

Research Article

Impact of LED Color Temperatures on Perception Luminance in the Interior Zone of a Tunnel considering Fog Transmittance

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LEDs are widely applied in highways and tunnels for their long life, low light attenuation, and being environment friendly in recent years. The influence of correlated color temperature (CCT) of LED on lighting safety has attracted people's attention as the demand increased. In this paper, a calculation model of perception luminance of human eye considering mesopic vision and fog concentration was proposed. The influence of different CCTs on perception luminance of human eye under different levels of fog concentration and luminance was calculated and analyzed. The CCT of LED employed in the interior zone of a tunnel was selected based on the highest perception luminance in mesopic vision. Seven kinds of LEDs with different CCTs (3000–6500K) were applied in the experimental system with adjustable fog concentrations. The results showed that the main factors affecting visual perception are luminance and fog concentration. Higher luminance or lower fog concentration provides drivers with higher perception luminance. In contrast, although CCT has a less effect on perception luminance, LEDs with higher CCT (about 6500K) can provide higher perception luminance considering fog in mesopic vision. This paper provides technical support for tunnel lighting and guaranteeing traffic safety.

1. Introduction

Tunnel lighting is an important aspect of ensuring traffic and transport safety in highway tunnel. Many countries have lighting requirements for each section of the tunnel and determine whether the requirements are met based on the measurements of the instrument [1–3]. In China, the Guidelines for Design of Lighting of Highway Tunnels JTGT D70/2-01—2014 (JTG) divided the tunnel into four parts (threshold zone, transition zone, interior zone, and exit zone) with different luminance requirements. The luminance of the entrance zone and exit zone is designed to be higher in order to reduce the influence of luminance difference between the inside and the outside of the tunnel on traffic safety in the daytime. Taking advantage of the adaptation of the human eye to the dark, the luminance of the interior zone is designed to be minimal in order to save energy. The tunnel division in four parts can provide a universal reference for the tunnel lighting design, while ensuring the safety of driving to maximize energy saving.

Based on the traffic volume and the designed speed, the luminance requirement for interior zone is the lowest for about $1 \text{ cd/m}^2 \sim 10 \text{ cd/m}^2$ [4]. Due to the semiclosed structure of the tunnel, the particles emitted from motor vehicles and deposited dust can hover for a long time in the air by gravity and cause a foggy condition. Both low luminance and fog conditions will pose a real threat to driving safely in the interior zone, and as a result, improving the visual quality of drivers by studying tunnel lighting is of significant importance.

The energy consumption of tunnel lighting is larger than half of the total energy consumption of tunnel [5, 6]. Nowadays, LEDs are widely applied in highways and tunnels because of their long life, low light attenuation, and energy saving, whose correlated color temperature (CCT) can cover a common range of 3000K~6500K [7, 8]. When the color of the light emitted by the light source is close to the color of the radiation of the black body at a certain temperature, the temperature of the black body is called the correlated color temperature of the light source. Researchers have carried out

many studies on energy saving of tunnel lighting. In 2011, Gil-Martín [9] presented tension structures for tunnel to save energy in the most energy requiring zone (the threshold zone) and reduce the number of luminaries. In 2015, Salata [10] presented that LEDs are suitable for the interior zone due to their luminous efficiency. Thanks to their longer service life, they reduce maintenance expenses. In 2018, Cantisani [11] computed and compared the environmental impacts of two lighting systems, LED and high-pressure sodium (HPS), in a twin-tube road tunnel. He presented that although LEDs cost more in terms of construction and installation than HPS, they cost less to maintain later. In 2019, he calculated the energy savings from replacing HPSs with LEDs in Italy's Greenlight project. The results showed that the new lighting systems will reduce electricity consumption by up to 50% of the current values [12]. Although energy saving is an essential issue in tunnel lighting design, safety should also be taken into consideration.

In the past few years, our laboratory has provided lighting design for several tunnels of Heda highway in Jilin province of China and accumulated some practical engineering experience and problems to be improved. The department of tunnel lighting design and management pays great attention to the selection of CCT of LED, but there are no official guidelines for reference. Therefore, it is meaningful to explore the effect of CCT on human vision. Luminance is the main influence factor of safety in tunnel lighting. Two main factors should be considered for safe driving in the interior zone of a tunnel considering fog condition: human eye perception and transmittance of LEDs with different CCTs in fog condition.

The luminance perceived by human eye is different when the ambient luminance and wavelength of light are different. Human vision is divided into photopic vision, scotopic vision, and mesopic vision according to the visual phenomena caused by light of different wavelengths acting on visual organs in different luminance ranges [13–15]. Photoreceptor cells in the retina can be divided into two types: cones and rods. The luminance range of photopic vision is about above 3 cd/m^2 , when cones play a major role. In this case, the human eye can distinguish the details and colors of objects. The luminance range of scotopic vision is about below 10^{-3} cd/m^2 , when rods play a major role. In this case, the human eye can only distinguish light and dark, and the ability to distinguish details and colors of objects is greatly reduced. Most of the luminance of tunnel lighting belongs to the range of mesopic vision when both types of cells work simultaneously in a specific proportion. The mesopic spectral luminous efficiency function varies depending on the luminance, and the interaction between cones and rods differs with luminance levels. Several researches concerned with mesopic vision have been carried out in recent years. In 2006, Viikari [16] and others measured the reaction time and contrast threshold to evaluate mesopic visual performance in different spectral conditions. In 2011, Li [17] and others presented that the higher CCT of LEDs have better visual effects by calculating the mesopic equivalent illumination of the different sources. In 2016, Huai [18] conducted a test on color discrimination and presented that the human eye's

ability to distinguish colors improves as CCT increases in mesopic condition. In 2018, Du [19] studied the overall luminance performance and indicated that LEDs with high CCT have better luminance performance in lighting reduction coefficient in threshold zone of tunnel. All the above studies satisfied the mesopic visual characteristics under general conditions. As tunnels are prone to the phenomenon of low visibility, it is necessary to consider the effect of fog when studying the mesopic vision in tunnel.

The value of CCT is determined by the spectrum of LED. The transmittance of light in fog is affected by the wavelength of light source. Therefore, it can be inferred that LEDs with different CCTs provide different visual perception in fog. Some researchers studied the relationship between monochromatic lights and transmittance in fog. In 2012, Otas [20] and others presented an experimental investigation of the characteristics of the propagation of light emitted by various colors in artificial fog with varying density. The experiment showed that the light of shorter wavelengths (blue and green) is seen to be less attenuated by scattering than that of longer wavelengths. In 2013, Zeng [21] and others researched the penetration properties of LED light sources in water fog and sea fog, showing that the transmittance of yellow LED was the best, followed by blue, green, and red. In 2016, Brandon [22] and others studied the attenuation characteristics of LEDs with six different wavelengths in a controlled fog chamber. They got the result that the red light has the least attenuation, followed by yellow and green. The blue light had the worst performance. Reaching a unified conclusion about the relationship between wavelength and transmittance from the above researches is hard. Huai [18] studied the effect of three CCTs (1870K, 2985K and 5020K) on penetration properties in fog and presented that low-color-temperature (around 3000K) LEDs are more suitable for street lighting by calculating the transmittance. Most studies of light transmittance are concerned with monochromatic light, not with CCT. As a result, we should consider the influence of LED with different CCTs on both the transmission and the mesopic spectral luminous efficiency function on tunnel lighting. The most sustainable luminaire in tunnel, LED, was studied, and the impact of CCT on perception luminance in the interior zone of the tunnel considering different levels of luminance and fog concentrations was explored for traffic and transport safety. The calculation and experimental results showed that high luminance or low fog concentration could provide high perception luminance. High CCTs (about 6500K) could provide higher visual clarity. But the effect of CCT is relatively inferior to luminance and fog concentration. These conclusions provide reference for tunnel lighting design guidelines for traffic safety, energy saving, and the selection of CCTs.

