.
on luminance requirements on road surface in the threshold zone. The results of the experiments thus obtained are shown in Fig. 1, as relationships between the luminance of the standard field (L₁) and the luminance of the background (L₂) against which the object is just to be perceived.

Japanese scholar Narisada has carried out similar investigations in his laboratory under similar conditions to those of Schreuder's experiments [4]. However, due to different values taken as luminance in the threshold zone, the results obtained by Schreuder are higher than those by Narisada. If their visual adaptation conditions, object size and contrast are normalized, it can be found that both results agree with each other within the limits of experimental accuracy.

![Figure. 1 Relationships between luminance inside the tunnel L₂ and luminance outside the tunnel L₁](image)

In 1973, based on Schreuder's theoretical research and experiment results and existing practical experience, International Commission on Illumination issued a tunnel lighting report entitled *International Recommendations for Tunnel Lighting* (CIE 26-1973) [5].

In 1982, Adrian [6], based on research findings in neurophysiology and rhodopsin, noted that Schreuder's experiment results are problematic: the actual state of an approaching driver's visual adaptation is very different from the state assumed in the experiments.

In 1983, Schreuder noted in his paper *Entrance Lighting for Road Traffic Tunnels* that the contents of CIE 26-1973 International Commission on Illumination developed on the basis of his research results should be re-examined. In reality, scenery outside the tunnel consists of road surface, mountains and vegetation, all of which vary in luminance. However, Schreuder used uniform luminance of the experimental screen to simulate the scenery outside the tunnel and gave too much weight to the luminance of the road surface at the portal in the calculation of luminance outside the tunnel, thus leading to an unnecessarily high luminance in the threshold zone and exceeding the actual requirement. Therefore, the experiment results cannot be directly applied in engineering practice. Practical experience shows that the design performed according to CIE 26-1973 will result in too high energy consumption by tunnel operation with an increasing number of tunnels annually, which is not allowed in the economic situation background at that time. On the other hand, several long tunnels well known worldwide at the time were not designed in accordance with CIE 26-1973 but functioned well.

### 3. Method for determining the luminance of the threshold zone

In 1985, International Commission on Illumination issued the *Tunnel Entrance Lighting —A Survey of Fundamentals for Determining the Luminance in the Threshold Zone* (CIE61-1984). This report focuses on enhanced lighting in the threshold zone [7]. It reconfirms the validity and reliability of the basic experiments carried out by Schreuder, involving mainly the influence of object size, presentation time and recognition rate on tunnel entrance lighting. On the basis of the experimental results, a
method for determining the luminance of the threshold zone based on the L\textsubscript{20} method and perceptual contrast method based on the equivalent light curtain theory have been gradually developed.

### 3.1. L\textsubscript{20} method to determine the luminance of the threshold zone

#### 3.1.1. Definition and calculation method of L\textsubscript{20}

As shown in Figure 2, at the reference point located in the center of the approaching lanes at a height of 1.5m and at a distance from the entrance of the tunnel equal to one stopping sight distance (SD), an observer projects a cone with a cone angle of 20° (2\times10°) toward the tunnel entrance. The axis of the cone passes through a point at h/4 on the centerline of the vertical plane of the tunnel entrance. L\textsubscript{20} is the average luminance of all objects on the ground surface, road surface, portal, mountains, etc. within the cone.

![Figure 2 Schematic diagram of L\textsubscript{20}](image)

The L\textsubscript{20} method is based on static vision theory, often represents the state of an approaching driver’s visual adaptation at the reference point, it is simple in calculation mode and easy to perform. There are three methods to determine L\textsubscript{20} values: table method, environmental sketch method and blackness method.

- In the table method, the luminance outside tunnel is estimated based on the percentage of sky to a 20° conical field of view, portal orientation and traveling speed.
- The environmental sketch method is based on the luminance of the scene outside the tunnel in a 20° field of view multiplied by the area percentage of various scenes, and then the calculated values of each part are added to obtain the luminance outside the tunnel, as shown in Figure 3. If there is a reference value of the luminance of the tunnel location at the beginning of the design, the process of determining the luminance outside the tunnel by the environmental sketch method is relatively simple. If there is no reference data at the beginning of the design, it can be measured in the field or recommended by CIE 88-1999 [8] Scene brightness.

