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Towards a Unified Equation to Provide S/P Relationship with Application to Mesopic Conditions

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Abstract— This paper discusses the importance of adapting conventional photometric quantities when lighting systems with low luminosity levels are under analysis. In this way, this work presents an alternative methodology that can be applied to lighting projects in outdoor lighting which typically operate under mesopic conditions. The CIE technical report 191:2010 proposes correction factors that convert conventional photometric quantities (photopic) into adapted ones aiming a better correspondence with mesopic conditions. A required parameter for obtaining these correction factors is the relationship between the scotopic and photopic luminous fluxes of the light source employed (S/P ratio), whose determination requires special equipment that is not easily available. Thus, this paper proposes a general equation that provides S/P ratio as a mathematical function of specific photometric parameters, namely the correlated color temperature and the color rendering index, which are information normally provided in manufacturers' catalogs or products packaging. Almost two hundred samples of lamps, including arc discharge models and solid-state lamps, have been evaluated in a specialized laboratory in order to provide enough data that helped the obtaining of the desired unified equation.

Finally, a case study concerning a street lighting project is presented as an example of application of the proposed methodology.

Keywords—outdoor lighting, energy efficiency, human visual system, photometry, mesopic vision, scotopic/photopic ratio, CIE 191:2010 report

I. INTRODUCTION

The human visual system works as a sophisticated system of capturing and processing images, where the eye senses the light and transforms it into signals that are sent through the optic nerve to the brain, which interprets the visual stimuli. The eye is a very complex organ, comprising a set of lenses, muscles, nerves, sensory cells and lachrymal fluid. The pupil controls the passage of light into the eye, until the light reaches the retina, where the image is formed [1]. There are in the retina, cells which are sensitive to light, known as rods and cones. There is also a third type of photoreceptor cell, which, however, does not directly contribute to vision [2].

Cones are less sensitive to light and constitute the photoreceptors responsible for color perception. They are found at higher density in the retina central region, known as fovea, and are divided in cells which are sensitive to spectral ranges green, blue and red. The rods, moreover, have a much higher sensitivity to light than the cones. However, they are not sensitive to colors, being primarily responsible for the perception of lightness and darkness. These cells have a higher concentration in the peripheral region of the retina, and to be more sensitive, are adapted for environments with low levels of lighting, i.e., luminance levels below 0.01 cd/m^2 [3].

Because of these different functions and characteristics of the cells that are sensitive to light, the human eye has distinct visual responses under different lighting conditions. According to the light level of the environment, one of those two sensitive-cell types is predominantly responsible for the dynamic sensitiveness of the human eye. In environments with high light levels (luminance greater than 3 cd/m^2), the pupil is more closed, and the light is focused mainly in the central retinal region, where the cones are predominant, allowing the colors to be differentiated more clearly. In this case, it is defined the photopic operating regime. On the other hand, in environments with luminance levels under 0.01 cd/m^2, the pupil expands itself much more and the image is projected on a much greater area on retina. Thus, the number of sensitized rods is greater than the sensitized cones, what characterizes the so called scotopic vision [3]. Thus, it is possible to determine the relative spectral sensitivity curves for the photopic ($V(\lambda)$) and scotopic ($V'(\lambda)$) operation regimes [4], as shown in Fig. 1. Those curves were determined by the CIE (*Commission Internationale de l'Éclairage* - The International Commission on Illumination). Any intermediate condition between photopic and scotopic systems lies in the mesopic regime. In this operating range it is considered that both the rods and cones are active [3].

Given these peculiarities of view, it is important to consider the true visual response of the human eye in different circumstances and environment when it draws up a lighting design. Equipment devised to measure photometric quantities equipment are calibrated according to the photopic visual system, and what is observed is that the lighting projects are usually designed based on the photopic response of the eye, regardless of lighting conditions on site. In addition, the technical standards in many countries, including Brazil, do not mention that the effect of the human visual response under mesopic conditions should be considered in the preparation of a project.

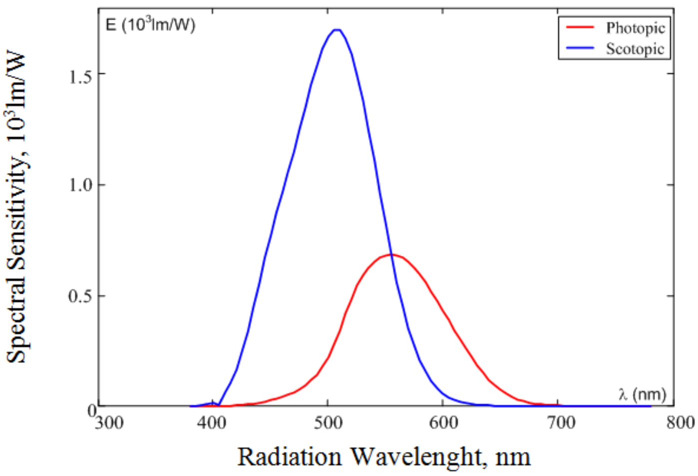

Fig. 1. Spectral sensitivity curves of the human eye, for photopic and scotopic conditions. Source: IESNA/ CIE [4].