2. Theory of Perception Luminance

Considering fog conditions in tunnel, the perception luminance of human eye is affected by the mesopic spectral luminous efficiency function, the spectrum and luminance of LED, and the fog transmittance. Human eye perception

luminance in mesopic vision considering transmittance of light can be calculated by the following equations:

$$L_f = \int_{380}^{780} k_m V_{mes}(\lambda) L_e^*(\lambda) d\lambda, \quad (1)$$

$$L_p = \int_{380}^{780} 683V(\lambda) L_e^*(\lambda) d\lambda, \quad (2)$$

$$L_e^*(\lambda) = L_e(\lambda) \cdot T(\lambda), \quad (3)$$

where L_f refers to the perception luminance of human eye in mesopic vision, whose units of measurement is cd/m^2 . k_m refers to maximum spectral light performance corresponding to mesopic vision luminance. $V_{mes}(\lambda)$ is the mesopic spectral luminous efficiency function depends on L_p . $L_e^*(\lambda)$ refers to spectral radiance distribution (SPD) under a certain concentration of fog. L_p refers to the luminance of light through fog in photopic vision, whose units of measurement is cd/m^2 . $V(\lambda)$ refers to the photopic spectral luminous efficiency function. $L_e(\lambda)$ refers to SPD measured by spectral radiance meter under the absence of fog, and $T(\lambda)$ refers to the transmittance of different wavelength at a certain fog concentration.

2.1. $L_e(\lambda)$. $L_e(\lambda)$ refers to the SPD measured by spectral radiance meter under the absence of fog. Seven kinds of LEDs with different CCTs applied in highway tunnel were selected in the following experiment to analyze their SPDs, whose CCTs are 3000K, 3500K, 4000K, 4500K, 5000K, 5700K, and 6500K, as shown in Figure 1.

The LEDs employed in highway tunnels are mainly superimposed by the blue light emitted by the GaN chip and the yellow light excited by yttrium aluminum garnet (YAG) phosphor [23]. The SPDs of LED with different CCTs ($L_e(\lambda)$) shown in Figure 2 are measured by a spectrophotometer called Konica-Minolta CS-2000 under the luminance of $10 \text{ cd}/\text{m}^2$. The characteristics of the spectrum are double peaks broad spectrum. The valley between the two peaks is close to 480 nm.

2.2. $T(\lambda)$. $T(\lambda)$ is defined as the transmittance of different wavelengths under a certain fog concentration and is calculated by the ratio of illuminance with fog to illuminance without fog. Transmittance can indicate the concentration of fog, and the two are negatively correlated. To make the data more reliable, the transmittance of nine monochrome LEDs with different center wavelengths were measured under five different fog concentrations in a sealed fog chamber. Figure 3 shows the relative luminance intensity of nine monochromatic LEDs. The range of central wavelength is 420 nm~660 nm.

Figure 4 shows the schematic diagram of experimental setup. Nine monochrome LEDs of the same model were put at one side of the fog chamber, and the illuminometer was put at the other side of the chamber. The following shows the experimental procedure. Firstly, when there was no fog in the chamber, nine monochrome LEDs were adjusted to have

the same illuminance (40lx) measured by the illuminometer. All light sources were turned off except monochrome LED with a wavelength of 420 nm, as a reference light source. Secondly, the fog generator released fog into the chamber. The concentration of fog can be maintained at a certain value by observing the readings of illuminometer and controlling the flow rate. The transmittance of the reference light source (T) was calculated to represent various concentration levels ($T=20\%, 40\%, 60\%, 80\%$, and 100% in this experiment). Thirdly, when the concentration of fog reached a stable and demanded value, the reference light source was turned off and the other eight monochrome LEDs were turned on by turns. The values of illuminance of eight monochrome LEDs in a certain concentration of fog were recorded and the values of transmittance were calculated by turns. Nine monochrome LEDs were placed in the same location. The same procedure was repeated 10 times to reduce the experimental error.

Figure 5 shows the average transmittance of 10 groups including nine monochrome LEDs under five levels of fog concentration. It can be seen from Figure 5 that, in the case of different fog concentrations, the tendencies of luminance attenuation of the respective wavelengths are the same, and the main difference is the amplitude of the attenuation. $T(\lambda)$ can be obtained by interpolation based on the experimental result.

2.3. $K_m V_{mes}(\lambda)$. $K_m V_{mes}(\lambda)$ refers to the mesopic spectral luminous efficiency function. It is generally considered that the mesopic luminance is in the range of $10^{-3} \text{ cd}/\text{m}^2$ to $10 \text{ cd}/\text{m}^2$ [14], while the luminance of tunnel lighting mostly falls within this range [4]. The human retina is composed of countless photoreceptor cells. They are divided into cone cells and rod cells according to their shape. Unlike photopic vision and scotopic vision, in which only one type of cell functions, mesopic vision is activated by two types of cells at the same time, and the number of the two types of cells is determined by luminance [24, 25]. Therefore, the mesopic spectral luminous efficiency function cannot represent the relative sensitivity of the human eye to different wavelengths of light using a single spectral luminous efficiency curve. It is necessary to use a series of curves at different luminance levels to describe the mesopic spectral luminous efficiency function. In 2010, the International Commission on Illumination [26] recommended four mesopic vision models based on visual efficiencies: USP model, MOVE model, MES1 model, and MES2 model.

Figure 6 plots the difference curves between mesopic luminance and photopic luminance ($L_{mes}-L_p$) which vary with the photopic luminance when S/P values of LED are 1.4, 2.0, and 2.3, respectively. It can be seen from Figure 6 that the mesopic luminance calculated by four different mesopic models under the same photopic luminance is different. Moreover, the mesopic luminance calculated by the four mesopic vision models is greater than the photopic luminance.

The upper luminance limit ($0.6 \text{ cd}/\text{m}^2$) of the mesopic region is too low for the USP model. USP model limits the



FIGURE 1: Seven kinds of LEDs applied in tunnel with different CCTs.

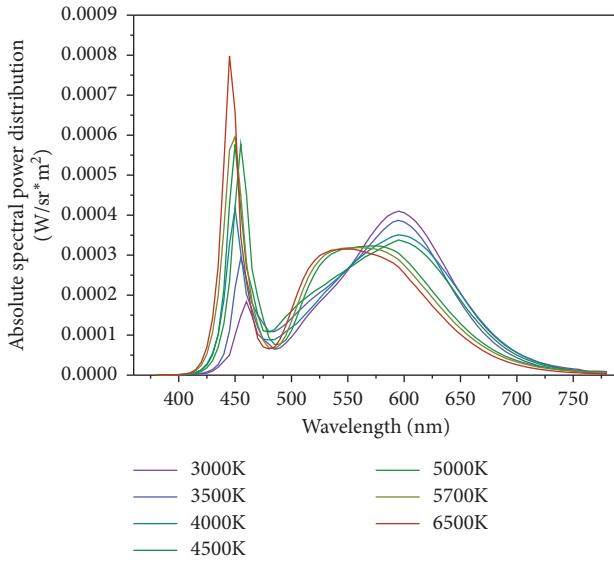


FIGURE 2: Spectral power distribution of 7 LEDs with different CCTs.

