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Abstract: While light-emitting diodes (LEDs) are a very efficient lighting option, whether phosphor-coated LEDs (PC-LEDs) are suitable for street lighting remains to be tested. Correlated color temperature (CCT), mesopic vision illuminance, dark adaption, color perception, fog penetration, and skyglow pollution are important factors that determine a light's suitability for street lighting. In this paper, we have closely examined the lighting performance of LED street lights with different color temperatures and found that low-color-temperature (around 3000 K) PC-LEDs are more suitable for street lighting.

Index Terms: Light emitting diodes, lighting, mesopic vision, skyglow, fog transmission.

1. Introduction

Because of their increased luminous efficacy, reliability, and desirable color rendering qualities, white light-emitting diodes (LEDs) have been considered as the replacements for high pressure sodium (HPS) for street lighting. LEDs are efficient, have better longevity, and can be more easily controlled. In addition, LEDs have two other major advantages. One is that the shape of their light spot can be easily controlled for various purposes; the other is that their spectral power distribution (SPD) can be versatilely tailored using different kinds of LED chips or different kinds and different amounts of phosphor. Thus, the correlated color temperature (CCT) and illumination performance of an LED light source can be easily tailored as well.

The international luminance recommendation for road lighting is between 0.3 and 2 cd/m^2, which is at mesopic light levels [1]–[4]. This is important for safer and more energy-efficient driving conditions. If the light is too dark, it may negatively affect road safety; on the other hand, if the light is too bright, it will lead to more skyglow pollution and waste more energy. In mesopic lighting conditions, both rods and cones are active and participate in the visual response, which results in changes in spectral sensitivity [5]–[8]. Thus, under mesopic vision, the human eye is more sensitive to light of short wavelength. Therefore, white LEDs that have higher blue light component would have higher luminous efficacy under mesopic vision than under photopic vision. This trait has been previously seen as an advantage of white LEDs. However, these types of white LEDs, which have high blue light component and high CCT, have several disadvantages: a) They will harm the human eye's dark adaption and color perception abilities, b) they have insufficient fog penetration, and c) they produce fairly strong skyglow pollution. In other words, they may be harmful for road safety, astronomic observation, night time ecology and the aesthetics of the night sky [9]–[13]. Zabiliūtė *et al.* have also analyzed the effect of pc-LED road lighting on circadian action; the proposed pc-LEDs have low circadian action factor and, thus, are advantageous for use in low-luminance outdoor lighting that is photobiologically safe [5].

However, there are several important factors which determine whether a kind of light source is suitable for street lighting. First, at night, the environment luminance is of mesopic vision conditions. Thus, illuminance of a light source under mesopic vision conditions is important because street lights are primarily used to illuminate the roads during night time. Different roads and streets have different requirement for illuminance, and that provides another factor for choosing the right kind of LED for different kinds of roads. Second, the CCT of an LED needs to be considered. Humans are used to drive and walk under street lights of relatively low CCT, which is comfortable for humans. However, low CCT also reduces the color rendering index (CRI) and luminous efficacy of a light source, so a suitable CCT must be chosen. Third, the light's effect on human's dark adaption and color perception needs to be considered. According to statistics by CIE, the traffic accident rate during the night is three times the traffic accident rate during the day, and inefficient dark adaption is one important factor that leads to traffic accidents [1]. In order to make dark adaption faster and improve night time driver's driving safety and efficiency, low color temperature lights are generally used for illumination. Last, but not the least, fog penetration ability is an important factor because street lights are used to illuminate the road under foggy or hazy weather. Currently, the fog penetration ability of most white LEDs is not ideal. Low fog penetration ability also leads to higher urban skyglow pollution from white LEDs because of molecular (Rayleigh) and aerosol (Mie) scattering. Such scattering not only reduces the illumination of the ground and make ground objects difficult to see (and thus make the roads even less safe), the skyglow from scattering also has a harmful effect on astronomical research, and negatively affect the general aesthetics of the sky at night.

