The Impact of Color Rendering on Perception Luminance in Interior Zone of Tunnel Considering Low Visibility

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Abstract. LED lights are widely used in highways and tunnels because of their long life, low light attenuation in recent years. The influence of color rendering (CRI) on lighting safety has attracted people's attention as the increase in demand. In this paper, the influence of different CRI on perception luminance of human eyes under different fog transmittance and different luminance was calculated and analyzed. A calculation model of human eye perception luminance considering mesopic vision and fog concentration was proposed. An experiment was conducted by observing different colored targets in a fog chamber. The results showed that yellow targets and high CRI can provide higher perception luminance and the latter is recommended for tunnel lighting in interior zone.

1. Introduction
Tunnel lighting plays an important role in ensuring traffic safety in the tunnel. Many specifications segment the tunnel into several zones, in which the luminance of interior zone is the lowest for about 1cd/m² ~ 10cd/m² [1-3]. In interior zone, the particles from vehicle emission and deposited dust can hover in the air for a long time and cause a low visibility condition. Both low brightness and visibility will seriously affect traffic safety.

LEDs are widely used in tunnel because of their long life and energy saving. Due to the manufacturing technique is different, the value of color rendering is different. The design department of tunnel lighting has no clear basis for the selection of this parameter at present. Some researchers have published articles on the transmittance of LED and mesopic vision. In 2006, Viikari [4] and others evaluated mesopic visual performance by measuring the reaction time and contrast threshold in different spectral conditions. In 2011, Li [5] and others presented that higher correlated color temperature (CCT) can provide better visual effects. And the mesopic equivalent illumination of the different sources was calculated. Huai [6] studied the effect of three CCTs on penetration properties in fog and presented that 3000K are more suitable for street lighting by calculating the transmittance. As for the application of color rendering, in 2003, Chol-Kon Chee [7] and others studied visual acuity with color rendering of light sources. The results showed that visual acuity is approximately proportioned to average color rendering index (CRI). In 2015, QY Zhai [8] and others presented that high CRI (over 90) LEDs are more suitable for observing museum paintings considering color quality. 2016, F Szabó [9] and others presented that LED with even spectral distribution and high color rendering can provide a better visual effect in offices, commerce and homes based on color quality scale.

At present, few researchers have studied the effect of color rendering on fog transmittance. In this paper, the impact of CRI on perception luminance of human eye under low visibility was studied. The results can provide reference for tunnel lighting specification.
2. Theoretical calculation

Whether the driver can perceive the obstacles ahead is the main factor affecting the traffic safety, which involves the theory of target-background contrast and perception luminance considering fog transmittance and mesopic vision. They can be calculated by the equation (1) ~ (4)

\[
C = \frac{|L_t - L_b|}{L_b},
\]

\[
L_t = \int_{200}^{780} k_{\text{mes}}(\lambda) \cdot \lambda \cdot L_{\text{mes}}(\lambda) \cdot R_t(\lambda) \, d\lambda,
\]

\[
L_b = \int_{200}^{780} k_{\text{mes}}(\lambda) \cdot \lambda \cdot L_{\text{mes}}(\lambda) \cdot R_b(\lambda) \, d\lambda,
\]

\[
L_c^*(\lambda) = L_c(\lambda) \cdot T(\lambda)
\]

where \(C\) refers to the target-background contrast, \(L_t\) refers to the perception luminance perceived from the targets, \(L_b\) refers to the perception luminance received from the background of targets. \(k_{\text{mes}}\) refers to the mesopic spectral luminous efficiency function. In this paper, the value of luminance was set to 4 cd/m² in the experiment, the curves of \(k_{\text{mes}}\) were shown in Figure 1(a). \(L_c^*(\lambda)\) refers to spectral radiance distribution curve under a certain concentration of fog. \(R_t(\lambda)\) refers to the reflection wavelength of background. The curves of \(R_t(\lambda)\) and \(R_b(\lambda)\) are shown in Figure 1(b). \(L_c(\lambda)\) refers to spectral radiance distribution curve measured by spectral radiance meter under the absence of fog, which was shown in Figure 1(c). \(T(\lambda)\) refers to the transmittance of different wavelength at a certain fog concentration, which has been tested before and shown in Figure 1(d).