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In interior lighting designs, classical photometry (photopic condition) applies satisfactorily, since, in such circumstances, the environments are closed, concentrating the light inside, and the luminance is usually greater than 3 cd/m^2. However, although the physical quantities used in classical photometry are weighted by the human visual response in the photopic condition, it is common to encounter many circumstances that obey the mesopic condition, as is the typical case of street lighting [5], [6]. In such cases, therefore, the conventional photometric quantities, as measured by calibrated equipment according to the photopic response of the human eye, need to be corrected in order to represent the true visual perception in low luminance conditions. In other words, the conversion of conventional photometric quantities into adapted photometric quantities, weighted for the human eye response in mesopic conditions, implies in a more consistent analysis with a real sense of luminosity in street lighting. On the other hand, the use of mesopic models is very complex, since for each luminance level it should be required to determine characteristic curves of relative spectral sensitivity of the human eye, making it necessary to adapt the photometric quantities for each specific mesopic level [5], [7].

In an attempt to establish coordinated actions to deal with this subject, the CIE organism has published the technical report CIE 191:2010, which proposes a method to adapt the photometric quantities by means of corrective factors that can be used to convert conventional photometric values into suitable counterparts according to the respective mesopic level. In order to obtain the corrective factors, it is required to know the relationship between the scotopic and photopic luminous fluxes of a given light source, known as *S/P* ratio (scotopic/photopic), as well as the level of photopic luminance on the working plane [8]. However, getting the *S/P* relationship requires specialized photometric equipment (which are often expensive), not easily accessible for lighting system designers. Thus, this paper proposes an equation that provides the *S/P* ratio on the basis of parameters commonly provided by the lamp manufacturers in specialized catalogs or in the product packaging of commercial bulbs, such as the correlated color temperature (CCT) and color rendering index (CRI), then eliminating the need of using special equipment.

Moreover, the use of adapted photometric quantities in street lighting projects, beyond enabling a better perception of the light spectrum of a given light source, may result in higher energy efficiency of the lighting systems, contributing to a more effective use of energy resources under low luminance conditions.

This paper is organized in six sections. The first one has introduced the subject and presented a brief bibliographic overview. The second section details the adaptation of photometric quantities under mesopic conditions according to the recommendation of CIE 191:2010 technical report. The third section describes the employed methodology that provided the experimental data used to obtain the desired unified *S/P* equation. Section IV deals with the mathematical tools employed to derive the intended general equation and to verify the error limits while adopting the proposed procedures. Section V presents a case study that applies the methodology proposed here in an actual lighting project. Finally, Section VI presents some discussions and conclusions.

II. ADAPTATION OF PHOTOMETRIC QUANTITIES

As already mentioned, when low luminance levels take place (mesopic conditions), the optimum design of a lighting project requires the use of adapted photometric quantities, which must be weighted by the photometric sensitivity of the human eye according to the luminance level of the environment [5]-[10]. Using photometric quantities adapted to each luminance level is quite complex and requires obtaining a relative spectral sensitivity curve for each mesopic conditions. As there are infinite luminance levels between the photopic and scotopic ranges, it can be generated infinite systems of adapted magnitudes. This kind of adaptation, despite of being more accurate and bringing great similarity with the real feeling of light perception, can generate a large ambiguity with respect to projects, equipment calibration and presentation of results. Models that try to translate accurately the response of the human eye in the mesopic region can be found in the literature, some of these being analyzed in [7], which proposes a unified system of photometry. In [9] it is proposed a model for mesopic spectral sensitivity curves based on a color assessment method. However, these methods, although well-developed, are usually very complex, which makes them sometimes unworkable.

The CIE 191:2010 recommendation proposes a more accurate method that considers various mesopic levels of illumination. Each mesopic condition is related to the photopic luminance level observed in the environment. Thus, using the photopic luminance together with the value of *S/P* ratio of the light source, it is possible to obtain from a table the effective luminance multiplier. This factor performs the correction of the photometric magnitude, which is measured by means of a conventional photometric equipment, to the adapted magnitude according to the respective mesopic level.

Table I shows one of the tables available in the document CIE 191:2010, which is used to perform the conversion of photopic units for different mesopic conditions. The dark cells indicate where the required correction factor is equal or greater than an absolute value of 5%. On the other hand, percent multipliers lower than 5% are shown in clear cells. For light sources with *S/P* ratio greater than 1, the effective (mesopic) luminous flux is greater than the photopic flux. On the other hand, for light sources with *S/P* ratio less than unit, the effective luminous flux is lower.

Thus, according to the method proposed by CIE 191: 2010 report, knowing the *S/P* ratio of a given light source is of capital importance to determine the correct percent multiplier that corresponds to a specific mesopic condition.

However, obtaining the *S/P* ratio for each type of lamp is not an easy task. While the luminance *L* can be easily calculated from the illuminance *E* and the surface reflectance ρ (such as the asphalt or concrete in the case of street lighting) by using (1) [11], obtaining the *S/P* ratio of some light sources requires the use of sophisticated and sometimes expensive equipment.

$$L = \frac{\rho \cdot E}{\pi} \qquad (1)$$

Some of the equipment that can be used to determine the scotopic as well as the photopic fluxes of artificial light sources are the integrating sphere (also known as Ulbricht sphere) and the goniophotometer [12]. As already mentioned, those equipments are of difficult access and are normally found only in advanced research laboratories. So, it is interesting to propose alternative methods for calculating *S/P* in order to simplify the design of lighting systems.