In this work, we have simulated the SPD of different LEDs, with different correlated color temperature (CCT), and calculated their performance including their mesopic vision illuminance, fog penetration ability, and skyglow. We also conducted experiments to explore their effect on human's dark adaption and color discrimination abilities. We then used actual LEDs with similar SPD, and measured their performance as well, and acquired the kind of LED suitable for street lighting.

2. Performance Calculation Methods

2.1. The Spectral Design of Street Lights

The optical performance, such as CCT, CRI, and LER are important. In this work, five LEDs of different CCT are designed by two part Gauss simulation model to design the spectra of LEDs [14], [15], and corresponding LED street lights are made accordingly, these LED street lights have CCTs of 1870 K, 2490 K, 3007 K, 4075 K, and 5020 K. The two part Gauss model in our previous research was a highly accurate model; among the five street lights, LED simulated by the model and the actual designed LED have a CCT difference under 40 K, a CRI difference under 1, color coordinates difference under 0.001 and an LER difference under 4%. The performance of LEDs we made is listed in Table 1. LED with 1870 K CCT has relatively low CRI, and low CCT LEDs have relatively low LER. Fig. 1 shows spectra of the five LEDs used in this research.

2.2. Analysis of Mesopic Vision Illuminance

Illuminance is defined as light flux over the area of a surface, as perceived by human eye. At night, the roads are illuminated only by street light instead of sunlight, and the surrounding is

TABLE 1

Performance of LEDs made

CCT (K)	CRI	LER (lm/W)	Coordinates (x, y)
1870	65.1	286.8	0.548, 0.400
2490	69.7	333.8	0.475, 0.413
3007	71.9	348.7	0.441, 0.412
4075	67.2	379.7	0.395, 0.430
5020	69.4	345.6	0.340, 0.358

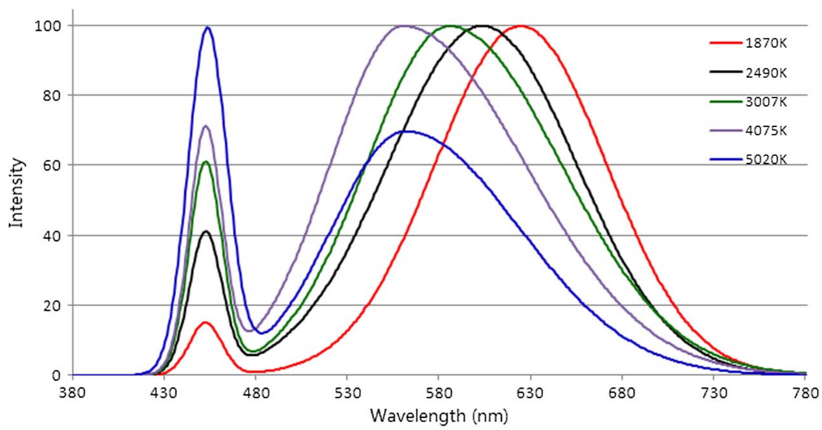

Fig. 1. Spectra of five LEDs used in this research.

relatively dim, which is under mesopic vision conditions (0.3 to 2 cd/m^2). Lights that have the same illuminance under photopic conditions may have different mesopic vision illuminance. According to Viikari *et al.*'s [6], [7] model on mesopic vision illuminance, Mesopic vision illuminance E_{mes} can be calculated using the following formula [8]:

$$E_{mes} = [x/683 + (1-x)(S/P)/1699]K_{mes}E_v/M(x) = B \bullet E_v \tag{1}$$

where $B = (x/683 + (1-x)(\mathrm{s}/\mathrm{p})/1699)K_{mes}/M(x)$ is a mesopic vision illuminance modified coefficient for different correlated color temperature LED light sources under mesopic light levels, s/p is the ratio of scotopic to photopic luminous output, x is a function of the photopic and scotopic values of the background luminance quantity, and $M(x)$ is a normalizing coefficient under this x. K_{mes} is the spectral luminous efficacy coefficient under the mesopic vision. Ev is the photopic illuminance value which can be obtained using a photopic luxmeter.