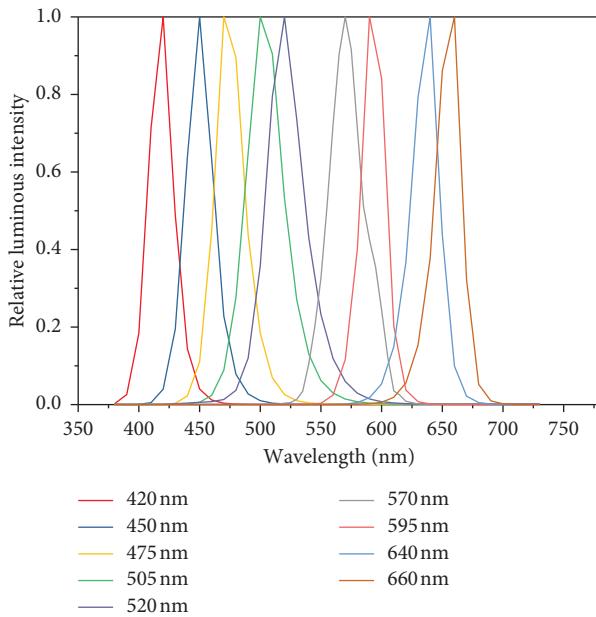


FIGURE 3: Relative luminance intensity of nine monochromatic LEDs.

applicability to achromatic tasks only. The chromatic tasks dominated in MOVE model. But in real-tunnel situations, such as driving through a tunnel, both achromatic and chromatic tasks are involved, and the achromatic tasks may

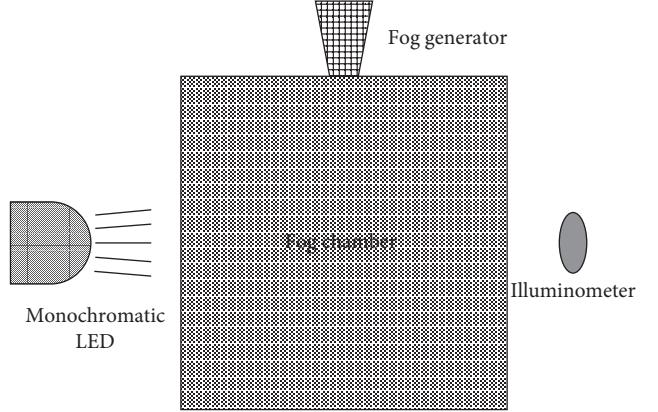


FIGURE 4: The schematic diagram of experimental setup.

be slightly underweighted in the MOVE model [25]. Comparing MES1 and MES2 models, MES2 model has a wider range of luminance, which means that MES2 model is more suitable for both color vision tasks and achromatic vision tasks and more suitable for the analysis model of mesopic vision in the tunnel. In MES2 model, if $L_{mes} \geq 5.0 \text{ cd/m}^2$, then $m=1$; if $L_{mes} \leq 0.005 \text{ cd/m}^2$, then $m=0$. That is to say, if the MES2 model is adopted, the photopic luminance should be selected to be below 5.0 cd/m^2 . Although the upper limit for the photopic luminance of the interior zone of the tunnel is 10 cd/m^2 , considering the fog condition in tunnel, the perceived luminance may be lower than 5 cd/m^2 , so it is reasonable to use MES2 model in this research. The mesopic spectral luminous efficiency function can be obtained through MES2 model. The following are the calculation equations of MES2 model:

$$k_m = \frac{683lm \cdot W^{-1}}{V_{mes}(\lambda = 555 \text{ nm})}, \quad (4)$$

$$V_{mes}(\lambda) = 683 \frac{m_2 V(\lambda) + (1 - m_2)V'(\lambda)}{m_2 + (1 - m_2)V'(\lambda_0)}, \quad 0 \leq m_2 \leq 1, \quad (5)$$

$$m_{2,n} = 0.3334 \log L_{mes,n} + 0.767, \quad 0 \leq m_{2,n} \leq 1, \quad (6)$$

$$L_{mes,n} = \frac{m_{2,n-1} + (1 - m_{2,n-1})(S/P)V'(\lambda_0)}{m_{2,n-1} + (1 - m_{2,n-1})V'(\lambda_0)} L_p, \quad (7)$$

$$\sqrt{a^2 + b^2 S/P} = \frac{\int V'(\lambda)L_e(\lambda)d\lambda}{V'(\lambda_0) \int V(\lambda)L_e(\lambda)d\lambda}, \quad (8)$$

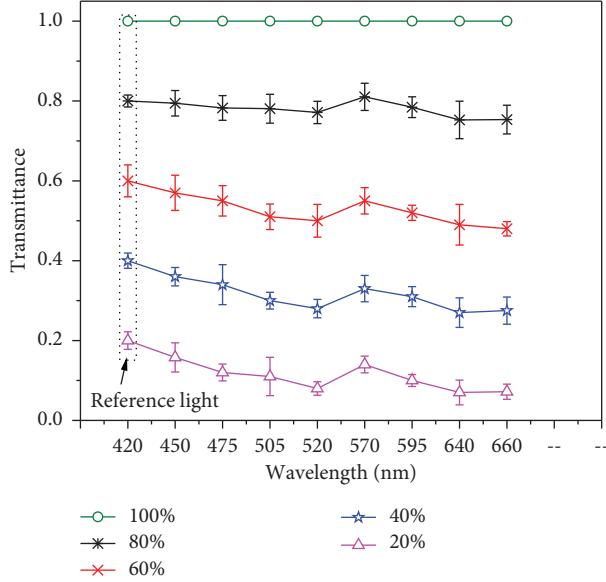


FIGURE 5: SPDs of nine monochromatic LEDs. Error bars indicate standard deviation.