L\textsubscript{20} is calculated by means of the following Eq. 3.1:

\[
L_{20} = \gamma L_c + \rho L_r + \varepsilon L_e + \tau L_{th}
\]  
(3.1)

- \(L_c\) is luminance of the sky; \(\gamma\) is % of sky in the 20° field; \(L_r\) is luminance of the road; \(\rho\) is % of road; \(L_e\) is luminance of the surroundings; \(\varepsilon\) is % of surroundings; \(L_{th}\) is luminance of the threshold zone; \(\tau\) is % of tunnel entrance and \(\gamma + \rho + \varepsilon + \tau = 1\).

In general, the formula for calculating L\textsubscript{20} can be simplified as Eq. 3.2:

\[
L_{20} = \gamma L_c + \rho L_r + \varepsilon L_e
\]  
(3.2)
As shown in Figure 2, the blackness method takes a black and white photo with the conical axis as the line of sight. A standard gray plate is erected next to the opening as a reference. While taking a picture, the luminance of the standard gray plate is measured with a luminance meter, and the processed film is placed in black. The blackness of each scene in the 20° field of view is read on the meter, and the average blackness is calculated from the weights. Then the luminance $L_{20}$ outside the tunnel is determined. With the advancement of technology, digital cameras have gradually replaced film cameras, which has improved measurement accuracy. The key to using the blackness method to determine the luminance outside the tunnel is the calibration of the optical characteristics of the digital camera, and the optical characteristics of each digital camera are different, and the calibration process is more troublesome. In addition, it is necessary to ensure that all the measured objects can be correctly exposed, but in fact the luminance of the sky and snow may reach tens of thousands of cd/m² and the luminance of the opening may only be tens of cd/m², which leads to some areas in the photo Overexposed and some areas still underexposed, causing large measurement errors.

After determining the luminance outside the tunnel, the threshold luminance ($L_{th}$) can be expressed as Eq. 3.3.

$$L_{th} = k \cdot L_{20} \quad (3.3)$$

The proportionality coefficient $k$ depends on travelling speed and the type of lighting in the threshold zone. The higher the travelling speed, resulting in a higher value of $k$. Counter beam lighting can provide a higher contract of objects making it easier for the driver to perceive objects and leading to lower luminance requirements inside the tunnel. Therefore, the value of $k$ is lower for counter beam lighting than for symmetrical and pro beam lighting.

3.1.2. Application and Research Progress of $L_{20}$. Taking account of practical experience gained in tunnel lighting system and CIE61-1984, the International Commission on Illumination issued in 1990 the Guide for the Lighting of Road Tunnels and Underpasses (CIE88-1990) where the lighting requirements for the threshold zone are still based on the L20 concept [8]. This Guide is a significant revision of CIE 26-1973.

China’s Code for Design of Ventilation and Lighting of Highway Tunnels (JTJ 026.1-1999) [9] recommends using the blackness method in the L20 method to measure the luminance outside the tunnel and determine the luminance in the threshold zone. Highway Tunnel Lighting Design Details (JTG-T-D702-01-2014) [10] is also based on the $L_{20}$ method to measure the luminance outside the tunnel, and then multiply it by $k$ to determine the luminance of the threshold zone.

Cao Yanrui et al. [11] used the blackness method to measure the luminance outside the tunnel, and took different tunnels on the highways of Yongtaiwen, Fuzhou, and Luoning in the southeast coast of China as the measurement objects. The measurement results are basically consistent with the data provided by the CIE file and the relevant industry standards of the Ministry of Transport of China. These tunnels are basically highway tunnels in the mountainous regions that run from north to south, but there are also tunnels with high $L_{20}$ due to the structure of the scenery outside the tunnel.
Qu Zhihao et al. [12] used the environmental diagram method to rely on the engineering practice of the northern and southern sections of the Beijing-Zhuhai Expressway tunnel in Guangdong, and used the illuminance-luminance meter to test the luminance of the ambient reflectors at the tunnel entrance, determined the luminance outside the tunnel based on the project. After return visits and expert exchanges, the environmental diagram method adopted this time has been unanimously affirmed.