According to typical road luminance requirement of 1.8 cd/m^2, which is the road luminance requirement in Hangzhou, a typical Chinese city, the modified coefficient B of the five CCT street lamps above are 1.018,1.020,1.026,1.033, and 1.047, respectively. This means when using these five LED street lamps for road illumination, road illuminance can be 1.8%, 2%, 2.6%, 3.3%, and 4.7% lower than the designed needs (20–30 lx), and this will have minimal effect on the design and production of actual street lamps.

2.3. Lighting Performance Tests

2.3.1. Dark Adaption Test

According to required steps in Industry standard of Chinese Ministry of transportation (Automobile driving suitability evaluation test, JT/T 442-2001) [16], we have conducted a test to measure the dark adaption of the five LED light sources. Fifty healthy subjects, i.e., 33 men and

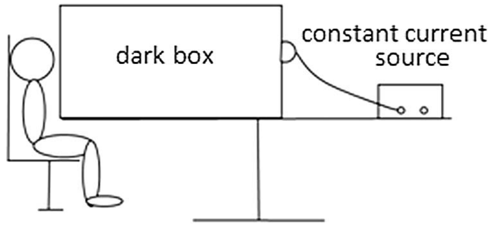

Fig. 2. Dark adaption test set up.

TABLE 2
Dark adaption time for five LED light sources of different CCTs

CCT(K)	1830	2490	3007	4075	5020
Dark adaption time(s,30lx)	85	102	112	120	126
Dark adaption time(s,50lx)	95	114	124	133	140

17 women of 22 to 56 years old, with normal color sense and vision acuity (corrected vision above 1.0) are tested. We also made sure they do not have any conditions that may affect their night vision. We are using five LED lights, of CCT of 1870 K, 2490 K, 3007 K, 4075 K, and 5020 K, for the dark adaption test.

2.3.1.1. Test set up

The lab room is 3.8 m $\times$ 7.6 m; the LED light source (power: about 30 W) of each CCT is installed 0.5 m from the ceiling, and the test subject sits normally before the dark box as in Fig. 2. The observation window of the dark box is 1.25 m from the ground, and the illuminance values of all LED lights are adjusted to 50 or 30 lx. The vision objective is a Landau's ring whose diameter is 3 cm and luminance is 3×10^{-4} cd/m^2. The Landau's ring is fixated in the central of the back of the 0.97 m long dark box; its luminance is controlled by a constant current power source.

2.3.1.2. Test process

Turn on the LED lights. After the test subject sits for 10 minutes, turn off the LED light, and count the dark adaption time using a stopwatch. Register the dark adaption time when the test subject recognizes the opening position of the Landau ring. Repeat for other LEDs with other CCTs.

Table 2 is the average dark adaption time of test subjects when illuminated by the five LEDs with different CCTs at 50 and 30 lx. As we can see, high CCT LEDs with higher blue components is not ideal for dark adaption, while low CCT LEDs have higher long wavelength components and are ideal for dark adaption. Also, when illuminance increases, dark adaption time increases as well. Therefore, low CCT, warm white LED light source is more suitable than high CCT LEDs for safe road lighting in terms of dark adaption.

2.3.2. Color Discrimination Test

The test is conducted in a dark room, and uses the five LEDs above as test light sources, and uses color pieces of 15 different colors that show different colors in natural light as reference. Test subject view the color pieces from 20 cm away; each subject tries to distinguish randomly placed 60 color pieces (every color has four pieces) under every type of light, group the color pieces of the same color type together. If the same color type is not grouped together or if the color pieces are not grouped in the order of the reference color pieces, it counts as a failed attempt to discriminate the colors [17]. The color and CIE $L^*a^*b^*$ values are shown in Table 3.