![Figure 1](image1.png)

![Figure 1](image2.png)

Figure 1. The curves of the parameters in equation (1) ~ (4). (a) \(k_{\text{mes}}\). (b) \(R_t(\lambda)\) and \(R_b(\lambda)\). (c) \(L_c(\lambda)\) and (d) \(T(\lambda)\).

Figure 2 shows the calculation results of the target-background contrast under the luminance of 4 cd/m², the transmittance of 20% and 80%, 4 CRI conditions (55, 65, 75 and 85) and 4 colors for target (blue, green, yellow and red). It can be seen that the value of contrast under the transmittance of 20% is
smaller than the value under the transmittance of 80%. As for the influence of CRI on contrast, the contrast of blue, green and yellow targets increase with the increase of CRI. On the contrary, the blue target shows the opposite trend. From the results of theoretical calculation, it can be preliminarily judged that the use of high CRI can provide higher target-background contrast, yellow is better than the other colors, which are helpful for improving traffic safety.

![Figure 2](image)

**Figure 2.** The calculation results of the target-background contrast under 4 CRIs and 4 colors. (a) Transmittance = 20%, (b) Transmittance = 80%.

3. **Experiment and results**

3.1. **Experimental setup**

Figure 3 shows the schematic diagram of experimental set-up. The fog chamber was made by wood and organic glass, the size of which was 500×500×500 mm³. The interior of the chamber was painted black to avoid the diffuse reflection of light. The inside of the chamber was divided into 2 sealed cavities, which do not affect each other. It has been confirmed that the organic glass has little effect on spectral power distribution or visual perception except reducing luminance. Two sides of the chamber were made of glass and LEDcubes which can simulate different SPDs were put on two sides. The side near the observer was also partly made of glass for observing. Two visual targets were attached on the side away from the observer, below which were two illuminometers to measure the illuminance and calculate the transmittance. The fog generator was put behind the fog chamber, which could produce stable and uniform fog. The distance between the subjects and the fog chamber is 1 m. 10 observers with normal color vision and normal eyesight participated in this experiment.

According to previous studies on CCTs, 4500K was considered to be the best choice, so CCT with 4500K was also used in this article. The value of luminance was selected as 4 cd/m² as same as in interior zone of tunnel. We chose 4 CRI values (55, 65, 75 and 85), 4 colors for target (blue, green, yellow and red) and 2 fog transmittance values (20% and 80%). The values of transmittance can be calculated by dividing the illumination in the presence of fog by the illumination in the absence of fog. The stability of fog concentration can be maintained by controlling the emission flow of the fog generator.

Firstly, the LEDcubes on both sides were adjusted into a standard light (CRI = 85) for reference to calculated the fog transmittance. The fog generator emit fog until the fog concentration of the two cavities reaches the demanded value. The effect of different colors on contrast was tested first. Under the premise of keeping other conditions unchanged, subjects were asked to observe and compare the brightness of different colored objects in both cavities (transmittance = 20%, CRI = 75, as the trends in theory calculation are same under different parameters). The colors of the objects in both cavities remain the same when studying other variables.

Then LEDcubes were adjusted into different CRIs for comparison. Subjects were asked to observe the brightness of the targets in two cavities and choose a brighter one. Then change another CRI to
compare with it. When 4 kinds of CRI were sorted in order of perception luminance, another color target was used for observation, and the perception luminance provided by the 4 CRIs was compared again. When all 4 colors were tested, the other fog transmittance was used in the experiment. According to the value of the perception luminance provided by the CRIs, the value of CRI was sorted. 4 points for the maximum perception luminance and 1 point for the minimum. Figure 4 shows part of the conditions under different CRIs, transmittance and color of targets.

