New considerations about light pollution in rural and protected areas based on a global perspective savings-pollution-safety: Impact on real installations.

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Keywords: Energy Management, Legislative & Regulatory Activity, Light & Lamp Spectra, Nonvisual Effects, Visual Performance.

Abstract

The broad implementation of LED light sources in public lighting has become a revolution in the last years. Their low power consumption and good performance make LED an optimal solution in most of outdoor applications. In addition, the white light emitted by the vast majority of the LED used in public lighting and their good color rendering allow pedestrians and drivers enjoy of more comfortable cities at night, especially commercial zones and city centre. However, the regulations on light pollution, that in some countries have been developed in parallel to the introduction of LED lighting, present strong constrains to white light due to Rayleigh scattering. These regulations request filtering of blue wavelengths in some rural areas, and thus they limit the projects to high pressure sodium sources or amber LEDs, whose prices are higher and performances lower than for white LEDs. In this work, the pros and contras of white and amber LED lighting in rural areas are analyzed and compared through real simulations and considerations based on efficiency and light pollution. Important conclusions for installations in rural and protected areas are presented.

Keywords: Energy Management, Legislative & Regulatory Activity, Light & Lamp Spectra, Nonvisual Effects, Visual Performance.

1. Introduction

Public lighting is an essential element in big cities, small villages, roads and other opencast spaces. Although different trends may recommend higher or lower levels of illuminance in different situations, the agreement on the importance of public lighting to ensure a good visual performance of drivers and pedestrians and, hence, the safety and well-being of people and goods is out of doubt.

However, the impact of public lighting in both, financial and environmental terms is also a problem of the major importance. This situation has led the industry to develop and improve the most accurate technologies (LED, induction bulbs etc) in order to maximize the sustainability of public lighting, whereas the efforts of many researchers have been aimed to use renewable sources to power lighting installations and optimize their configuration (Gómez-Lorente et al., 2013; Rabaza et al., 2013; Rabaza et al., 2016; Peña-García et al., 2016; Sędziwy, 2016; Sędziwy, 2017; Hermoso-Orzáez et al., 2017). In parallel, international bodies and national governments have published standards (CIE Publ. 115, 2010) and national laws (Ministry of Industry, Tourism and Trade of Spain, 2008) with recommendations and mandatory regulations. Although these standards are deeply concerned with energy savings and the use of efficient light sources, not all of them deal the topic of light pollution.

In addition, the increasing knowledge on non-visual effects of light is now influencing the design of lighting installations, and some important recommendations must be seriously considered when designing or improving light installations (Lucas et al., 2014).

Hence, visual performance, non-visual effects of light and light pollution are topics of great importance when designing or carrying out corrective actions on public lighting. Before going further, both concepts will be briefly analyzed together with the reference framework of mesopic vision.

1.1. Light pollution

The International Commission on Illumination (CIE), gives a general definition of light pollution: it is a general term that indicates the sum of all adverse effects caused by artificial light (CIE Publ. 017/E:2011, 2011).

The National Lighting Product Information Program is more specific and defines light pollution as an unwanted consequence of outdoor lighting and includes such effects as sky glow, light trespass, and glare (Lighting Research Center, 2007).

Some national regulations in Europe are in the line of the Lighting Research Center and specify which effects constitute what we call light pollution. For example, light pollution is defined in Spain as the emission of luminous flux by the artificial light sources constituting the nighttime lighting with inaccurate intensities, directions or spectral ranges for the development of the activities foreseen in the lighted zone (Ministry of Industry, Tourism and Trade of Spain, 2008).

Some of these requirements on light trespass and inaccurate directions are quite clear and the elimination of light intrusion is relatively feasible in most of the cities around the world. However, the sky glow or atmospheric scattering is a topic which must be considered in depth. A short background of the physics of atmospheric scattering is presented in the next subsection.

1.2. Atmospheric scattering of light

Light is scattered by the molecules and particles in the atmosphere. Depending on the size of the particles, this scattering will take place according to Rayleigh or Mie theories (Iqbal, 1983). The first is for air molecules and small sized particles, and the intensity of the scattering depends on the wavelength of the incident light (Strutt, 1899), whereas the second is caused by bigger particles such as aerosols and is independent from light wavelength (Mie, 1908).

In public lighting, Rayleigh scattering has a deeper impact. It is much more intensive for blue light (that is, the light with the shortest wavelength within the visible spectrum) than for the red one (the light with the longest wavelength within the visible spectrum), as shown by Equation (1), which takes account of the amount of light scattered by the atmospheric molecules as a function of the wavelength:

$$I = I_0 \frac{8\pi^4 N\alpha^2}{\lambda^4 R^2}\left(1+\cos^2\theta\right) \qquad (1)$$

Where:

I is the intensity of light in one given point after going through one given medium.