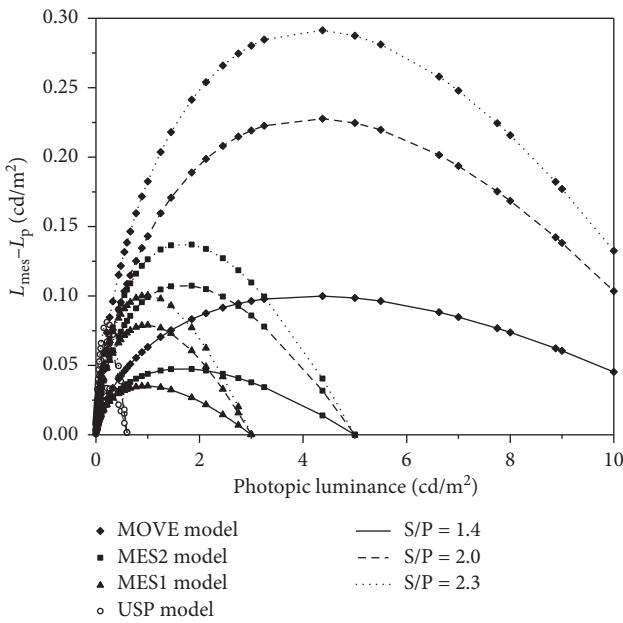


FIGURE 6: Comparison of four mesopic photometry models with different S/P ratio.

where $V_{\text{mes}}(\lambda = 555 \text{ nm})$ is the value of $V_{\text{mes}}(\lambda)$ at 555 nm. m_2 refers to the luminance adaptation factor. $V'(\lambda)$ refers to the value of scotopic spectral sensitivity function. $V'(\lambda_0)$ refers to the value of scotopic spectral sensitivity function at $\lambda_0 = 555 \text{ nm}$, the value of which is 683/1699. L_{mes} refers to the mesopic luminance. The value of m_2 can be calculated based on (6) and (7) by a sequence of interactions. n refers to an iteration step. The value of S/P refers to scotopic to photopic luminous flux ratios of light sources.

The calculation process of getting mesopic spectral luminous efficiency function is shown in Figure 7. Firstly, the

value of S/P is calculated by (8) according to the spectral distribution of different light sources ($L_e(\lambda)$). The S/P ratios of the seven kinds of LEDs used in this study are shown in Table 1. Secondly, $L_e^*(\lambda)$ is calculated by $L_e(\lambda)$ and $T(\lambda)$. And then the value of L_p can be calculated by (2). Thirdly, substituting S/P and L_p into the calculation equations (6) and (7), the value of the parameter m_2 can be obtained. And then, $K_m V_{\text{mes}}(\lambda)$ can be calculated by (4) and (5). The spectral luminous efficiency curves of photopic, scotopic, and mesopic vision are shown in Figure 8. The mesopic curves are located between the photopic vision and scotopic vision. For spectral luminous efficiency curves of photopic, mesopic, and scotopic vision, the four luminance values in the upper left corner correspond to the mesopic luminance. For the spectral luminous efficiency curves of the seven LEDs on the right, the value of photopic luminance is 1 cd/m². In Figure 8, mesopic curves do not have the same pattern as the curves at the top right. As the luminance decreases, the mesopic curves get closer to the scotopic vision and the peak of mesopic curves gets higher. Under a certain luminance level, LEDs with low CCTs provide higher luminous efficiency curves.

2.4. L_f L_f refers to the perception luminance of human eye in mesopic vision, and it is one of the main influencing factors of visual quality. According to formulas (1)~(8), the calculation process of L_f is shown in Figure 9. After measuring $T(\lambda)$ and $L_e^*(\lambda)$, $V_{\text{mes}}(\lambda)$ can be plotted by (2)~(8), and then L_f can be calculated by (1) and (3).

2.5. The Calculation Results of Perception Luminance. The results of the theoretical calculation results are shown in Figure 10. The values of each parameter are shown in Table 2 considering the luminance in MES2 and various transmittances. The main research content of this paper is the difference of CCT, so discretization will not affect the experimental results. It can be seen from Figure 10 that L_f is greatly affected by the luminance under absence of fog (L) and fog concentration and is less affected by the CCT. The value of L_f increases as the luminance or transmittance increases. Under a certain luminance and fog concentration, LEDs with higher CCT always provide higher L_f . The difference of L_f provided by two adjacent CCTs is about 0.02 cd/m⁻², which means that the influence of CCT on L_f is relatively small in the theoretical calculation, and perhaps in a real tunnel, the human eye can hardly perceive the differences of CCTs. However, the calculation results are not completely consistent with the actual human eyes, and it still needs experimental verification.

3. Experiment

3.1. Experimental Setup. As perception luminance cannot be directly measured by instruments, this experiment indicated the perception luminance by judging the clarity levels of the target by human eye. Visual clarity refers to the theory about the target-background contrast. The contrast can be calculated by

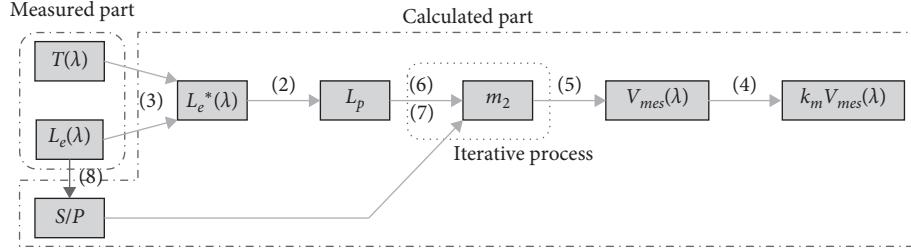


FIGURE 7: Calculation process.

TABLE 1: The S/P value of seven light sources.

CCT (K)	S/P ratio
3000	1.2191
3500	1.4902
4000	1.5390
4500	1.7893
5000	1.8174
5700	1.8977
6500	2.0232

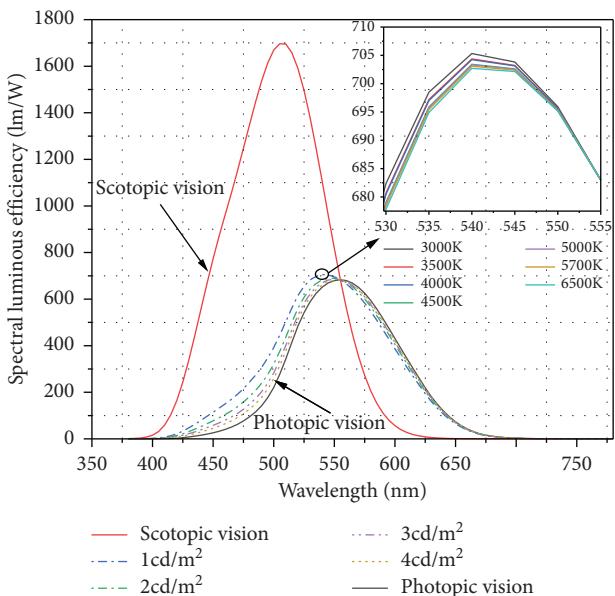


FIGURE 8: Spectral luminous efficiency curves of photopic, scotopic, and mesopic vision of seven kinds of LEDs with different CCTs.

$$C = \frac{L_b - L_t}{L_b}, \quad (9)$$

where C refers to the target-background contrast, L_b refers to the background luminance, and L_t refers to the target luminance. In this experiment, the color of the target (visual chart) is black. As a result, C is mainly affected by the perception luminance of the background. It can be concluded that the higher the perception luminance, the higher the visual clarity.

Although experiments in real tunnel would be closer to actual driving condition, some variables are hard to control. For example, the fog concentration and uniformity of each

experiment cannot be guaranteed as they change over time, which will seriously affect the accuracy of experimental results. The fog chamber can produce stable fog and was used to ensure the accuracy of data. The danger of driving in a tunnel is caused by the fact that the eyes do not perceive obstacles in front in time, which involves the theory about target-background contrast, and the main factor is perception luminance. As a result, it is reasonable to replace the traffic model of real tunnel with the static simplified model.