Adrian [13] pointed out through theoretical analysis that the L_{20} method could not accurately express the adaptive luminance when the driver approached the tunnel, and even the adaptive luminance corresponding to the same L_{20} value would vary greatly, and then the field test verified that the conclusion was correct.

CEN.CR-143-80.2003 [14] recommends the use of the L_{20} method, which considers traffic conditions. It is based on the L_{20} method and takes into account factors such as traffic volume, traffic type, guidance lighting, and driving comfort. Impact, although more factors are considered than the L_{20} method, it still does not solve the problem that L_{20} cannot accurately express adaptive luminance.

3.1.3. Summary of the L_{20} method. The three calculation methods for determining L_{20} were introduced earlier, and the following conclusions can be drawn:

- The table method is the simplest and quickest method, but it only considers a few basic parameters of the tunnel. It does not consider that the luminance outside the tunnel is affected by the area where the tunnel is located, the weather, the season, the form of the gate, and the type of vegetation outside the tunnel [15]. The measurement error is the largest.

- For the environmental sketch method, different geographical locations will cause large differences in the luminance of the scene, and the types of scenes provided in CIE 88-1999 are also limited, so it is recommended to measure the luminance value on the spot.

- The key to using the blackness method to determine the luminance outside the tunnel is the calibration of the optical characteristics of the digital camera. In addition, it is necessary to ensure that all measured objects can be correctly exposed when measuring.

3.2. Perceived contrast method based on equivalent veiling theory

3.2.1. Definition of equivalent veiling theory. Based on the disability glare principle, Adrian [6] developed equivalent veiling theory with visibility of small targets as criteria. The light from the driver's 2° cone angle is reflected inside the human eyeball to generate scattered light. The scattered light forms a bright veiling in front of the retina. This veiling is superimposed on a clear scene image. Reduced contrast between target and background and the visibility of the target, as shown in Figure 4.

![Figure 4 Formation mechanism of equivalent veiling luminance L_{eq}]()
3.2.2. Definition and calculation method of perceived contrast method. Perceived contrast method is based on the equivalent veiling theory. The veiling interferes with the driver’s recognition of the target, and the veiling comes from the surface of the object in the driver's field of vision. The surface of these objects can be regarded as a glare light source, as shown in Figure 6. Consequently, the purpose of artificial lighting in the threshold zone is to counteract the adverse effect of the light veil by ensuring the contrast of the object is equal to or higher than the minimum required contrast [1]. The driver’s visual task is to determine the presence of other road users or objects in the tunnel while he is driving at a distance equal to the stopping sight distance. Due to the impact of natural light in the atmosphere the perceived contrast by a driver is generally lower than the intrinsic contrast.

The perceived contrast method requires determination of the luminance of the windscreen $L_{ws}$ and the atmosphere $L_{atm}$ before determining equivalent veiling luminance. Finally, the threshold zone luminance is determined on the basis of the minimum perceived contrast.

The equivalent veiling luminance $L_{seq}$ can be assessed directly by means of measurements at the tunnel site with special luminance meters equipped with a "glare lens" or with glare evaluation meters inside the car. When measurement conditions are insufficient, the equivalent veiling luminance can be determined by means of a graphical method. The graphical method is based on the Holladay-Stiles formula, Adrian designed a polar diagram [13], as shown in Figure 7.
Figure 7 Adrian's Polar diagram

Table 1. Perspective of each ring boundary calculated by Adrian

| Ring | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Angle of opening (°) | 1.0 | 1.5 | 2.0 | 2.9 | 4.0 | 5.8 | 8.3 | 12.0| 18.0| 28.4|

The key to using the graphical method is the angle \( \theta \), corresponding to the toroidal boundary in the polar diagram. Since the integrand in the integral term containing the angle \( \theta \) is not a basic function, Adrian ignores some of the decomposition terms after the decomposition, and calculates each perspective of the ring boundary is shown in Table 1.