This paper proposes to find an equation that provides the *S/P* ratio as a function of color related parameters, namely the correlated color temperature (CCT) and the color rendering index (CRI), which are easily accessible from the lamp manufacturers catalogs or product labelling. As well known, those parameters are associated to the spectral composition of a given light source. So, the intended equation could be very useful in the exterior lighting design (when the mesopic condition takes place), allowing the designer to accomplish the required tasks by employing conventional photometric measurements, with no need of using specialized equipment information.

It is important to note that the CIE 191:2010 report is not a standard or a recognized normative, but just a technical recommendation. Other similar recommendations also mention the mesopic photometry, such as the IES TM-12-06 [13] and the documents from LRC - Lighting Research Center [14], [15]. However, this subject is still very recent and rarely explored. For example, the roadway lighting Brazilian standard NBR 5101:2018 [16] and the American normative ANSI/ IES RP-8:2021 [17] do not cover the mesopic conditions as expected.

TABLE I.
PERCENT MULTIPLIERS FOR EFFECTIVE LUMINANCE [8].

	Photopic Luminance (cd/m²)									
S/P	**0.01**	**0.03**	**0.1**	**0.3**	**0.5**	**1**	**1.5**	**2**	**3**	**5**
0.25	-75%	-52%	-29%	-18%	-14%	-9%	-6%	-5%	-2%	0%
0.45	-55%	-34%	-21%	-13%	-10%	-6%	-4%	-3%	-2%	0%
0.65	-31%	-20%	-13%	-8%	-6%	-4%	-3%	-2%	-1%	0%
0.85	-12%	-8%	-5%	-3%	-3%	-2%	-1%	-1%	0%	0%
1.05	4%	3%	2%	1%	1%	1%	0%	0%	0%	0%
1.25	18%	13%	8%	5%	4%	3%	2%	1%	1%	0%
1.45	32%	22%	15%	9%	7%	5%	3%	3%	1%	0%
1.65	45%	32%	21%	13%	10%	7%	5%	4%	2%	0%
1.85	57%	40%	27%	17%	13%	9%	6%	5%	3%	0%
2.05	69%	49%	32%	21%	16%	11%	8%	6%	3%	0%
2.25	80%	57%	38%	24%	19%	12%	9%	7%	4%	0%
2.45	91%	65%	43%	28%	22%	14%	10%	8%	4%	0%
2.65	101%	73%	49%	31%	24%	16%	12%	9%	5%	0%

Although the use of mesopic photometry is not yet widespread or required in technical standards for exterior lighting projects, particularly in street lighting, several studies in the literature point to its importance, including the suggestion of improvements in the conversion factors of CIE 191:2010 [18]-[20].
Once the luminance (calculated from the illuminance by means of a lux meter) and the *S/P* ratio (calculated on the basis of the desired equation) are accessible, the external lighting projects can be conducted in the mesopic system, providing more consistent results and a real perception of the light condition.

III. EXPERIMENTAL METHODOLOGY

In order to obtain an equation that relates the *S/P* ratio as a function of CCT and CRI, measurements of photopic and scotopic luminous fluxes, CCT and CRI of several light sources were obtained by means of an integrating sphere from Labsphere, model LMS-400, with a diameter of 40".

The choice of CCT and CRI as parameters for this approach is justified because they are associated to the spectral distribution of a given light source [11]. It is well known that the luminous flux (photopic or scotopic) depends on the spectral power distribution of a light source, thus making sense to try expressing the *S/P* ratio in function of such information.

Integrating spheres can provide, among other data, the required parameters to enabling the derivation of the desired equation: the correlated color temperature, the color rendering index and the photopic and scotopic luminous fluxes. External equipment (such as power supplies, AC or DC, and measurement instruments) were also used to provide electrical power and information, especially the input voltage, current and lamp power. Based on the measurements performed, it was calculated the values of *S/P* ratio for each light source by the quotient between the respective scotopic and photopic fluxes.

The measurements were performed in high pressure sodium lamps (HPS), high pressure mercury vapor (HPMV), metal halide lamp (MH) and modules of light emitting diodes (LEDs) of different powers, manufacturers and ranges of CCT and CRI. The choice of these technologies can be justified because they are lamps commonly used in roadway lighting and outdoor environments. Although LEDs are not widely employed in most of the cities nowadays, they are expected to be the preferred solution for street lighting in the years to come, either by their growing energy efficiency characteristics or owing to their good mechanical resistance profile and low maintenance requirements. The samples of HPS, HPMV and MH lamps were driven by high power factor (PF) commercial ballasts, i.e., featuring a PF greater than 0.92. On the other hand, the LED modules were driven directly from a DC power supply, which provided continuous and constant voltage and current.