Figure 3. The schematic diagram of experimental set-up.

Figure 4. The schematic diagram of subjects’ perspective under different transmittance, CRI and color conditions.

3.2. Results and discussion
Figure 5 shows the experimental results using different colors of targets in two cavities under the condition of 20% of transmittance and 75 of CRI. The Y-axis on the left indicates the perception luminance of the subjects in the experiment, and the error bar indicates the standard deviation. The Y-axis on the right indicates the theoretical calculation of perception luminance. It can be seen that the experimental results are consistent with the theoretical values. The yellow target provided the highest perception luminance, followed by red, blue and green. The standard deviation of yellow is the smallest.

It can be seen in Figure 6 that when using blue, green and yellow targets, CRI is positively correlated with perception luminance. However, when using red targets, as CRI increases, the perception luminance decreases. Different transmittance didn’t affect the trend of results. Because as the fog concentration increases, the luminance must decrease, which isn’t discussed in detail here. Compared with the theoretical calculation results, the experimental results have a similar trend. As most colors
show a positive correlation between CRI and perception luminance, it can be concluded that LED with high CRI should be used in interior zone of tunnel for safety.

Figure 6. The experimental results under different transmittance, CRI and color conditions. (a) Transmittance = 20%. (b) Transmittance = 80%. Error bar shows the standard deviation.

4. Conclusions
In this paper, the impact of CRI of LED was discussed considering different fog transmittance of colors of targets under mesopic vision. Firstly, the theoretical calculation model is established. Then a fog chamber system was built to simulate the environment of the interior zone of tunnel. Subjects were asked to compare the perception luminance of objects in the two cavities. The results showed that the yellow target provided the highest perception luminance, followed by red, blue and green. It can be concluded that yellow cars are safer and green cars are less safe. Use yellow traffic signs could be more visible and striking. Most colors show a positive correlation between CRI and perception luminance. Given the transmittance and mesopic vision, high CRI (over 85) is recommended for tunnel lighting.

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References
[1] Commission Internationale de l’Eclairage, CIE. Tunnel Entrance Lighting: A Survey of Fundamentals for Determining the Luminance in the Threshold Zone; CIE Publication: Vienna, Austria, 1984; Volume 61.
[2] European Committee for Standardization, Lighting Applications-Tunnel Lighting, European Committee for Standardization, BS EN Publication UK, 2003.
[3] Commission Internationale de l’Eclairage, CIE. Guide for the Lighting of Road Tunnels and Underpasses; CIE Publication: Vienna, Austria, 2004; Volume 88.
[4] Viikari, M.; Chen, W.; Eloholma, M.; Halonen, L.; Chen, D. Comparative study of two visual performance based mesopic models based on reaction time and contrast threshold data. Light & Engineering 2006, 14, 21-32.
[5] Li, X.; Shang, Z.J.; Song, Y.C.; Le, W.; Xiao, Y.L. The mesopic effect of different color temperature LED light sources on road lighting. Communications and Photonics Conference and Exhibition, Shanghai, China, 8-12 Dec 2010; pp. 343-344.
[6] Huai, Z.J.; Shang, Z.J.; Liang, C.; Kun, Y. Research on the lighting performance of led street lights with different color temperatures. IEEE Photon. J 2015, 7, 1601309.
[7] Chol-Kon Chee, Chin-Woo Yi, Kyung-Ae Cho, A Study on Visual Acuity According to Color Temperature and Color Rendering of Light Sources, Proceedings of Annual Conference of The Illuminating Engineering Institute of Japan,2003,81.
[8] Zhai, QY et al. The impact of LED lighting parameters on viewing fine art paintings. Lighting Research & Technology. 2016,711-725.
[9] Szabó et al. A study of preferred colour rendering of light sources: Home lighting. Lighting Research & Technology. 2016, 103-125.