TABLE 3

Fifteen kinds of color pieces and $L^*a^*b^*$ values

Reference color	Color	L*	a*	b*
1	Deep green	39.19	-27.39	20.4
2	Blackish green	27.89	-10.24	4.02
3	Yellow	69.04	-5.24	62.51
4	Turquoise	66.36	-25.36	-6.34
5	Dark blue	60.95	-1.67	-20.05
6	Gold	55.29	18.62	57.81
7	Green	79.62	-28.94	62.44
8	Watermelon red	42.34	39.77	4.25
9	Red	30.04	44.8	14.38
10	Orange	40.71	37.26	44.37
11	Light purple	54.22	15.19	-20.18
12	Pink	66.55	17.06	-8.37
13	Sapphire	22.64	12.49	-35.85
14	White	73.2	-0.5	-6.22
15	Beige	72.05	0.19	5.51

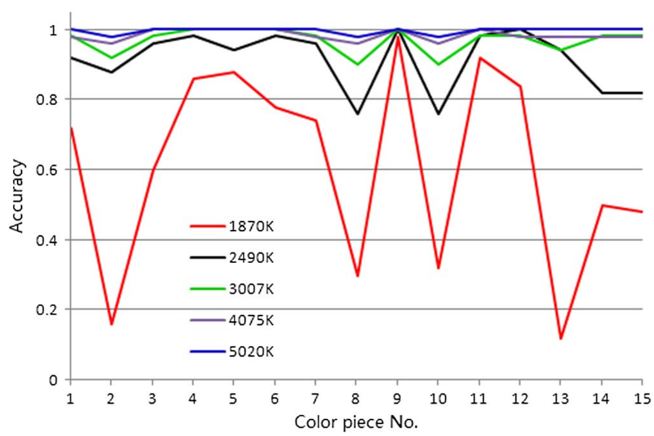

Fig. 3. Color discrimination accuracy under LEDs of five CCTs.

Fig. 3 illustrate the color discrimination accuracy under LEDs of different CCTs. Under 1870 K, the color discrimination accuracy of different color pieces vary greatly, and the total correct rate is low. As CCT increases, the human eye's ability to distinguish colors improves as well. When CCT is above 3007 K, color discrimination accuracy is near 100%. This means that a human's color discrimination abilities are the lowest when illuminated by LED of 1870 K CCT in these five LEDs.

2.3.3. Analysis of Light's Fog and Haze Penetration

Light can transmit through air easily. However, because of Rayleigh scattering and Mie scattering, light could not fully transmit through fog or haze. Light of different wavelength transmits differently through fog or haze: the amount of Rayleigh scattering caused by light is inversely proportional to the fourth power of wavelength, while the amount of Mie scattering is inversely proportional to wavelength.

The amount of Rayleigh and Mie scattering gives a general idea of fog and haze penetration ability of a light source. However, light has different penetration capabilities through different kinds of fog or haze compositions. In general, and yellow light has better fog penetration capabilities than white light. In this research, an experiment is used to measure the fog penetration ability.

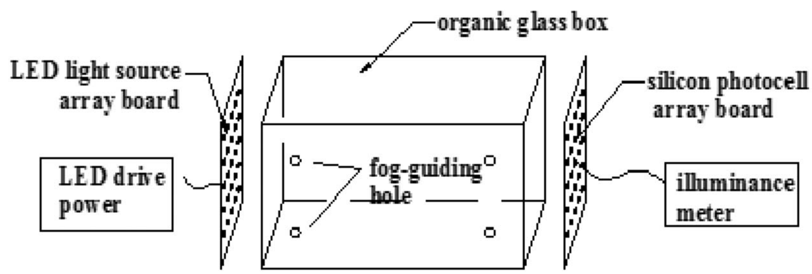

Fig. 4. Schematic drawing of the measurement apparatus.

It included an organic glass box, the volume of which was 500 $\times$ 500 $\times$ 1000 mm3, and five different CCTs above groups of LEDs, each group of which was composed of 25 LEDs of the same CCT. 25 V(λ) calibrated silicon photocell detectors and illuminance meters are used for measurement. Each LED light source included a heat dissipation device, which could avoid the influences caused by the heat of light source, a reflector cup, a drive circuit board, and a fixed mount. Reflector cup is used so the light emit by the LEDs become near collimated light. It is shown in Fig. 4.