Most of the LED modules under test (all of them built of high power LEDs - HP LEDs) were obtained from commercial luminaires for street lighting. In addition, some chip on board LEDs (COB LEDs) were also employed. Each module was tested in three dimming levels, with 100%, 80% and 60% related to the nominal conditions, resulting in 3 different operating points. Since most of the LED modules have been taken away from their luminaire mechanical structure, the power measurements as registered by the laboratory watt meters were related to the modules itself and not for the entire luminaire. For the HPS, HPMV and MH lamps, a warm up time of 15 minutes before each measurement has been observed in order to accomplish the process with the lamp in full luminous flux. In the case of LEDs, the correspondent stabilizing time was of 5 minutes. The laboratory ambient temperature has been monitored and during all measurements it was delimited to the range of $23^{o}C$ to $26^{o}C$. The most important measurement information has been organized into a global table, as presented in the next section.

The lamp manufacturer names have been omitted in the results, but it is important to mention that the lamps of the same type and power wattages were acquired from different manufacturers. Finally, in order to take into account the possibility of measurement errors during the operation of the integrating sphere, 22 measurements of the photopic and scotopic fluxes, CCT and CRI have been registered. The standard deviation of the measures was of 0.2 % of the arithmetic mean, assuring a good integrity of optical equipment and procedures.

IV. EXPERIMENTAL RESULTS

Table II summarizes the main experimental data acquired for all the samples under test, which constituted a set of 185 lamps. The nominal power (arch discharge lamps) or the power delivered to the LED modules, the photopic and scotopic fluxes, the CCT, CRI and the *S/P* ratio were registered in this table. Due to the amount of samples and lack of space, Table II does not show all the individual measurements performed in the laboratory. The range of parameter values have been indicated instead.

The lamps of the same nominal power were grouped into a single line and the number of samples of the respective group is shown in the third column. In the case of LED modules, the indicated power values were related to the power delivered to the LED string since some of the modules have been taken away from the luminaire, as mentioned before. For this reason, it was indicated a range of powers in each line. Thus, it is presented for each group of lamps only the range of values found for photopic luminous flux, scotopic luminous flux, CCT, CRI and *S/P* ratio.

With the obtained, it was possible to propose an equation that provides the *S/P* ratio as a function of CCT and CRI. In addition, the data were organized in graphics, which allowed to evaluate the dependence of *S/P* with CCT and CRI, besides the absolute difference and the percentage error between the measured values and adjusted values from the proposed equation. To obtain the desired equation it was employed the Lagrange interpolating polynomial method [21].

Thus, (2) has been obtained, as a function of two variables relating the *S/P* ratio in function of CCT and CRI.

$$S/P = -1.886\cdot10^{-8}(CCT)^2 + 4.311\cdot10^{-7}(CRI)(CCT) + \\ +6.430\cdot10^{-5}(CRI)^2 + 3.590\cdot10^{-4}(CCT) + \\ +1.247\cdot10^{-3}(CRI) - 0.114 \quad (2)$$

Fig. 2 shows the surface graph of the proposed function of the two variables. The graph of Fig. 3 shows a comparison between the values of *S/P* of reference (measured in lab) and the values found from (2) for all samples under test. Fig. 4 shows the relative error between the measured and calculated values given by (2). The relative error (E_r (%)) is calculated by (3), where *S/P* is the ratio between the scotopic flux and photopic flux measured in the integrating sphere and S/P_e is the value estimated by (2).

$$E_r(\%) = \frac{S/P - S/P_e}{S/P}\cdot 100 \quad (3)$$

According to Fig. 4, the relative error between the values obtained with the proposed equation and the measured values was close to 9% in the worst cases (few samples), while for the majority of the samples it was restricted below 5%.

Observing the surface graph of Fig. 2 and (2), in the plane formed by the axes *S/P* vs. CCT, it can be seen a projection of parabolas with downward concavity, while in the plan *S/P* vs. CRI it is possible to realize a set of parabolas with upward concavity. This leads to the conclusion that, for a fixed value of CRI there is a set of second order polynomials of *S/P* taking CCT as a parameter. On the other hand, for specific values of CCT there exist second order polynomials with *S/P* taking the CRI as a parameter. Fig. 5 shows, for example, the curve of *S/P* as a function of CCT for CRI equals to 50 and the curve of *S/P* varying with CRI when CCT is constant and equals to 5000 K. These functions of one variable would provide simpler equations; however, these relationships would only be valid for very narrow ranges of one of the two variables (CCT or CRI) and it would be necessary a large set of equations to describe the whole range of conditions. In this sense, [22] and [23] provide an alternative approach and propose some equations that offer *S/P* values as a function of just one variable. Again, these equations are limited to narrow ranges of CCT and CRI and, therefore, could not respond for all lamp technologies.

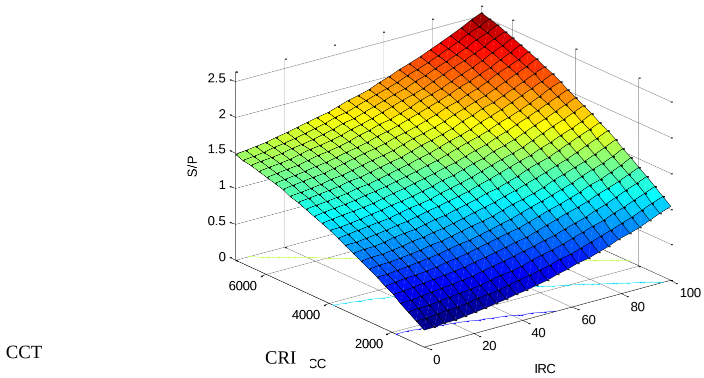

Fig. 2. Surface graph of *S/P* relationship as a function of CCT and CRI.