At the stopping sight distance from tunnel entrance, take a photograph of tunnel surroundings. With the clear height of the tunnel portal as reference, use computer technology to superimpose the polar diagram on the tunnel scene. The tunnel opening is to be located in the center of the graph. Calculate the average luminance \( L_{ij} \) occurring in each section of the polar diagram; taking into account the windscreen, the perceived luminance of each section by the driver in the car is derived as Eq. 4.1.

\[
L_{ij'e} = \tau_{ws}L_{ij} + L_{ws}
\]  

(4.1)

Using the Holladay-Stiles formula the equivalent veiling luminance \( L_{seq} \) is found from Eq. 4.2.

\[
L_{seq} = 5.1 \times 10^{-4} \sum L_{ij'e}
\]  

(4.2)

CIE recommends 28% as the level of minimum required perceived contrast in CIE88-2004[16]. Finally, the luminance in the threshold zone can be calculated by Eq. 4.3 and Eq. 4.4.

\[
L_{th} = \frac{L_m}{\tau_{ws} \tau_{seq} - 1}
\]  

(4.3)

\[
L_m = \frac{\tau_{ws}L_{atm} + L_{seq}}{\tau_{ws} \tau_{atm}}
\]  

(4.4)

where \( \rho \) is reflectance factor of object surface; \( C_m \) is the minimum required perceived contrast (see previous discussion where 28% is recommended). This contrast may be considered as negative (for any \( q_c \) being greater than 0.06 with a reflectance factor \( \rho \) of the target equal to 0.2) in most cases; \( L_{atm} \) is atmosphere luminance.

The contrast revealing coefficient \( q_c \) is taken as 0.6 for CBL systems and 0.2 for symmetrical systems. Therefore, the luminance requirement of the threshold zone is influenced by the type of lighting.

3.2.3. Application and research progress of perceived contrast method. The perceived contrast method based on the equivalent light curtain brightness theory has been used in the Netherlands for many years to determine the luminance in the threshold zone of long tunnels. This method is based on CIE61-1984. CIE61-1984[7] mentions two factors that influence driver's visual adaptation, i.e. equivalent veiling luminance \( L_{seq} \) generated by tunnel surrounds and the luminance in the center of the
driver's field of view (road surface ahead and the tunnel entrance itself). $L_{\text{seq}}$ is the key factor that influences the driver's visual adaptation.

Based on the equivalent veiling theory [16], the International Commission on Illumination issued the Guide for the Lighting of Road Tunnels and Underpasses (CIE88-2004) in 2004. This Guide sets out the perceived contrast method for determination of the threshold zone luminance.

Augdal [17] uses the series expansion method to calculate the integral term containing the angle $\theta$ on the basis of Adrian. Since some expansion terms are also ignored, the results calculated by the two methods are very different.

Hu Yingkui et al. [18] analyzed the problems existing in Adrian and Augdal's calculation of the perspective of polar coordinate ring boundary, and proposed a numerical integration method for this integral term. This method can prevent Adrian and Augdal from ignoring a part of the decomposition terms In order to more accurately determine the angle of view corresponding to each ring boundary, the angle of view corresponding to each ring boundary and the corresponding equivalent veiling luminance calculation formula obtained by numerical integration are given. After actual measurement, the results obtained by the perceptual contrast method are more in line with the actual situation of tunnel traffic. He suggested that the perceptual contrast method can be used in tunnel lighting design in China, and recommended the $\theta$ table he calculated.

3.2.4. Summary of perceived contrast method. By introducing the theory and research progress of the perceived contrast method, the following conclusions can be drawn:

- The perceived contrast method based on the luminance of the equivalent veiling not only considers the luminance of various scenes outside the tunnel, but also considers the impact on vision caused by the different positions of various scenes relative to the driver's eyes, while also taking into account the atmosphere and the transmission of natural light by the windshield, which also affects the driver's vision. A more comprehensive expression of the driver's adaptive luminance when entering the tunnel is more in line with the actual situation of tunnel traffic.
- The key problem of the perceived contrast method is the value of the angle of view of the polar coordinate ring boundary. The calculation method needs to be further improved in the actual measurement to make the measurement result more accurate.
- When calculating with the perceived contrast method, there is a difference in the luminance of the threshold zone calculated by different lighting methods. Backlighting is more conducive to energy saving in tunnels than symmetrical lighting. In the design of tunnel lighting, the choice of lighting method can be considered appropriately.