The LED light source of each CCT was arranged into a 5 $\times$ 5 array, with spacing of 80 mm. The 25 Silicon photocell detectors were also arranged into a 5 $\times$ 5 array in the same interval. During the whole process of the experiment, we must make sure that the location of each detector was in a line with the LED light source on the same position. The LED light source array, the organic glass box, and the silicon photocell array were both fixed on an optical platform. In front of each LED light source, there was a small black baffle, which would block the light from the other LEDs to affect the testing effects.

2.3.4. The Measurement Process

1) Make sure the experiment is proceeding in a dark room, and correct the illuminance meters' value to zero;
2) Turn on the LED drive power supply to turn on the LED light sources;
3) When the output of the LED light source is stable, open the black baffles in front of each LED light respectively and write down the value of the corresponding illuminance meter. The values of all illuminance meters will constitute a incident energy matrix M_0:

$$M_0 = \begin{bmatrix} ccc\mathrm{a}_{11} & \cdots & \mathrm{a}_{15} \\ \vdots & \ddots & \vdots \\ \mathrm{a}_{51} & \cdots & \mathrm{a}_{55} \end{bmatrix}. \quad (2)$$

4) Atomize the fresh water with four air humidifiers, and transmit the artificial fog into the organic box from the bottom and the upside;
5) When the artificial fog is stable and uniform, check if we can see the biggest words "E" (size 72) clearly which has been placed on a distance of 500 mm away from the box side face. Act as step 3, write down the value matrix M_{fresh} of illuminance that each LED light source illuminating in fog:

$$M_{fresh} = \begin{bmatrix} ccc\mathrm{b}_{11} & \cdots & \mathrm{b}_{15} \\ \vdots & \ddots & \vdots \\ \mathrm{b}_{51} & \cdots & \mathrm{b}_{55} \end{bmatrix}. \quad (3)$$

6) Divide M_{fresh} by corresponding item in M_0, we get

$$\mathrm{T}_{\mathrm{ij}} = \frac{\mathrm{a}_{\mathrm{ij}}}{\mathrm{b}_{\mathrm{ij}}} \quad \mathrm{i}, \mathrm{j} = 1, \ldots, 5 \quad (4)$$

TABLE 4

T and $MGVI_A$ of five LED sources

	1870K	2495K	2985K	4075K	5020K
T(%)	0.479	0.452	0.415	0.372	0.334
$MGVI_A$	0.48	0.67	0.79	0.99	1.32

which are the transmittances in 25 spots in the dark box. The average of the 25 spots' transmittances is average transmittance T through fog for that LED light source. Table 4 showed the T in this fog. The T of 1870 K LED light sources was the largest.

3. Analysis of Urban Skyglow Caused by the Light Source

Urban skyglow is a byproduct of light's transmission through air that has atmosphere particles and water. Because of Rayleigh scattering and Mie scattering, some of the light would be scattered to the sky during the night, causing skyglow pollution. Urban skyglow is harmful for astronomical research and negatively affect the overall aesthetics of the night sky. Because it is caused by Rayleigh and Mie scattering, the amount of urban skyglow is related to light's penetration capabilities through atmosphere particles (haze) and water (fog). In other words, urban skyglow is caused by light that could not penetrate through particles or atmosphere water.

Night time urban skyglow can be represented using mesopic general vision index (MGVI). $MGVI_A$ represents visually perceived skyglow in the entire visible spectrum compared to light source A; its calculation method is as follows only by Rayleigh scattering [15]:

$$\mathrm{MGVI_A} = \frac{\int_{380\,\mathrm{nm}}^{780\,\mathrm{nm}} \lambda^{-4} V'(\lambda) S(\lambda) d\lambda}{K_{mes0} \int_{380\,\mathrm{nm}}^{780\,\mathrm{nm}} V_{mes}(\lambda) S(\lambda) d\lambda} \Bigg/ \frac{\int_{380\,\mathrm{nm}}^{780\,\mathrm{nm}} \lambda^{-4} V'(\lambda) S_A(\lambda) d\lambda}{K_0 \int_{380\,\mathrm{nm}}^{780\,\mathrm{nm}} V(\lambda) S_A(\lambda) d\lambda} \tag{5}$$