Figure 11 illustrates a schematic diagram of experimental setup. Figure 12 shows the real experimental situation. The fog chamber was made of wood and organic glass, the volume of which was $500 \times 500 \times 500 \text{ mm}^3$. The interior of the chamber was painted black except the organic glass to avoid the diffuse reflection of light and designed to be sealed. It has been confirmed that the organic glass has little effect on spectral luminous efficiency or visual perception except reducing luminance. Two sides of the chamber were made of glass so that the light of LEDs placed on either side could shine into the chamber. Besides, the side near the observer was also partly made of glass for observing. In order to reduce the experimental error, two LEDs with different CCTs were placed on both sides of the chamber, and the lights were placed alternately like Figure 11(c). It has been confirmed through a preliminary experiment that such a placement of lights does not affect the experiment. A visual chart was attached on the side away from the observer. Below the visual chart was an illuminometer to measure the illuminance and calculate the transmittance. The E letter was painted in black with a reflectance of 0.2, and the reflectance of different wavelengths is the same. In mesopic vision, the cone cells do not play a major role, so the human eye's resolution of color is greatly reduced. In JTG, there is a description of the driver's visual cognition of obstacles in the tunnel. JTG specifies that the obstacle uses a small black target with a reflection coefficient of 0.2. We designed the visual acuity chart based on this rule.

The observer could just observe the visual chart through the glass. The fog generator (FOGGER A-1500) was put behind the fog chamber and could produce stable and uniform fog. The walls around the chamber were painted black to prevent the influence of diffuse reflection on the experiment and to simulate the dim environment in real tunnel. The distance between the subjects and the fog chamber is 1 m.

50 observers (25 females and 25 males) aged 24 to 56 with normal color vision and normal binocular eyesight participated in this experiment. We chose four luminance

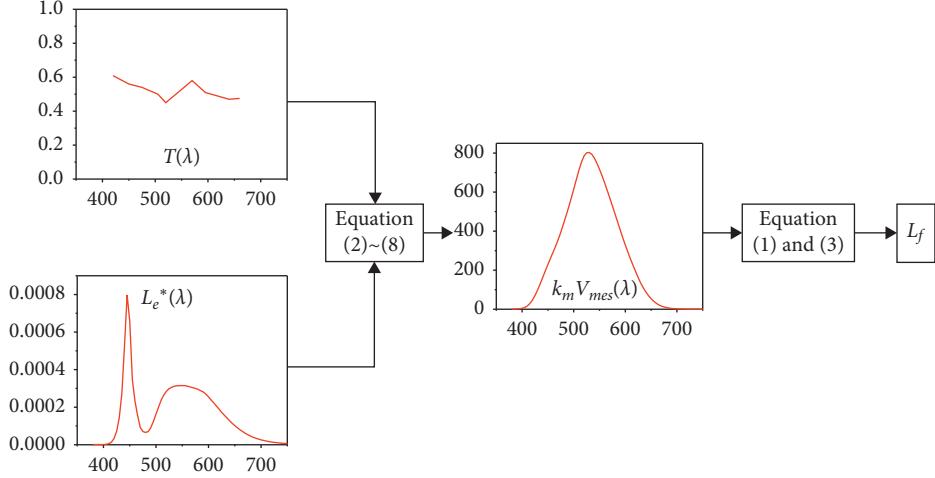
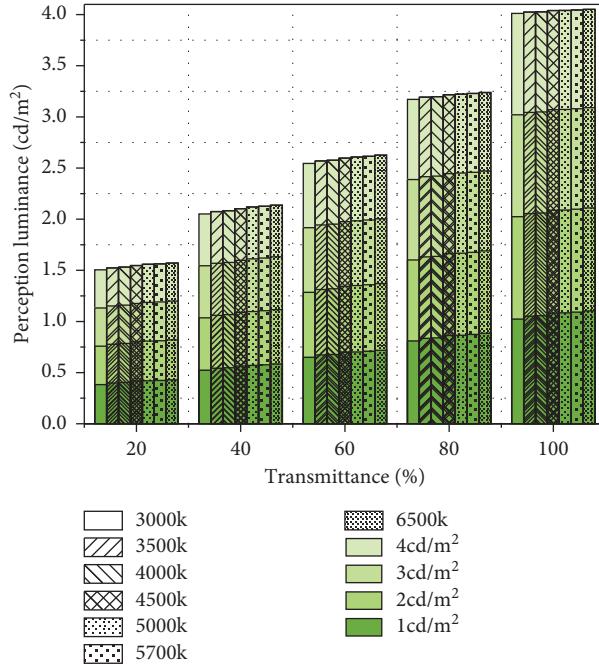
FIGURE 9: The calculation process of L_f FIGURE 10: The calculation results of L_f

TABLE 2: The values of each parameter.

Luminance without fog (L)	CCT	Transmittance (T)
1cd/m ² , 2cd/m ² , 3cd/m ² , 4cd/m ²	3000K, 3500K, 4000K, 4500K, 5000K, 5700K, 6500K	20%, 40%, 60%, 80%, 100%

levels (1 cd/m², 2 cd/m², 3 cd/m², and 4 cd/m²), five transmittance levels (20%, 40%, 60%, 80%, and 100%), and seven CCTs (3000K, 3500K, 4000K, 4500K, 5000K, 5700K, and 6500K), totally 140 lighting conditions.

3.2. Effects of Luminance and Fog Transmittance. In designing this part of the experiment, we have attempted to request the subjects conduct the experiment under the conditions of seven CCTs. However, due to the

discretization of the visual chart, when using LEDs with different CCTs under the same luminance and fog concentration, the line where the smallest E could be seen clearly and the subjects distinguishing the direction was almost the same. The difference is only a matter of the degree of clarity. This phenomenon verifies the theoretical calculation results of perception luminance: compared with CCT, luminance and fog concentration have a much greater impact on visual clarity. It can be concluded that when considering the effect of LEDs on the perception luminance of the human eye in