I_0 is the intensity of light in one given point before going through one given medium.

λ is the wavelength of the light

R is the radius of particles

θ is the angle between the incident ray and the point under consideration

N is the number of particles

α is the molecular polarizability

It is necessary to remark that intensity in (1) is not the photometrical intensity, but the wave intensity, being an electromagnetic quantity related with the irradiance and the illuminance.

When a given amount of luminous flux goes through one plane-parallel layer of the atmosphere, the loses are given by the Beer-Bouguer-Lambert law:

$$E_\lambda = E_{0\lambda} \exp\{-\tau(\lambda) m\} \quad (2)$$

Where:

E_λ is the spectral irradiance going out of the layer.
$E_{0\lambda}$ is the spectral irradiance before going through the layer.
$\tau(\lambda)$ is the optical thickness of the layer. It is due to the contribution of several factors such as Rayleigh scattering and absorption by gases and aerosols.
m is the optical mass, which defines the optical path length.

Since the scope of this research is a reflection about the constrains on light sources emitting short wavelengths in areas specially protected (mainly rural or near to observatories), the calculations will be focused on Rayleigh scattering.

One good approach to Rayleigh optical thickness within the visible spectrum is (Duttom et al., 1994; Bodhaine et al., 1999):

$$\tau_R(\lambda) = \frac{p}{p_0} 0{,}000877 \lambda^{-4{,}05} \quad (3)$$

Where p is a site pressure, p_0 = 1013.25 mb (millibars), and λ is a wavelength expressed in micrometers. Due to the comparative nature of this work, it will be considered $p = p_0$.

Thus, this strong dependence of Rayleigh scattering on wavelength makes it responsible for the blueness of the sky during daytime and the red of the sunset. However, in spite of these beautiful atmospheric phenomena, Rayleigh scattering causes light pollution, because a scattered flux produced by a lighting installation does not illuminate a visual task, but goes everywhere with the subsequent waste of energy and disturbance for astronomical observations.

These considerations highlight how important the economic and environmental impact of light color is. For this reason, installations providing an amber or yellow-sodium light (mainly using high pressure sodium bulbs) are considered as that most environmentally friendly from the perspective of light pollution than those providing a white light (mainly metal halide and LED).

Although the elimination of Rayleigh scattering must be a priority, the constrains of many regulations, compelling to forbid luminaries emitting short wavelengths must be handled with care: as seen, these wavelengths cause higher scattering in the atmosphere, but it is necessary to remark that the human eye is more sensitive to them in conditions of very low (scotopic) and, mainly, intermediate (mesopic) luminance levels, where the visual task of public lighting users develop their activities (CIE Publ. 191:2010, 2010).

In the next subsection, the importance of considering mesopic vision when dealing with public lighting is outlined.

1.3. Public lighting and Mesopic vision

The calculation of luminance, illuminance and other quantities involved in vision requires the conversion of radiometric quantities into photometric ones, that is, going from physic quantities to human-adapted ones. It is accomplished by using the photopic spectral sensitivity, $V(\lambda)$ in conditions of a high luminance (also called photopic conditions) or the scotopic spectral sensitivity $V'(\lambda)$ in conditions of a low luminance. In our experiments we dealt with two fixtures having identical photometric solids. For both the spectral radiant flux values, $\Phi_e(\lambda)$, were measured for $\lambda \in [360nm,780nm]$ with the resolution $\Delta\lambda = 1nm$. The flux values were negligible outside of this range. The spectral luminous fluxes were obtained by multiplying $\Phi_e(\lambda)$ by spectral sensivities $V(\lambda)$ or $V'(\lambda)$ (for photopic and scotopic conditions respectively) which are common known distributions, whereas the total luminous fluxes were the summation of the spectral ones after multiplying by factor 683 lm/W and 1700 lm/W repectively.

When dealing with urban and road lighting, the use of $V(\lambda)$ to measure luminance and illuminance has led to confusion and wrong estimations because the ranges of luminance involved belong neither to the photopic nor scotopic region, but to the wide region called *mesopic* where both, cones and rods, participate in one proportion depending on the concrete luminance levels.

The assimilation of the measurements of public lighting in photopic conditions underestimates the output of installations emitting white light, because the participation of rods, that are more sensitive to bluer wavelengths, allows road user a better perception than the provided with yellow light sources. Hence, less white light enables the same visual performance than more yellow-sodium light.

