Research Article
Vol. 59, No. 3 / 20 January 2020 / Applied Optics 683
applied optics

Luminance calculation method accounting for mesopic vision and fog penetration ability

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Received 30 September 2019; revised 27 November 2019; accepted 2 December 2019; posted 3 December 2019 (Doc. ID 379163); published 15 January 2020

A new luminance calculation method that accounts for mesopic vision and fog penetration ability is presented. This method aims to select a suitable light source for street lighting and is obtained using the mesopic luminance calculation and transmittance calculation methods at each individual wavelength. Additionally, the new method was evaluated using six LED light sources between 3500 and 6000 K. Overall, the calculation results indicate that suitable LEDs' CCT decreases with an increase of luminance for low transmittance rates. However, for high transmittance rates, high CCT LED lamps are the most suitable for street lighting. The recommended CCT of LED light sources for street lighting under different visibility and luminance conditions is presented.

https://doi.org/10.1364/AO.59.000683

Human visual response varies according to ambient light levels, where the mesopic luminance level ranges from 0.001 cd/m^2 to "at least several cd/m^2" [1,2]. Street lighting is one of the essential application areas for mesopic photometry [3–5]. Mesopic, scotopic, and photopic vision differ from each other in that, in the first, both cones and rods contribute to the vision; in the second, only rods contribute to the vision; and, in the third, only cones contribute to the vision [6]. Thus, the spectral luminous efficiency function in the mesopic range is not constant and varies at different mesopic luminance states, which can be expressed as a liner combination of photopic V(λ) function and scotopic V′(λ) function [7]. Additionally, human visual response in the mesopic region varies greatly with the spectral power distribution of light sources. Various studies show that light sources with more short-wavelength spectral content lead to higher perception luminance or luminous efficiency [8–10]. Yukio *et al.* [11] compared the response time of subjects when using ceramic metal halide (CMH) and high-pressure sodium (HPS) to provide light under mesopic light levels. The study concluded that response time for CMH was shorter compared with HPS at the same light level. Yang *et al.* [12] compared the performance of five light sources: high-pressure sodium (HPS) 1958K; fluorescent (FL) 5537K; LED1# 3177K; LED2# 4054K; and LED3# 4765K. Experiment results showed that reaction times for FL and LED were shorter compared with those of HPS for the same background luminance. Additionally, the reaction time for the high CCT LED was shorter compared with the low CCT LED. Jin *et al.* [13] studied three types of white light-emitting diodes (LEDs) to investigate the luminous efficiency difference in the mesopic region: the cold white LED (8000K); the neutral white LED (4500K); and the warm white LED (3500K). Experiment results showed that the luminous efficiency of an 8000K LED is 53% higher than that of a 3500K LED in the mesopic vision state at 0.1 cd/m^2. Dong *et al.* [14] estimated six types of LEDs to evaluate the effect of LED CCT on visual performance in the mesopic condition. Results showed that the mesopic luminance is increased with the increasing of CCT, and the reaction time of observers in mesopic vision is decreased with the increasing of the CCT. Jin *et al.* [15] reported that high CCT (color-correlated temperature) LEDs have higher mesopic vision illuminance and luminance efficiency. Sushais [16] studied the effect of LEDs' spectral power distribution on mesopic lighting design. This study showed that LED light sources with more long-wavelength components produce a lower mesopic luminance than those with more short-wavelength components. Zak and Zalesak [17] studied the effect on visual perception of different light sources in street lighting. The results showed that the spectral properties influence the visual comfort and visual performance in public lighting. It is noted from the studies that, in the mesopic region, the perception luminance of LED is higher than other light sources. In addition, the higher the CCT of LED, the higher the perception luminance. Based on the studies, an LED with high CCT would be more suitable for street lighting.

Another important factor to consider in street lighting is the fog penetration ability of a light source [16], as street lamps are intended to illuminate a street under lower meteorological visibility conditions (foggy or hazy weather). Shi *et al.* [18] investigated the penetration ability of different color LED light sources, including white, red, yellow, green, and blue. Experiment results showed that the yellow LED had the best fog penetration ability, followed by white LED. The red LED had the worst fog penetration ability. Xu *et al.* [19] evaluated the lighting performance of two LEDs (3100K and 6500K) under a fog environment during day and night. Results showed that the object recognition rate for the low CCT LED is higher than for the high CCT LED. Xe *et al.* [20] studied the fog penetration ability of four common light sources, i.e., tungsten filament lamp (TFL), LED, MH, and HPS, in mesopic vision. Experiment results showed that the fog penetration ability of the tungsten filament lamp is the best, while that of LED is the worst. It is noted from the studies that yellow light has better fog penetration ability than white light. Thus, from the fog penetration ability point of view, low CCT LED is more suitable for street lighting.