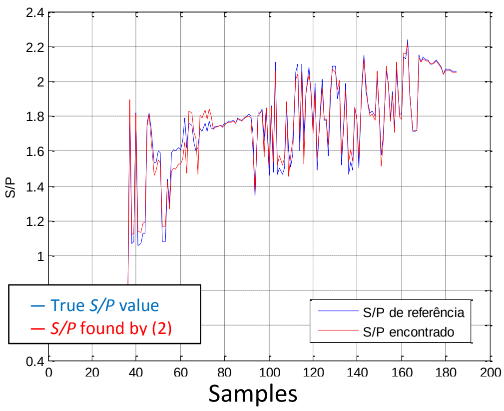

Fig. 3. Difference between *S/P* measured and calculated.

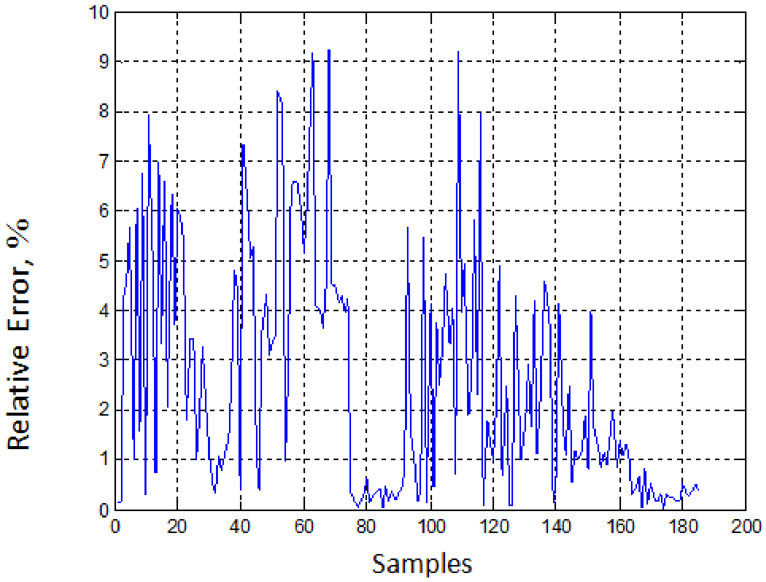

Fig. 4. Relative error between *S/P* measured and calculated.

In turn, the equation proposed in this paper can be used for all the evaluated categories of lamps, which are typically applied to roadway lighting or outdoor lighting and generally operate under mesopic conditions.

With a mathematical model available, such as the one represented by (2) of this paper, the analytical tools for representing and designing lighting systems could be used in a more easily way. Moreover, it must be recorded that the proposed model considers the dynamic response of the human eye and can be used to provide the *S/P* ratio as required to determine the correction factors referred by CIE 191:2010 recommendation. However, it should be emphasized that the *S/P* factors provided by integrating spheres or gonio-photometers are still the most accurate method in this case.

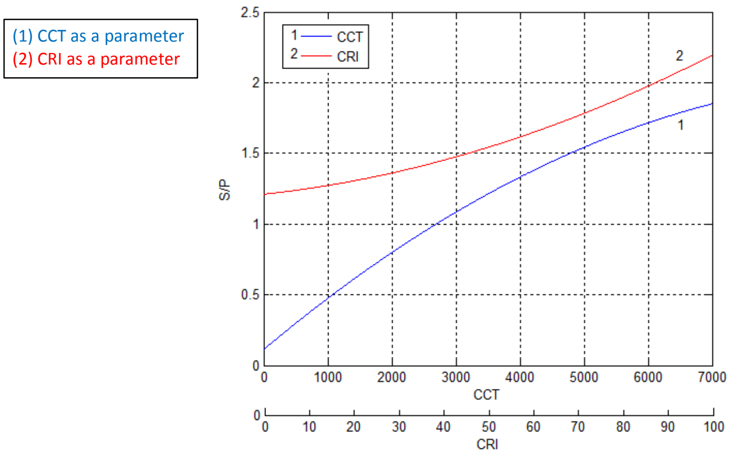

Fig. 5. *S/P* relationship as a function of: (1) CCT for CRI = 50 and (2) CRI taking CCT = 5000 K.

V. CASE STUDY EXAMPLE

In order to illustrate the application of the proposed methodology, it is presented in this Section a study of case where a simplified street lighting project is developed employing the traditional method and then compared with the methodology proposed in this paper.

The digital simulation of the lighting project has been accomplished with the help of Dialux utility, with ies files of luminaires available according to [24] and [25]. The street example of such study has a width of 7 meters, being considered a local street with high circulation of pedestrians, according to the classification of the traffic in ANSI/ IESNA RP-8-21 [17].