Given the vast variety of luminance levels included within the mesopic range, the elaboration of tables and formulas to calculate mesopic magnitudes has been a priority.

The International Commission on Illumination (CIE Publ. 191:2010, 2010) proposed a mesopic spectral sensitivity given by:

$$\mathrm{M(m)V_{mes}}(\lambda) = mV(\lambda) + (1-\mathrm{m})V'(\lambda) \quad 0 \le m \le 1 \tag{4}$$

where M(m) is a normalization function ensuring that the maximum value of $\mathrm{V_{mes}}(\lambda)$ is 1.

In addition some proposals like the USP system (He et al, 1997; He et al., 1998; Rea et al, 2004) or the MOVE system (Eloholma et al., 2005; Goodman et al., 2007) allow the calculation of mesopic luminances departing from photopic luminances and the S/P ratio of the sources under consideration. The tables to calculate these values are compiled in (CIE Publ. 191:2010, 2010).

The low levels of luminance on rural roads, due to the lack of light sources other than the public ones, give place to a mesopic condition nearer from the scotopic than in any other situation in public lighting. For this reason, the natural framework of work will be within this range.

1.4. Non-visual effects of light

Non-visual effects of light have been reported for ages. However, the paths implied from the eyes to the final effects have been relatively unknown until recent times. Even after a good knowledge of the melatonin influence of melatonin on arousal, attention, circadian rhythms and other important variables for health and wellbeing, some mysteries remained. Maybe, the most important was to identify the photoreceptor initiating the melatonin path in humans if any. The complete evidence of a new non-cone, non-rod photorreceptor in humans, the intrinsically photosensitive retinal ganglion cells (ipRGC) (Brainhard et al., 2001; Thapan et al., 2001) was a real advance. Since then, very active groups around the world are achieving important successes in the determination of the so called “melanopic” curve (Lucas et al., 2014), that leads to quantification of melatonin suppression due to lighting conditions and, hence, to the prevision of non-visual effects and their impact on safety, performance, health and wellbeing.

Although the panorama could seem to be on the track for a global solution in matter of non-visual paths, it is not expected to reach one exact and definitive melanopic curve because the ranges and interactions with cones and rods (Dacey et al., 2005) are not clear so far. In addition, melatonin is not the only hormone relating lighting conditions with other effects on human health and behavior: cortisol, alpha-amylase and other are deeply involved and seem to follow different paths that still need further research (Figueiro and Rea, 2010).

Anyhow, an exact knowledge of the melanopic curve, is a real necessity for industry and safety science, since the construction of melanopic luxmeters or quick tools to go from radiometric to melanopic measures, will allow engineers and designers to evaluate the real impact of lighting installations on non-visual effects. Now it is clear that the characterization of these effects departing from photopic, meopic or scotopic measurements is not correct. The situation is similar to the one described in section 2.1, where it is shown that photopic measures were not accurate to work in public lighting (mesopic conditions).

Besides the above reasons, there is a remarkable controversy between people that prefer amber or yellow-sodium light and people stating that white light enhance wellness and increases night life or commerce due to its excellent chromatic reproduction (Peña-García et al., 2015). This topic is related to visual and non-visual effects of light because of the spectral sensitivity of cones and ipRGC (blue wavelenghts are more efficient to suppress melatonin), but also to psychological aspects that have not been undertaken from a global perspective yet. This situation makes the problem

In this work, the pros and contras of lighting installations emitting amber and white light will be analyzed and weighed in terms of visual performance, non-visual paths and light pollution. The scenario is a rural road in a protected area where constrains on light pollution are strong in most of the countries.

2. Materials and method

The Rayleigh scattered flux has been computed for a typical roadway layout: a two lane single carriageway of the width *w*=7 m, illuminated by the right handed row of luminaires arranged with spacing *D*=30 m has been taken as an accurate scenario of rural road in protected areas. The parameters of the installation have been calculated with DIALux (http://www.dial.de/DIAL/en/dialux.html) .

The fixture inclination angle was assumed to be α = 5º, fixture mounting height *h*=8m, arm length *a*=3 m and the pole setback *s*=0.5 m (see Figure 1). An important parameter required for computing a luminance are reflective properties of a road. It was assumed that the road surface is coated with the tarmac R3 with the average luminance coefficient, *Q0*=0.07. Photometric calculations was performed according to the EN 13201-3:2007 standard.