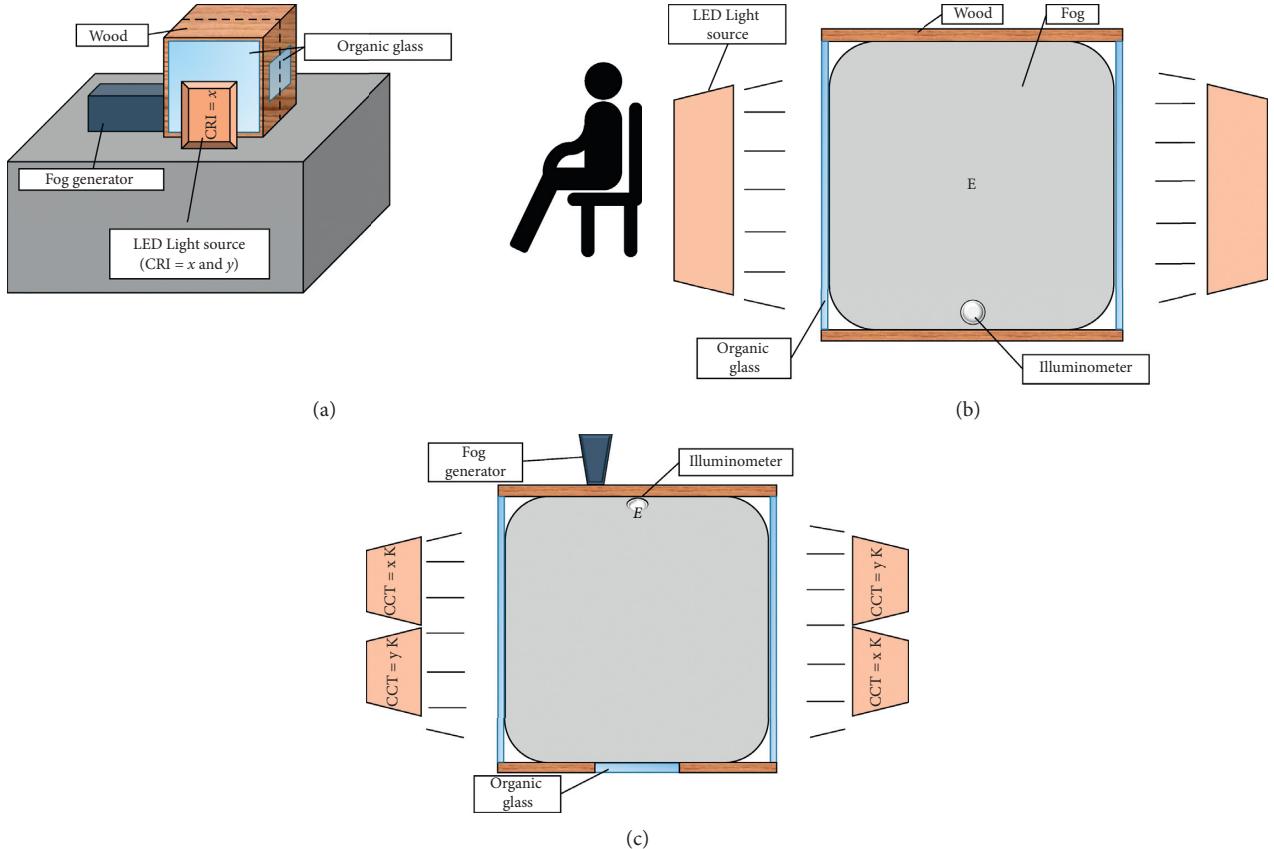


FIGURE 11: Schematic diagram of experimental setup. (a) Overview of experimental facility. (b) The section of the front view. (c) The section of top view.



FIGURE 12: The experimental situation.

fog conditions, which CCT to use does not make much difference. As a result, it is appropriate to select only one CCT in this part of the experiment. LEDs with 6500K were used as the light source.

In Step 1, LEDs with CCT of 6500K were adjusted to a demanded illuminance level under the absence of fog. According to the average luminance-average illumination conversion coefficient given by JTG (usually taken as $10\text{lx}/(\text{cd}\cdot\text{m}^{-2})$) [4], the values of illuminance (L_i) were selected as: 10lx, 20lx, 30lx, and 40lx.

In Step 2, the fog generator released fog into the chamber. The concentration of fog could be adjusted by controlling the flow of the fog generator. The illuminometer

was used to calculate the transmittance under the current fog concentration and judge whether the fog is stable. Wait until the fog stayed steady, and the transmittance reached the demanded stable value (20%, 40%, 60%, 80%, and 100%).

In Step 3, when the fog chamber was in a certain demanded condition (1 of 4 illuminances \times 5 transmittances), subjects were asked to observe the visual chart and provide the number of lines of the smallest E they could see clearly and distinguish the direction. To quantify the results, six lines of E indicate six score levels: six points for the smallest line and one point for the largest line, respectively.

3.3. Effects of CCTs. Figure 13 shows the experimental procedure. As the effect of CCT on visual clarity is relatively insignificant, the CCT that can provide higher perception luminance in a certain condition (the same fog concentration and the same luminance) was selected by means of pairwise comparison. Seven CCTs were sorted according to the degree of visual clarity they provided and were scored in order to make the experimental results more intuitive.

In Step 1, LEDs with seven kinds of CCTs were adjusted to a demanded illuminance level under the absence of fog. The position and angle of LEDs are fixed, so that each time two kinds of LEDs which were going to be compared were placed on both sides of the chamber, and the illuminance of the two kinds of LEDs remained the same as the value set before.

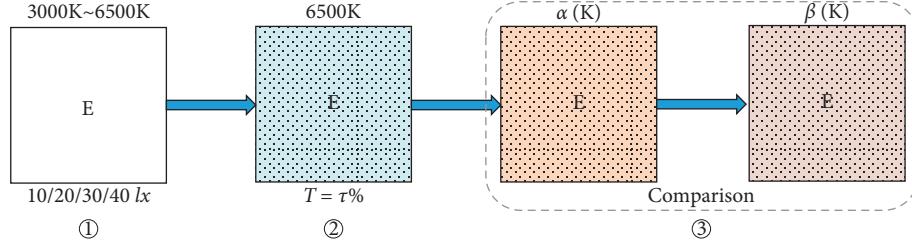


FIGURE 13: The experimental procedure.

In Step 2, the fog generator released fog into the chamber. Wait until the fog stayed steady. Because the upper part of the experiment used 6500K as the light source, in order to maintain consistency, 6500K was still used in this part of the experiment as the reference of the fog concentration and the calculation of the transmittance.

In Step 3, the LEDs were switched from one CCT to another. Subjects were first asked to observe the smallest line which could recognize the direction of the E in the visual chart. Then, they were asked to choose between the LEDs before switching and the LEDs after switching which can provide a clearer vision when observing the visual chart. There was always only one kind of LED that is bright during the experiment.

Seven CCTs were sorted by the method of selection sort, as shown in Figure 14. A randomized order of seven kinds of LEDs was prepared in advance to ensure the accuracy of experimental data. Firstly, the first CCT and the second CCT were selected for comparison as the experimental procedure described above. The CCT that can provide higher visual clarity was selected (no. 1 in Figure 14) to be compared with the third CCT. When all seven CCTs were compared, the CCT that can provide the highest visual clarity was selected (no. 3 in Figure 14). Then, the above steps were repeated with the remaining six CCTs to select the CCT which can provide the highest visual clarity among the six CCTs. In this way, the seven CCTs can be arranged according to the magnitude of the visual clarity (as shown in the third part of Figure 14). To quantify the results, the seven kinds of LEDs were graded in order with seven points for the clearest and one point for the least clear.

3.4. Experimental Results. Figure 15 shows the effects of luminance and fog concentration on human eye perception luminance when using 6500K of LED. The theoretical calculation results in Figure 15(a) are taken from Figure 10. The smallest E that the subjects could see clearly and distinguish the direction is indicated by the scores in Figure 15(b). The higher the scores, the better the visual clarity.