TABLE II.
S/P RATIO OF SEVERAL LIGHT SOURCES

Type of Lamp	Power (W)	Number of Samples	Luminous Flux		CCT	CRI	*S/P* value
			Photopic (lm)	*Scotopic (lm')*			
HPS	100	7	6775 - 8153	3638 - 4636	1938 - 1963	7.65 - 20.42	0.53 - 0.57
HPS	150	8	13620 - 15530	8422 - 9592	1980 - 2000	19.46 - 30.09	0.60 - 0.63
HPS	250	12	26480 - 27920	17300 - 18810	1983 - 2044	22.27 - 39.18	0.62 - 0.70
HPS	400	9	44030 - 46070	29260 - 31270	2026 - 2044	22.57 - 26.85	0.66 - 0.68
HPMV	250	4	10010 - 11060	10650 - 11850	3628 - 3683	44.89 - 46.26	1.06 - 1.08
HPMV	400	4	16720 - 17630	18840 - 19000	3353 - 3768	47.79 - 53.29	1.08 - 1.13
MH	70	8	5820 - 6525	9464 - 11090	4120 - 4441	59.60 - 68.43	1.59 - 1.70
MH	150	1	7999	15410	4711	84.23	1.93
MH	250	33	16060 - 23780	27870 - 39170	3497 - 7194	41.55 - 77.42	1.30 - 1.99
MH	400	49	30590 - 48030	44330 - 79590	3480 - 6745	67.34 - 96.48	1.34 - 2.15
LED	< 10	14	181 - 2836	322 - 4240	3817 - 6496	65.43 - 85.39	1.47 - 2.09
LED	10 - 20	16	1732 - 5117	3210 - 10100	3937 - 6610	65.67 - 75.04	1.49 - 2.09
LED	20 - 30	8	1510 - 4917	3381 - 9067	5142 - 7317	66.07 - 80.88	1.76 - 2.24
LED	30 - 50	3	3086 - 8889	6238 - 13470	3978 - 6194	72.81 - 76.66	1.52 - 2.02
LED	50 - 60	3	3029 - 7843	6267 - 14530	5492 - 6559	68.43 - 77.64	1.85 - 2.07
LED	60 - 70	3	3461 - 14250	7113 - 22420	4174 - 6368	68.96 - 77.28	1.57 - 2.06
LED	70 - 80	2	3167 - 3254	6773 - 6931	6883 - 6945	78.65 - 78.86	2.13 - 2.14
LED	105	1	9985	18700	5573	69.97	1.87

According to this standard, the lighting design for the chosen class of road requires a minimum average illuminance of 9 lux, minimum average luminance of 0.6 cd/m^2 and minimum uniformity 6.0. The parameter uniformity considers the ratio between the average illuminance and the minimum illuminance. Furthermore, it was considered a distance of 30 meters between lighting poles in a unilateral arrangement. Each post is 10 meters high, with 45 cm of arm and a tilting of 0° (see Fig. 6 for references).

Four simulations with Dialux software were conducted. Initially, the street lighting design has considered only high pressure sodium vapor lamps (HPS) following the classical photometry (photopic) guidelines. Then, the project was redone considering LED luminaires, but still adopting the classical photometry, which resulted in a second simulation case. Subsequently, it was applied a correction factor for mesopic photometry (see Section II.B) in the projects previously performed, and it was accomplished a third simulation with HPS lamps. Finally, it has been applied the correction factor and the design employing and LED fixture gave rise to the last simulation condition. The light distribution curves of the adopted luminaires are shown in Fig. 7.

Concerning the sodium lamp case, it was initially adopted a classical luminaire (with 84% of luminous efficiency) housing a sodium vapor lamp of 70 W, CCT 1900 K, CRI 20% and a luminous flux of 6000 lm. The luminous efficacy of the light source was considered to be 85 lm/W. Fig. 8 shows the simulation that has been carried out with Dialux utility, from where one can see the diagram of false colors representing the iso-illuminance distribution on the ground. Additional simulation numbers are abridged in Table III.

The second case proposed the replacement of sodium lamps by LED-based luminaires. Seeking to meet the same illuminance level on the pavement as the one desired with sodium vapor lamps, it was employed an LED luminaire with an output power of 40 W, featuring a CCT equal to 5000 K, a CRI of 75% and a luminous flux of 3720 lm. The luminous efficacy of the LED luminaire was of 93 lm/W. Fig. 9 shows the simulation that has been carried out in Dialux, from where one can see the diagram of false colors representing the illuminance distribution on the ground level. Is it possible to note an improvement in illuminance levels while additional simulation numbers are presented in Table III.

Then, the mesopic condition has been taken into consideration for both projects (HPS and LED luminaires) by following the methodology proposed in this paper. Therefore, it was used the proposed equation (2) for calculating S/P ratio, which helped to obtain the correction factor from Table I (CIE 191:2010 corrections). It must be observed that the multipliers were derived from interpolation of table data.

Using the information provided by the HPS lamp maker for CRI and CCT the value of S/P has been found to be 0.56. Hence, by using the luminance level of 0.75 cd/m^2 (see first row of Table III, sixth column) the correction factor of 0.935 (or a decrease of -6.5% to the effective luminous flux) has been obtained. Fig. 10, which is based in the CIE table data (Table I), can be used to obtain this correction factor. The simulation numbers concerning the mesopic case using an HPS luminaire are also presented in Table III.