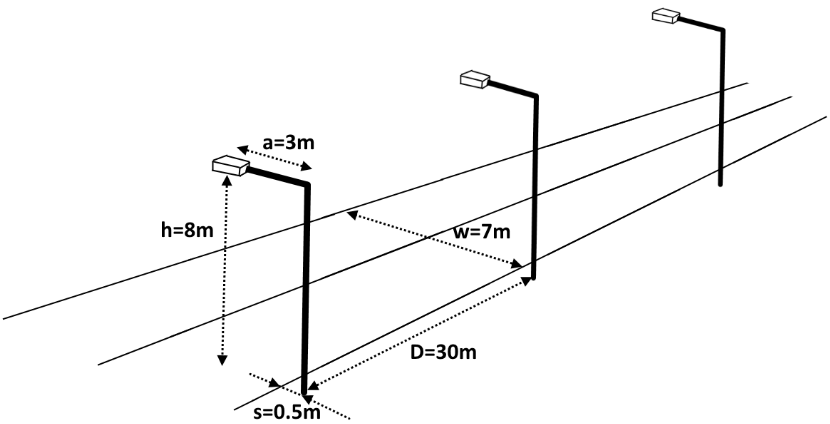

Figure 1. Basic scheme of the simulated situation.

In this scheme, the distance luminary-measuring point is:

$$d = \sqrt{(3.5 + 0.5 - 3)^2 + 8^2} = \sqrt{65} = 8.06\, m$$

The lighting parameters of the both amber and white LED-based installations are:
Average luminance level: L_{av} = 0,75 cd/m^2
Overall uniformity: U_0=0,44
Threshold increment: *TI*= 11,16

3. Results

Two luminaries under consideration (amber and white) have been measured with a CL-500A radiometer. The measurements of spectral irradiance have been converted into spectral radiant flux by means of a perfectly reflecting cavity of size 23 x 23 cm. The correlated color temperature (CCT) has been also measured for each luminary.

Departing from the radiant flux, two kinds of quantities have been calculated: photometrical and physical.

Concerning photometry, the luminous fluxes of both luminaries according to the spectral sensitivities in photopic, scotopic and melanopic and their mutual relationship are presented in Table 1.

	CCT (K)	Total radiant flux (W)	Photopic luminous flux (lm)	Scotopic luminous flux (lm)	S/P ratio	Melanopic luminous flux (lm)
Amber Luminary	1774	3.50	1263.85	518.71	0.41	1.04
White Luminary	5511	3.83	1250.76	2243.55	1.79	10.13

Table 1. Radiometric and photometric magnitudes per luminary on amber and white emitting light sources.

The results contained in Table 1 show that luminous fluxes are comparable for both sources (with the relative difference at the level of 1%) when considered in photopic conditions. However, such conditions are not realistic at night as explained in Introduction. On the other hand, in scotopic conditions, the luminous flux is four times higher, that is, the white light is more efficient. In other words, the same visual performance can be achieved with lower energy consumption. This fact is clearly shown by the S/P ratio. Given that rural roadways in protected areas are constrained to be weakly illuminated to not harm an ecosystem inhabited by animal and vegetal species as well as avoiding light pollution, the mesopic conditions under these circumstances will be nearer from the scotopic situation.

It is also remarkable that the melanopic flux is ten times higher for the white luminary in the simulated installation. It means that rural roads illuminated with white light will foster concentration, and arousal of drivers due to the major melatonin inhibition caused by short wavelengths like those in the white LED light. It is a clear advantage given their rude construction (it is easy to find poorly asphalted rural roads), dangers (precipices, wild animals suddenly crossing…) and separation from major trails.

On the other hand, it has been explained that short wavelengths suffer more intense Rayleigh scattering and, hence, more light pollution. For this reason, some countries forbid white lighting in protected areas.

The radiant flux scattered by a typical installation with fixtures mounted at the height of 8 m spaced by 30 m (i.e., approx. 33 luminaires per 1000 m) and a measuring point in the middle of a carriage of a width of 7 m (Figure 1), has been calculated. The results are shown in Table 2:

	Scattered radiant flux per luminary (W)	Scattered radiant flux per kilometer of road (W)
Amber Luminary	0.02	0.67

White Luminary	0.05	1.67

Table 2. Rayleigh scattered radiant flux emitted by a single sided installation located along a rural road as shown in Figure 1.

As seen, the radiant flux scattered by an installation with white luminaries is about twice the one scattered by the amber sources.