Because the perception luminance is influenced by mesopic vision and fog penetration ability, both factors should be considered when selecting a suitable light source for street lighting. In addition, the main purpose of street lighting is to provide adequate luminance to allow the safe maneuver of drivers [21]. Therefore, the perception luminance is the most appropriate metric for evaluating which light source is the most suitable. Based on the latter consideration, the study in this paper presents a new perception calculation method considering mesopic vision and fog penetration ability. This method aims to select appropriate LED light sources for street lighting.

During good visibility, mesopic luminance can be calculated using the MES2 method, which is recommended by the Commission internationale de l'éclairage (CIE) [22], and is written as

$$M(m)\, V_{\mathrm{mes}}(\lambda) = m V(\lambda) + (1-m)\, V'(\lambda)\,, \tag{1}$$

$$L_{\mathrm{mes}} = \frac{683}{V_{\mathrm{mes}}(\lambda_0)} \int_{380}^{780} V_{\mathrm{mes}}(\lambda)\, L_e(\lambda)\, \mathrm{d}\lambda, \tag{2}$$

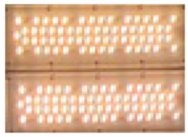
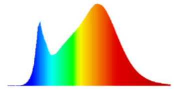
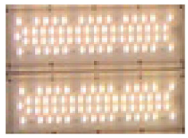
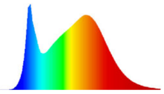
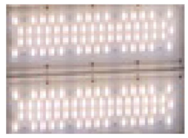
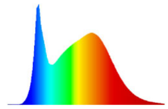
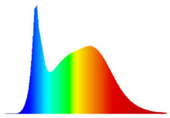
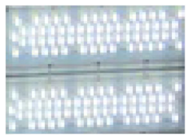
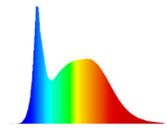
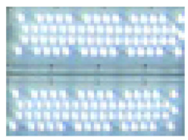
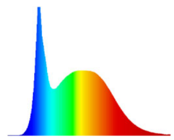
where $M(m)$ is a normalizing function such that $V_{\mathrm{mes}}(\lambda)$ attains a maximum value of 1; $V_{\mathrm{mes}}(\lambda)$, $V(\lambda)$, and $V'(\lambda)$ are the mesopic, photopic, and scotopic luminous efficiency curves, respectively; m is a parameter characterizing the proportion of the photopic luminous efficiency; L_{mes} is the mesopic luminance; $V_{\mathrm{mes}}(\lambda_0)$ is the value of $V_{\mathrm{mes}}(\lambda)$ at 555 nm; $L_e(\lambda)$ is the spectral radiance distribution curve measured under a fog absence condition ($\mathrm{W/m^2 \cdot sr \cdot nm}$); below $0.005\ \mathrm{cd/m^2}$, $\mathrm{m} = 0$; above $5\ \mathrm{cd/m^2}$, $\mathrm{m} = 1$.

The mesopic luminance L_{mes} and the coefficient m are calculated iteratively:

$$L_{\mathrm{mes},n} = \frac{m_{(n-1)} + \left(1 - m_{(n-1)}\right)(S/P)\, V'(\lambda_0)}{m_{(n-1)} + \left(1 - m_{(n-1)}\right) V'(\lambda_0)} L_p, \tag{3}$$

$$m_n = 0.767 + 0.3334 * \log 10\left(L_{\mathrm{mes},n}\right) \quad 0 < m_n < 1, \tag{4}$$

Table 1. S/P Ratio, Physical Picture, and SPD of Six LED Lamps

CCT(K)	S/P Ratio	Physical Picture	SPD
3500	1.5903		
4000	1.8376		
4500	1.9845		
5000	2.0966		
5500	2.2097		
6000	2.2979		

$$\frac{S}{P} = \frac{1699 \cdot \int_{380}^{780} S(\lambda)\, V'(\lambda)\, \mathrm{d}\lambda}{683 \cdot \int_{380}^{780} S(\lambda)\, V(\lambda)\, \mathrm{d}\lambda}, \tag{5}$$

where the S/P ratio is defined as the ratio of two luminous outputs evaluated by $V'(\lambda)$ and $V(\lambda)$, respectively, which only depends on the relative spectral power distribution of the light source. L_p is the photopic luminance; $V'(\lambda_0) = 683/1699$ is the value of the scotopic spectral luminosity function when $\lambda_0 = 555$ nm; n is the step of iteration; and $S(\lambda)$ indicates the spectral power distribution of LED lamps.