Finally, it was performed the correction under mesopic condition concerning the LED-based project. From (2), *S/P* was found to be 1.82. Average photopic luminance for the LED lamps project was of 0.73 cd/m^2 (see fourth row of Table III, sixth column). The CIE multiplier (also shown in Fig. 10) was of 1.11 (an 11% increase in the effective luminous flux). Thus, there is an additional gain with the LED-based project according to the fifth row of Table III.

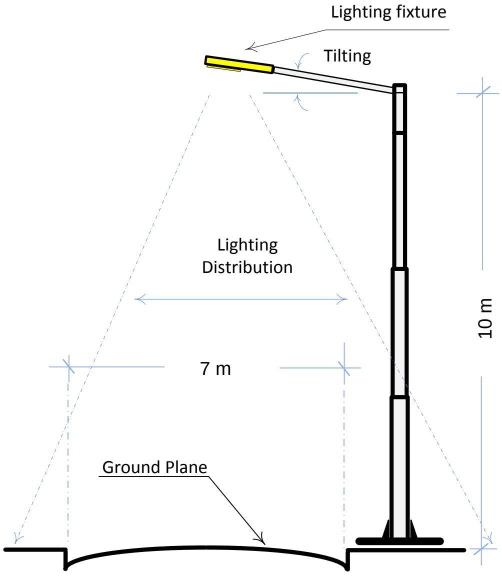

Fig. 6. Lamp post used in lighting project simulation.

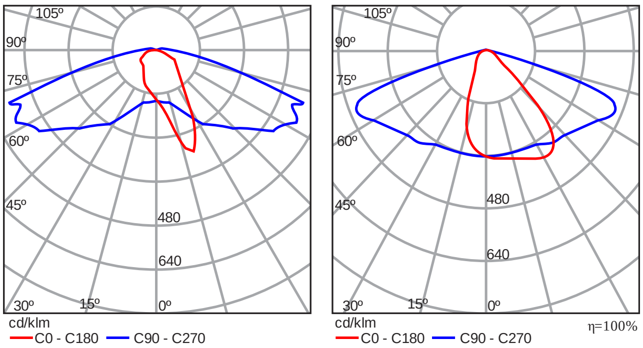

Fig. 7. Light distribution curves of the HPS luminaire (left) and LED luminaire (right).

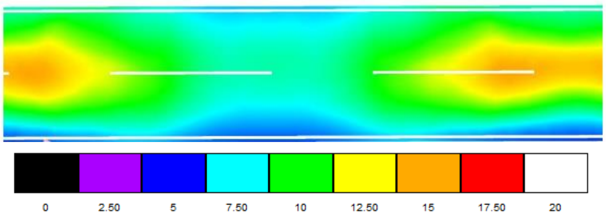

Fig. 8. Iso-illuminance representation between two poles (Dialux simulation) along the street with sodium vapor lamps adopting classical photometry (color scale in lux).

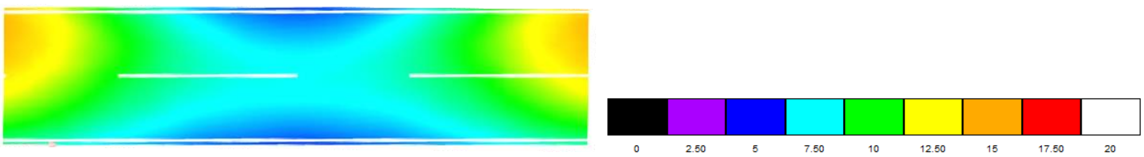

Fig. 9. Iso-illuminance representation (digital simulation) considering LED lamps and adopting the classical photometry (color scale in lux).

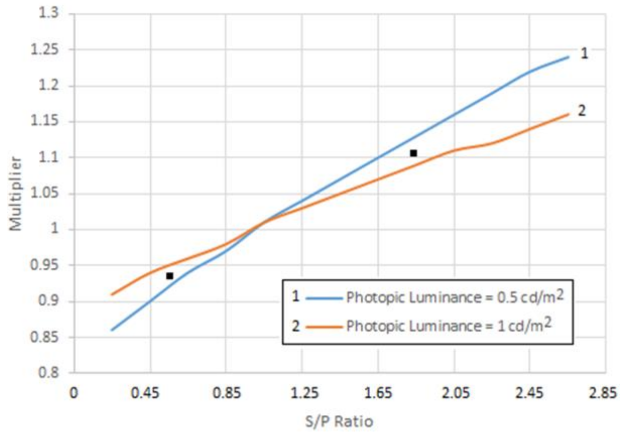

Fig. 10. Effective luminance multipliers against *S/P* ratio for luminance levels of 0.5 cd/m^2 and 1 cd/m^2. *S/P* marks of 0.56 and 1.85 were represented by black squares.