If we apply the results in Tables 1 and 2 to a typical rural road with a length of 5 km in a protected area and compare the scattered flux with the electrical power consumed in scotopic conditions, we find the following:

	Scattered radiant flux (W)	Consumed power for scotopic illumination (W)
Amber Luminary	3.35	4483.24
White Luminary	8.33	1046.52
White / Amber ratio	2.48	0.23

Table 3. Comparison of Rayleigh scattered radiant flux with electrical consumption in white and amber luminaries per 5 km in weakly illuminated rural roads.

The comparison of tables 1, 2 and 3, shows that the scattered radiant power and the consumed electrical power, even having different natures and, hence, different effects on the environment and energy balance, makes white luminaries more suitable for rural roads even in protected areas. The advantages in terms of visual performance, arousal, attention and, in summary, safety, are really remarkable.

3.1. Constraint of filter below 440 nm

If the light emitted by the light sources is filtered below 440 nm as requested by some national regulations (Ministry of Industry, Tourism and Trade of Spain, 2008), the resulting values would be as follows.

	Total	Photopic	Scotopic	S/P ratio	Melanopic

	radiant flux (W)	luminous flux (lm)	luminous flux (lm)		luminous flux (lm)
Amber Luminary	3.49	1263.77	515.42	0.41	1.02
White Luminary with filter	3.45	1246.79	2087.93	1.68	9.06

Table 4. Radiometric and photometric magnitudes per luminary on amber and white emitting light sources incorporating filters for wavelengths below 440 nm.

	Scattered radiant flux per luminary (W)	Scattered radiant flux per kilometer of road (W)
Amber Luminary	0.02	0.67
White Luminary with filter	0.04	1.33

Table 5. Rayleigh scattered radiant flux for a single sided installation along a rural road as shown in Figure 1 on amber and white emitting light sources incorporating filters for wavelengths below 440 nm.

A comparison between the values in tables 2 and 5 shows that the incorporation of filters to avoid the emission of light below 440 nm achieves savings of around 0.35 W/km even in the most favorable case (white luminaries). This figure leads to reflection on the convenience to install such filters whose manufacture process might consume more energy and be worse in terms of investment and sustainability than the installation of the white light luminary without any kind of filter.

4. Conclusions

The most used LED luminaries frequently emit an excessive amount of blue wavelengths, which has been a problem for their use in luminically protected areas. However, the results presented in this work, showing that the Rayleigh scattering can be counterbalanced by enhanced visual and non-visual performance, together with a lower power consumption should make them the first choice for lighting protected areas.

This proposal is supported by the following conclusions arisen from the results obtained in this work:

1. It is well known that amber or yellow light, suffers lower Rayleigh scattering than white light and, hence, lower light pollution is generated. This is critical in protected areas like those near from astronomical observatories, natural parks and other ones established by some national regulations. However, the improved visual performance obtained with white light in these weakly illuminated areas, whose conditions are nearer from the scotopic, make white light much more suitable in terms of energy consumption, visual efficiency and also in terms of non visual effects like those arisen from melatonin inhibition (better attention when driving, higher arousal…).

2. The melanopic luminous fluxes emitted by each of the luminaries under consideration are 10 times higher in the case of the white one due to the remarkable presence of blue wavelengths that enhance melatonin inhibition. This fact makes white light very accurate in the weakly illuminated and bad paved rural roads. The enhanced concentration due to the melatonin inhibition can be used to improve the safety in rural roads, where any lack of concentration can be fatal due to the presence of falls and not signaled obstacles.

3. If a high melanopic flux with lower scattering is pursued, the filtering of radiations below 440 nm, which is mandatory in some countries, could be a good solution as long as the emitted light remains nearly white, that is, avoiding the use of low and high pressure sodium due to their worse visual performance in weakly illuminated areas. Anyhow, the poor savings in scattered flux toward the atmosphere should make authorities consider the real convenience to install filters in the luminaries of some protected areas.

4. The importance of Rayleigh scattering is not the only factor in light pollution, whereas the high impact of visually efficient lighting on drivers alertness and, hence, safety is out of doubt. Thus the use of luminaries avoiding the emission of luminous

flux towards the upper hemisphere and the exact levels of illuminance could be enough to avoid light pollution in these zones even although white LEDs are used.

In summary, light pollution in protected areas is a problem of major concern whose impact is not questioned in this work. However, the consideration of light pollution almost exclusively from the perspective of Rayleigh scattering, has left aside other extremely important perspectives like the visual performance under low illuminance levels and the non-visual effects of light with a high content in blue wavelengths.

A more global perspective of lighting in rural and protected areas may show that Rayleigh scattering is not an isolated problem, but just an important piece of the polynomial safety-sustainability-wellbeing.

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