In this paper, a new metric for street lighting that accounts for fog penetration street is proposed. The proposed method uses Eq. (2) as the basis, which can be rewritten as follows:

$$L_p^* = 683 \int_{380}^{780} V(\lambda)\, L_e^*(\lambda)\, \mathrm{d}\lambda, \tag{6}$$

$$L_{\mathrm{mes}}^* = \frac{683}{V_{\mathrm{mes}}(\lambda_0)} \int_{380}^{780} V_{\mathrm{mes}}(\lambda)\, L_e^*(\lambda)\, \mathrm{d}\lambda, \tag{7}$$

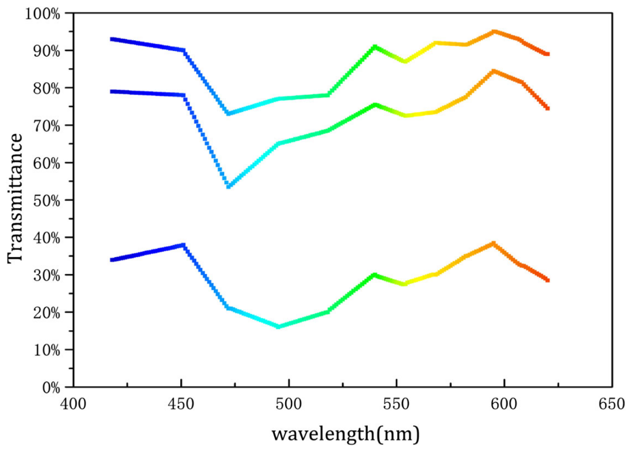


Fig. 1. Transmittance rate versus wavelength for three fog conditions (T1, T2, and T3).

where $L_e^*(\lambda) = T \cdot L_e(\lambda)$ is the spectral radiance of a light source after attenuation; T is the transmittance rate at each individual wavelength under a certain visibility condition.

Six street LED lamps with different CCTs were used to evaluate the effectiveness of the proposed method. The power and the photopic luminance efficiency are 80 W and 110 lm/W, respectively. Table 1 gives the S/P ratio, physical picture, and spectral power distribution (SPD) of six LEDs measured under transmittance rate = 1 and $L_p = 1\ \mathrm{cd/m^2}$.

Figure 1 shows the transmittance rate at each individual wavelength [23,24]. As observed in Fig. 1, the wavelengths in yellow, at about 580 nm, have the greatest transmittance ability. Moreover, the transmittance rate curves are similar for different visibility conditions. The main difference between these curves is the magnitude of the transmittance.

L_p^* and L_{mes}^* values for different transmittance rates are in Table 2. As observed from Table 2, L_{mes}^* is always larger than L_p^*. Furthermore, for the T1 condition, the largest L_p^* in $L_p = 1, 2,$ or $3\ \mathrm{cd/m^2}$ is achieved at 6000K LED; for the T2 condition, the largest L_p^* in $L_p = 1, 2,$ or $3\ \mathrm{cd/m^2}$ is achieved at 5500K LED; for the T3 condition, the largest L_p^* in $L_p = 1, 2,$ or $3\ \mathrm{cd/m^2}$ is achieved at 3500K LED. However, for the T3 condition, the largest L_{mes}^* in $L_p = 3\ \mathrm{cd/m^2}$ is achieved at 5500K LED; for other conditions, the largest L_{mes}^* is achieved at 6000K LED.

Figure 2 provides recommended suitable LEDs for a mesopic luminance range and different transmittance rates ($0.4 \sim 1$) when only the fog penetration factor is considered. Figure 3 shows the recommended suitable LEDs based on the new calculation method. A comparison between Figs. 2 and 3 illustrates how the new method influences the perceived luminance, which in turn affects the suitable LEDs for street lighting. It is noted from Fig. 2 that high CCT LED lamps are suitable for high transmittance rates. Likewise, low CCT LED lamps are suitable for low transmittance rates. However, according to Fig. 3, high CCT LED lamps are suitable for high transmittance rates and low luminance conditions. Also, according to Fig. 3, the suitable lamps vary with luminance conditions and transmittance rates. From the above analysis, under different transmittance rates and photopic luminance conditions, suitable LEDs are different for L_p^* and L_{mes}^*.