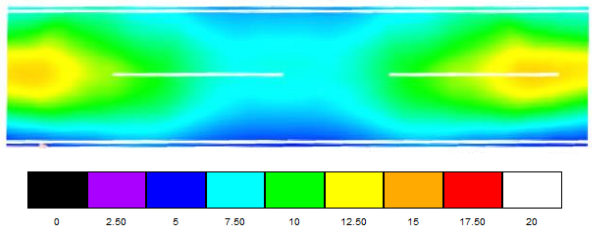

Fig. 11. Iso-illuminance representation (Dialux simulation) for sodium vapor lamps adapted to mesopic photometry (color scale in lux).

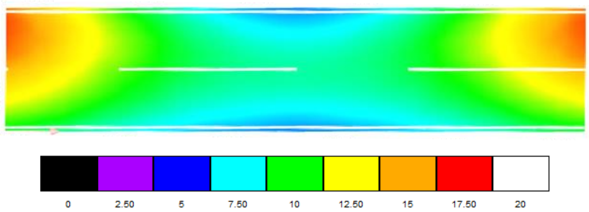

Fig. 12. Iso-illuminance (Dialux simulation) for LED lamps adapted to mesopic photometry and (color scale in lux).

TABLE III.
COMPARISON BETWEEN CONVENTIONAL AND MESOPIC PROJECT

Type of Lamp	Condition	ϕ (lm)	E_{avg} (lux)	ϕ/P_L (lm/W)	L_{avg} (cd/m^2)	U_O
HPS	Photopic	6000	9.58	85	0.75	0.66
	Mesopic	5610	8.95	80.14	–	
	$\Delta\phi$ %			– 6.5%		
LED	Photopic	3720	9.5	93	0.73	0.65
	Mesopic	4130	10.55	103.23	–	
	$\Delta\phi$ %			+ 11%		

Table convention names and parameters: ϕ (luminous flux), E_{avg} (average illuminance), P_L (lamp power), L_{avg} (average luminance) and U_O (uniformity).

Figures 11 and 12 show digital simulation graphs obtained with Dialux utility by employing the mesopic corrections. In such cases, the simulations have been accomplished similarly as the conventional (uncorrected) ones, only by changing the values of the luminous fluxes to the new (adapted) values, according to second and fifth rows, third column.

For the sake of comparison, the performance of both technologies under mesopic conditions can be summarized as follows. One can find a gain of 11% in effective luminous flux for the LEDs-based alternative concerning the project example of this paper. On the other hand, the HPS-based condition represents a decrease of 6.5% in luminous flux. Thus, besides a reduction in lamp power of about 43% when replacing 70 W HPS lamps for 40 W LED lamps, it could be considered a further reduction (dimming) of about 11% in luminous flux of the LED luminaires in order to be attained the same perceived behavior as the one of HPS lamps (i.e., in addition to the reduction of 30 W by replacement, approximately 4.4 W more with dimming, totaling a reduction of 34.4 W per luminaire). Note that HPS ballast or LED driver power losses have not been taken into account here.

VI. CONCLUSIONS

This paper presented a discussion about the need for adaptation of photometric quantities when lighting systems are employed under low luminance levels (mesopic conditions). Street lighting and some outdoor lighting conditions may justify an adapted methodology when developing lighting projects in those cases. In this sense, the CIE 191:2010 recommendation, for example, proposes correction factors that convert conventional photometric quantities into adapted quantities that better corresponds the mesopic levels.

However, a required parameter for obtaining the correction factors is the *S/P* ratio of the light source, whose acquisition requires special equipment that are not easily available to lighting engineers and technicians. Thus, it was proposed an equation that provides *S/P* as a function of the correlated color temperature and color rendering index of the light source, which are information found in the lamp catalogs or product packaging.

In order to try finding a general equation that provides the *S/P* relationship for most common lamps employed nowadays in outdoor lighting, 190 samples of lamps have been evaluated in a specialized laboratory. So, high pressure sodium lamps, high pressure mercury lamps, metal halide lamps, and LED modules of different power wattages, manufacturers and ranges of CCT and CRI have been considered in the present study. The results showed that it is possible to derive a single and relatively simple equation that could represent the lamps studied with relative errors lower than 10% concerning the effective *S/P* ratio. That equation has been attained by using the Lagrange's interpolating polynomial method.

As long as a reliable equation that provides the *S/P* ratio is available, it will be easier to develop street lighting projects considering the response of human vision in mesopic conditions, which will be more consistent with the true feeling of lighting in the external environment. However, it is important to mention that the consideration of mesopic vision may not be in accordance to the technical standards of certain countries. In those cases, the recommended lighting levels are normally associated to the classical photometry illuminance, i.e. the prescribed lighting parameters follows the photopic sensibility of the human eye. Thus, it would be highly recommended that those countries could adapt their regulations to the true lighting response of human beings under low luminance levels.

The use of adapted photometric quantities, besides allowing a better representation of lighting perception, can also improve the energy efficiency of the entire electrical system. The reason for that is related to the fact that some modern light sources (e. g. metal halide lamps, electrodeless lamps and LED modules) may emit light according to a spectral power distribution that better excites the sensing structures of normal human eyes under mesopic conditions.

Despite the equation proposed in this paper reached a good performance as described in the previous sections, authors understand that future studies could lead to better alternative expressions, especially if they could take into consideration a broaden set of samples with increased amount of commercial products representing actual bulb technologies.

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