Figure 16 shows a part of the experimental results and the values of L_f calculated in Figure 10. The rest of the results not presented in the figure have a similar pattern. The results of the experiment were taken as the average of 50 subjects. The dispersion of the data was estimated in terms of standard deviation. In Figure 16 Y-axis on the left shows the levels of perception luminance under different fog concentrations

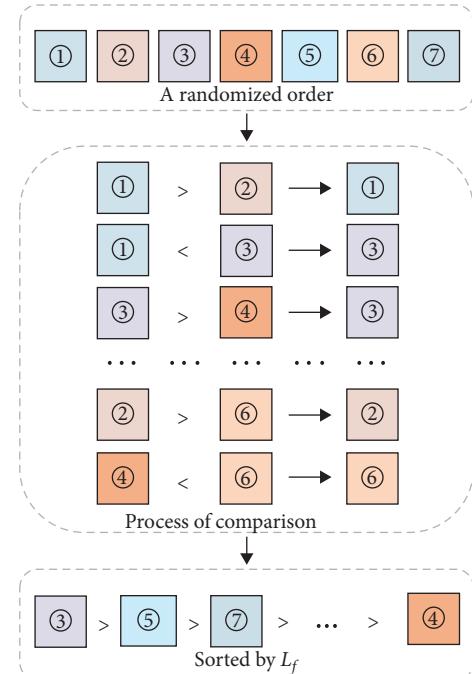


FIGURE 14: The method of selection sort.

and illuminance without fog and the one on the right shows the results of L_f .

4. Discussion

Comparing Figures 15(a) and 15(b), it is concluded that the curvilinear trends are substantially the same. When luminance or transmittance increases, the perception luminance or the score increases. That is to say, when the lighting environment or visibility is well, the human eye can obtain better visual clarity.

In Figure 15(b), when $L = 4 \text{ cd/m}^2$ and $T = 100\%$ and 80% , the standard deviation is 0 and the scores are 6. This is because when the luminance level is high, all the subjects can distinguish the minimum line of the visual chart. When the luminance and transmittance are very low ($L = 1 \text{ cd/m}^2$, $T = 20\%$), the standard deviation indicates that some subjects can distinguish the second largest line of visual chart, and others can only distinguish the largest line, indicating that the subjects have different ability of visual distinction under low luminance and low fog transmittance. In the lower left corners of the figure ($L = 1 \text{ cd/m}^2$, $T = 20\%$, 40% and 60%), the trend of the curve is growing slowly, indicating that,

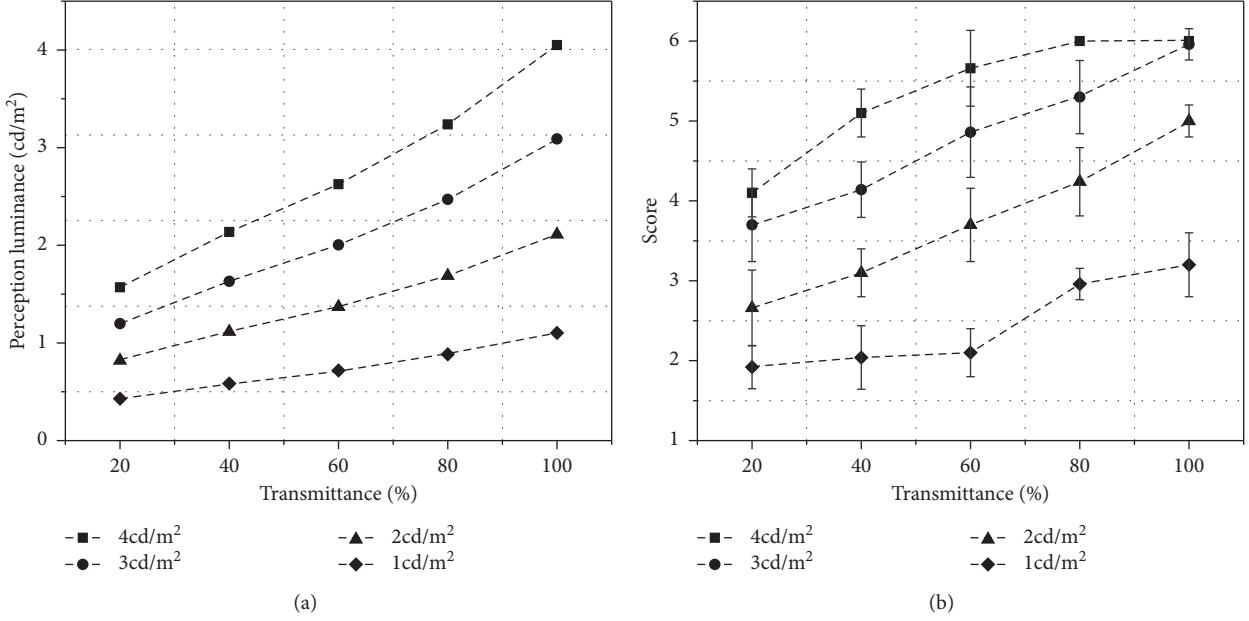


FIGURE 15: The impact of the luminance and the concentration of fog on perception luminance. (a) The theoretical calculation results of perception luminance under different luminance and fog concentration, CCT = 6500K. (b) The experimental results of the average scores of 50 subjects on visual perception under different luminance and fog concentration, CCT = 6500K. Error bars indicate standard deviation.

under such conditions, subjects can only distinguish the larger lines.

Combining these two figures, it can be inferred that luminance and fog transmittance greatly affect the clarity of the human eye. When the luminance is lowered or the fog concentration is increased, it will cause a decrease in visual clarity. When the luminance level is high, as the fog transmittance increases, the visual clarity will decrease more severely. High fog concentration environment seriously affects driver's visual clarity. Visual clarity can be improved to some extent by increasing the luminance, but this method is restricted. When the fog concentration is high, the degree of improvement in visual clarity is smaller.

In Figure 16(a), for example, according to the clarity of visual chart observed by subjects, the seven CCTs are ranked from large to small: 5700K > 6500K > 4500K > 5000K > 4000K > 3500K > 3000K. Although there are some errors between L_f obtained by theoretical calculation and the order of CCTs obtained by experiment, it is not difficult to deduce the rule that the visual clarity increases with the increase of CCT, which verifies the theoretical calculation results. The errors may be caused by the little influence of CCT on perception luminance, which cannot be determined by human eyes. The difference in perception luminance between two adjacent CCTs is about 0.02 cd/m². It seems that CCTs has little effect on visual clarity when compared to luminance and fog concentration. However, the subjective luminance perception is a psychological quantity rather than a physical quantity. When the ambient luminance is lower, the human eye can detect more subtle changes in luminance. That is why the subjects were able to distinguish between seven different CCTs in the experiment. In a real tunnel, when the

luminance is fixed and the fog concentration is high, the effect of CCT on the clarity of human eyes can no longer be ignored for safe driving.

It can be seen from Figure 16 that the mean score of clarity increases as CCT increases under a certain concentration of fog and illuminance. As the transmittance or the illuminance decreases, the curves become more linear and the standard deviations decrease, which means that, under a condition with high concentration of fog (low transmittance) or a low luminance (dark environment), the effect that LEDs with higher CCT can provide higher clarity is more obvious. The results are consistent with the theoretical analysis. It can be concluded that LED with higher CCT will provide higher visual clarity to human eyes in a certain fog concentration and luminance environment under mesopic vision. As the common range of CCT of LED is 3000K to 6500K, 6500K is recommended as a more reasonable CCT for the interior zone of tunnel.