where K_0 and K_{mes0} are spectral luminous efficacy of photopic and mesopic vision at night; $V(\lambda)$, $V'(\lambda)$, and $V_{mes}(\lambda)$ are spectral luminous efficiency of photopic, scotopic, and mesopic vision; $S(\lambda)$ is the spectrum of LED light source being used for illumination, $S_A(\lambda)$ is the spectrum of standard light source A. The results is list in Table 4 and compared to the measured transmittance in the previous section. When λ increases, $MGVI_A$ decreases. Low CCT LEDs have lower skyglow pollution: especially during rainy or foggy weather, low CCT LEDs have lower scattering than high CCT LEDs. In other words, low CCT LEDs have higher rain, fog or haze penetration abilities, and can improve driver's ability to distinguish different objects at night.

3.1. Fog Penetration Measurement of Actual Street Lights

We now compare the fog penetration capabilities of the three LED lights (CCTs are 1870 K, 3007 K and 5020 K) to that of high pressure sodium (HPS) lamp, whose CCT is 1954 K. Fig. 5 is the measurement set up. The power of the three LED street lamps are 130.5 W, 130.2 W and 128.3 W, respectively; the power of HPS lamp is 247.8 W. The lamps are 8.13 m above the ground.

In the spectrum emitted by 1870 K CCT LED, the blue component is relatively low, and its chromatic coordinates (0.5436, 0.4122) are similar to that of HPS light (0.5380, 0.4141).

Table 5 lists the average transmission through fog of the four street lamps under different levels of fog or haze. AQI and PM2.5 means air quality index and PM2.5 level, respectively. The higher these two numbers are, the heavier the fog/haze is. Because it is impossible to acquire a day with zero fog/haze level, we set the transmission (for all four lamps) on the lowest level fog/haze day to 1, as in Table 5. As we can see, as fog/haze level increases, the transmission decreases for all four lamps. Also, 1870 K CCT LED lamp and HPS lamp have the best fog

Fig. 5. Transmission test site.

TABLE 5
Transmission of four street lightings under different levels of fog/haze

Air quality			transmission			
Fog/Haze level	AQI	PM2.5	Low CCT LED （1870K）	Warm white LED （2985K）	Pure white LED （5020K）	HPS
1	38.7	18.0	1.000	1.000	1.000	1.000
2	67.3	42.0	0.980	0.966	0.964	0.983
3	97.3	72.0	0.935	0.910	0.908	0.949
4	131.7	100.0	0.913	0.870	0.830	0.928
5	184.3	139.3	0.874	0.837	0.798	0.902

penetration capabilities. The higher CCT a LED lamp has, the lower its transmission through high level of fog/haze is.

4. Conclusion

According to our research on dark adaption using LEDs with different CCT, as CCT increases, dark adaption time increases. High CCT LED light source, which has relatively high amount of blue light components, has the longest dark adaption time. On the other hand, warm white LEDs have relatively low CCT and a high amount of long wavelength components, and they have short dark adaption times. Also, as road illuminance increases, dark adaption time increases as well.

Test on color discrimination shows that under 1870 K LED light, the color discrimination success rates of different color pieces vary greatly, and the accuracy is low. As CCT increases, the human eye's ability to distinguish colors improves as well. When CCT is above 3000 K, color discrimination success rates are near 100%. Also, lights that have above 3000 K CCT have higher CRI, and this helps the color discrimination capabilities of human eye.

The test on fog penetration shows as fog or haze level increases, road illuminance decreases, which means light's transmission through fog or haze decreases. Higher CCT is correlated to lower transmission in fog or haze.

When using LEDs for road lighting, the human eye has decent dark adaption time and color discrimination abilities under street lights of around 3000 K CCT. LED light of 3000 K CCT also has relatively high luminous efficacy, and is suitable for road lighting.

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