Table 2. L_p^* and L_{mes}^* for Different Transmittance Rates

L_P (cd/m²)	T	CCT (K)	L_p^* (cd/m²)	L_{mes}^* (cd/m²)
1	T1	3500	0.8848	0.9428
		4000	0.8919	0.9710
		4500	0.8961	0.9875
		5000	0.8979	0.9984
		5500	0.9018	1.0114
		6000	0.9028	1.0192
	T2	3500	0.6997	0.7404
		4000	0.7030	0.7597
		4500	0.7050	0.7710
		5000	0.7054	0.7782
		5500	0.7074	0.7872
		6000	0.7073	0.7923
	T3	3500	0.2786	0.2908
		4000	0.2781	0.2966
		4500	0.2778	0.2999
		5000	0.2770	0.3019
		5500	0.2769	0.3045
		6000	0.2762	0.3058
2	T1	3500	1.6368	1.8316
		4000	1.6501	1.8686
		4500	1.6579	1.8902
		5000	1.6612	1.9036
		5500	1.6684	1.9213
		6000	1.6701	1.9305
	T2	3500	1.2945	1.4429
		4000	1.3006	1.4668
		4500	1.3043	1.4807
		5000	1.3050	1.4889
		5500	1.3086	1.5004
		6000	1.3084	1.5058
	T3	3500	0.5155	0.5703
		4000	0.5144	0.5760
		4500	0.5139	0.5792
		5000	0.5125	0.5807
		5500	0.5123	0.5834
		6000	0.5110	0.5842
3	T1	3500	2.6543	2.7044
		4000	2.6758	2.7443
		4500	2.6884	2.7676
		5000	2.6938	2.7809
		5500	2.7054	2.8006
		6000	2.7083	2.8094
	T2	3500	2.0991	2.1342
		4000	2.1091	2.1582
		4500	2.1150	2.1722
		5000	2.1162	2.1793
		5500	2.1220	2.1913
		6000	2.1212	2.1956
	T3	3500	0.8359	0.8465
		4000	0.8342	0.8502
		4500	0.8333	0.8525
		5000	0.8311	0.8526
		5500	0.8307	0.8546
		6000	0.8287	0.8543

In summary, we proposed a new calculation method for assessing the perceived luminance of different light sources. Although street lighting corresponds to the mesopic vision

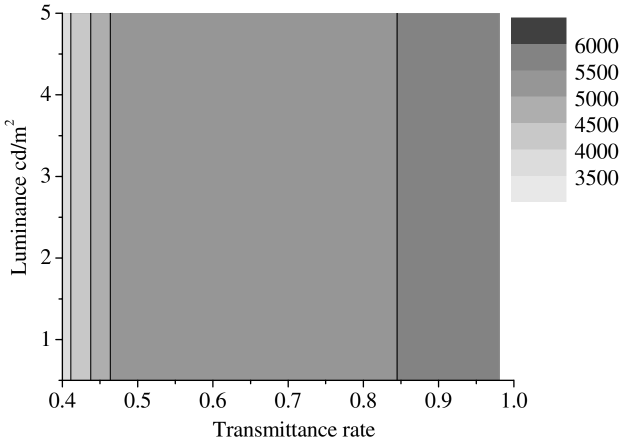


Fig. 2. Recommended light sources chosen results based on L_p^*.

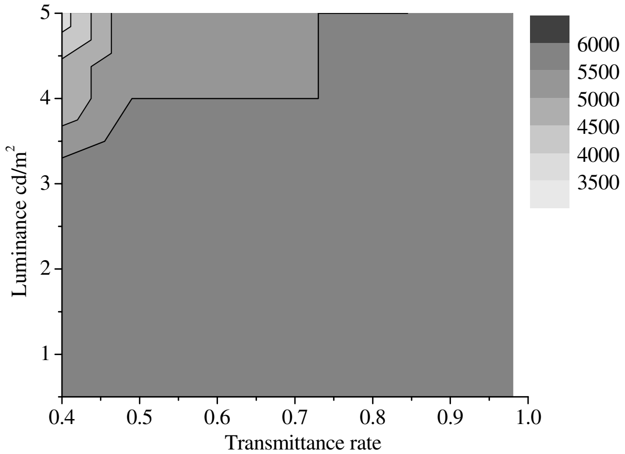


Fig. 3. Recommended light sources chosen results based on L_{mes}^*.

region, street lighting should consider foggy and hazy weather. Thus, a method for selecting suitable street lighting should account for fog penetration ability and mesopic vision. The applicability of this method was demonstrated using several LED light sources. Furthermore, the simplicity of the new metric makes it easy to apply and understand.

Funding. National Natural Science Foundation of China (61773225); K. C. Wong Magna Fund, Ningbo University

Disclosures. The authors declare no conflict of interest.

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