In a real tunnel, luminance is still the main factor for safety. The design of luminance requires a trade-off between energy saving and traffic safety. Fog concentration can be understood as equivalent luminance attenuation, and it also has an important impact on safety. By contrast, the CCT has little influence on the traffic safety, and LED with high CCT can slightly improve the visual clarity. In addition to improving the traffic safety in a tunnel from the perspective of lighting, it is also possible to improve the safety by limiting the vehicle speed (reduces visual reaction time) and improving the materials of walls and roads of tunnels (increase visual contrast). Considering that the vehicle speed and layout of lamps in the tunnel can cause a flickering seizure amongst drivers and passengers by generating cyclical repetitions of light flows [27], while ensuring that luminance

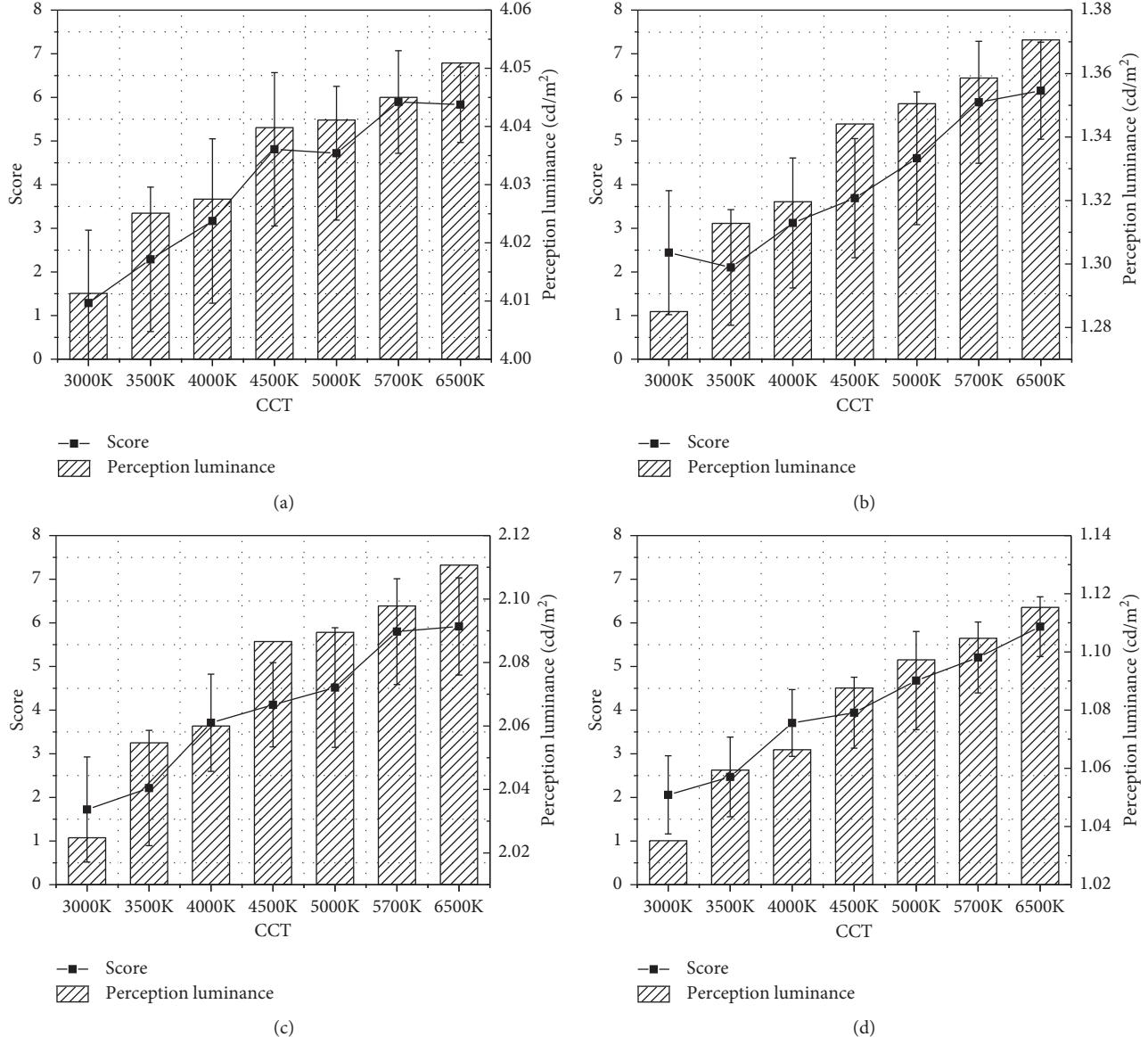


FIGURE 16: The Y-axis on the left shows the levels of visual clarity using different CCTs under different fog concentrations and illuminance without fog. The Y-axis on the right shows the theoretical calculation results of L_f . (a) $T=100\%$, $L_i=40\text{lx}$. (b) $T=60\%$, $L_i=20\text{lx}$. (c) $T=100\%$, $L_i=20\text{lx}$. (d) $T=40\%$, $L_i=20\text{lx}$. Error bars indicate standard deviation.

and lighting uniformity are in accordance with tunnel lighting specifications, the placement spacing of lamps should be considered to prevent the flickering problem in tunnels. According to the luminance requirements of the interior zone, using low-power LED with dense distribution will save energy and ensure traffic safety. The effect of CCT on flickering seizure can be further studied.

5. Conclusion

In this paper, the effects of LEDs with seven CCTs on perception luminance are studied considering fog transmittance and mesopic vision in tunnel from the point of view of energy saving and traffic safety. Firstly, the formula for calculating perception luminance was proposed, and the

transmittance of nine monochromatic LEDs was obtained by an experiment. And then it was applied to LEDs with seven CCTs composed of multispectrum. The SPDs of the seven CCTs were measured by spectral radiance meter under the absence of fog. Comparing several different mesopic vision models, the MES2 model was selected to calculate the mesopic spectral luminous efficiency function of human eye.

Then, the perception luminance was calculated considering different levels of fog and luminance in mesopic range. The results show that LEDs with higher CCTs (about 6500K) can provide higher perception luminance. Luminance and fog concentration have more influence on perception luminance, compared with CCT. Higher luminance or lower fog concentration can obtain higher perception luminance.

Finally, an experiment was conducted to measure the visual clarity of human eyes. The visual clarity is indirectly represented by the effect of LEDs on perception luminance under various CCTs and different levels of luminance and fog concentration. The results showed that LED with high CCT (6500K) will always provide higher visual clarity to human eyes in a certain fog concentration and luminance environment. High luminance and transmittance can provide the subjects with better visual clarity, whose effect is much greater than CCTs. In foggy environments, increasing luminance helps subjects improve visual clarity, but the improvement becomes more restricted as transmittance decreases.

These results can provide a reference for tunnel lighting considering mesopic vision and fog conditions. In the interior zone of tunnel, drivers can obtain higher visual clarity and safety index by increasing luminance (more energy consumption) or decreasing fog concentration (strengthening tunnel ventilation or regularly cleaning the dust inside the tunnel). When the fog concentration is too high, the effect of increasing the luminance to increase the visual clarity will become less obvious. If the fog concentration in the interior zone is too high, it is not recommended to open the tunnel to traffic for safety. The effect of CCT is relatively inferior to luminance and fog concentration. When designing a tunnel while putting into consideration the effect of LEDs on the perception luminance of the human eye or visual clarity in foggy conditions, which kind of CCT is applied does not make much difference. But LED with a CCT of 6500K is recommended as it still provides better visual clarity in a way if a comparison is to be made. The above content provides reference for the guideline of tunnel lighting for energy saving, traffic safety, and the selection of CCT of current popular luminaire, LED.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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