4. Summary

As the research focus of tunnel lighting, this paper discusses the methods for determining the luminance of the tunnel threshold zone from the 1960s to today, the practical application of the methods, and the research progress of each method, analyzes the shortcomings of each method, and focuses on the perceived contrast method points for attention in future research are pointed out. Practice shows that a series of research results from the steady-state vision adaptation theory to the equivalent veiling theory play a key role in rationally configuring artificial lighting at the threshold zone of the tunnel to improve driving safety, enabling drivers to approach, enter, and pass through the tunnel with confidence. With the deepening of human vision's research on the physiological perception and behavioral response of luminance, the theory of the luminance at the threshold zone of the tunnel will also be continuously updated and improved, so as to more reasonably guide the lighting design of the threshold zone and ensure the safety of tunnel driving.

Acknowledgements

The research was financially supported by National Key R&D Program of China (2017YFC0806003) and Key scientific research projects of Tibet autonomous region (2016XZ01G31).
References

[1] Ma, F., Wu, M J., Xie, H B. (2018) Lighting of Tunnel. Science Press, Beijing.

[2] Zhang, T G., Zhang, L F., Liu, S. (2017) Study on Natural Light Transition of Highway Tunnel Entrance. Journal of Highway and Transportation Research and Development, 145(01):137-140.

[3] Schreuder, D A. (1964) The lighting of vehicular traffic tunnels. Technische Hogeschool Nd hoven, 2:48-54.

[4] Narisada K, Yoseoikawa K. (1974) Tunnel entrance lighting—Effect of fixation point and other factors on the determination of requirements. Lighting Research and Technology, 6(9):9-18.

[5] CIE. (1973) CIE26—1973 International Recommendations for Tunnel Lighting. International Commission on Illumination, Vienna.

[6] Adrian W. (1982) Investigations on the required luminance in tunnel entrances. Lighting Research and Technology, 14(3):151-159.

[7] CIE. (1984) CIE61—1984 Tunnel Entrance Lighting—A Survey of Fundamentals for Determining the Luminance in the Threshold Zone. International Commission on Illumination, Vienna.

[8] CIE. (1990) CIE 88—1990 Guide for the Lighting of Road Tunnels and Underpasses. International Commission on Illumination, Vienna.

[9] Ministry of Communications of the People's Republic of China. (2000) Specifications for Design of Ventilation and Lighting of Highway Tunnel (JTJ 026.1—1999). People's Communications Press Co., Ltd., Beijing.

[10] Ministry of Communications of the People's Republic of China. (2014) Guidelines for Design of Lighting of Highway Tunnels (JTG-T-D702-01-2014). People's Communications Press Co., Ltd., Beijing.

[11] Cao, Y R., Zhang, H C. (2003) Discussion of Blackness Degree Measurement Method of Tunnel Exterior Luminance L20 and Tunnel Exterior Decorating. Lamps & Lighting, 3: 20-24.

[12] Qu, Z H., Zhao, Q B., Liu, X H. (2004) Tunnel Ambient Exterior Luminance L20(S) Tested by Environmental Sketch Method. Technology of Highway and Transport, 5: 117-121.

[13] Adrian, W. K. (1987) Adaptation luminance when approaching a tunnel in daytime. Lighting Research & Technology, 19(3): 73-79.

[14] CEN. (2003) CR-143-80.2003E Lighting Applications-Tunnel Lighting. European Committee for Standardization, Brussels.

[15] Hu, Y K., Chen, Z L., Zhang, Q W., Weng, J. (2013) Determination Method of Adaption Luminance Outside Road Tunnel. Lamps & Lighting, 37 (03): 13-17.

[16] CIE. (2004) CIE 88—2004 Guide for the Lighting of Road Tunnels and Underpasses. International Commission on Illumination, Vienna.

[17] Augdal, A. (1991) Equivalent Veiling Luminance Different Mathematical Approach to Calculation. Lighting Research & Technology, 23 (1): 91-93.

[18] Hu, Y K., Chen, Z L., Sun, C H. (2011) Calculation Method of Road Tunnel Threshold Zone Luminance Based on Equivalent Veiling Luminance. Journal of Highway and Transportation Research and Development, 28(05): 98-101, 120.