An Experimental Comparison Between Different Technologies Arising for Public Lighting: LED Luminaires Replacing High Pressure Sodium Lamps

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Abstract **– This work deals with the analysis and photometric comparison between different systems concepts for public lighting, hence the solid state lighting (SSL) employing LED luminaires with electronic drivers and the conventional high pressure sodium (HPS) lamp based luminaires along with electromagnetic ballasts. The study and comparison raise question on the relative perception of the human eye to different light sources with different spectral distributions, devoting special attention to low luminance conditions (scotopic) such as those present on public roadway lighting. Different LED-based luminaires are tested, in the lab and in loco. Photometric data of a SSL system being currently installed for the replacement of current HPS luminaires at the School of Engineering of the Federal University of Juiz de Fora are provided for the analysis and comparison.**

I. Introduction

Nowadays, Brazilian public lighting (PL) system employs mostly high pressure sodium (HPS) lamps. This relatively mature technology is used in approximately 62.93% of the lighting fixtures [1]. Traditionally, High Intensity Discharge (HID) lamps have been used on public illumination (about 95% of the points today). HID lamps are preferred in public lighting because of their high luminous flux and their long lifespan.

However, lighting systems have been experiencing a huge evolution quite recently, mainly concerning the two past decades, underpinned by the use of electronics in the processes of ignition and driving, aiming energy efficiency. By the last and present decades, a new lighting concept has emerged: the use of high brightness LEDs (HB-LEDs). This new Solid State Lighting (SSL) technology arises with the promise of being an efficient, durable and environmentally friendly light source.

For many years, LEDs were used only as indicators or luminous flags. Their application in indoor or outdoor lighting is, however, very recent. One of the great benefits from widespread SSL for general illumination is the reduction of energy consumption. About 50% of the energy spent on artificial light could be saved, which represents more than 10% of the global energy consumption [2].

Beyond that is the environmental question, since a large amount of the electrical energy produced in the world comes from burning fossil fuel. Another important point is that the HID bulbs employ heavy chemical elements in their construction (e.g., mercury). These highly prejudicial elements do not constitute LED lamps.

In contrast, the main drawback of SSL systems utilization in public lighting (PL) is probably its high cost.

As a matter of fact, a careful applicability study considering different light sources, the lighting perception on the human observer and also economic issues should be carried out to know if it is interesting to use SSL as an alternative for the current technology on PL.

This paper brings a case study addressing these main issues. A comparison between the use of HPS lamps and LEDs on a roadway PL system is proposed. Different SSL solutions found on the Brazilian market were analyzed; one of them employs low power HB-LEDs, while the other employs power HB-LEDs.

II. Human Visual Perception

Every lighting system is designed to fit certain requirements established in standards, which aim the adequacy of artificial lighting to the task being performed.

According to biophysical studies, the human eye has two different types of sensory cells known as cones and rods. Cones are concentrated, in greater quantity, in the central region of the retina (the fovea). These cells are responsible for high luminosity visual response, when it's possible to distinguish the colors, the so-called photopic vision. On the other hand, rods are responsible for vision at low luminosity conditions (scotopic vision). This type of cell is much more abundant than cones, being responsible for perception under dim light, as well as bright and dark differentiation (contrast) [3].

Under high luminance levels (above 3 cd/m^2), the pupil dilation is small, so the image focusing happens in the fovea region, where cone distribution prevails. This characterizes the photopic condition of vision. But when luminance gets lower (below 0.01 cd/m^2), the pupil dilation is greater and light is projected in a wide retina region, thus sensitizing more rods than cones. This effect implies on the scotopic visual response. In between the photopic and scotopic conditions is the so-called mesopic condition, which includes any intermediate luminance level and is an interaction between both kinds of sensory cells [3]. Figure 1 intends to show graphically the limits of the scotopic and photopic vision, as well as the mesopic region. This region may be subdivided into two parts: low mesopic, which goes from the scotopic boundary to the middle of the mesopic region, and high mesopic, which stretches from the middle of mesopic response to its limits with photopic region. In this figure, the point L_R, indicated with an x mark, refers to the measured luminance of the roadway studied in next section (0.3 cd/m²).

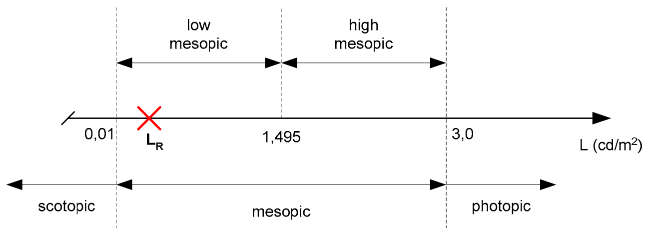

Figure 1. Limits of visual conditions in function of the luminance.

The currently used definition of luminous flux is based on the photopic response of the human eye. In many cases, such as indoor applications, this definition of luminous flux is acceptable, since the luminance levels considered are relatively high. But when luminance levels are lower, such as in public lighting applications, this model does not quite fit. In the PL case, low mesopic or scotopic luminosity functions could better represent the eye response [3]-[5]. Thus, when luminance levels are low, it might be useful to propose an adaptive redefinition of the photopic lumen (lm): the scotopic lumen (lm'), based on the scotopic eye response curve.

There are also some models employed to predict the eye response curve under mesopic conditions, when both rods and cones are in activity, such as the ones in [6] and [7].

Besides the retinal sensitivity variation with the luminance levels (it gets more sensible to light at lower luminance), there is also a wavelength shift of the peak sensitivity on the eye response curve, which is commonly referred to Purkinje Effect. Fig. 2 shows the spectral sensitivity curves for the photopic (V_1), scotopic (V'_1), and a low mesopic response for L = 0.3 cd/m². The mesopic curve shown was obtained using the model presented in [6], considering $L = L_R$, which is the luminance level measured in the roadway under study, assuming that the peak of the eye response decreases linearly from scotopic to this situation.

To reinforce the importance of this issue, the photopic and scotopic luminous fluxes of some modern light sources currently used on PL were measured in an integrating sphere.

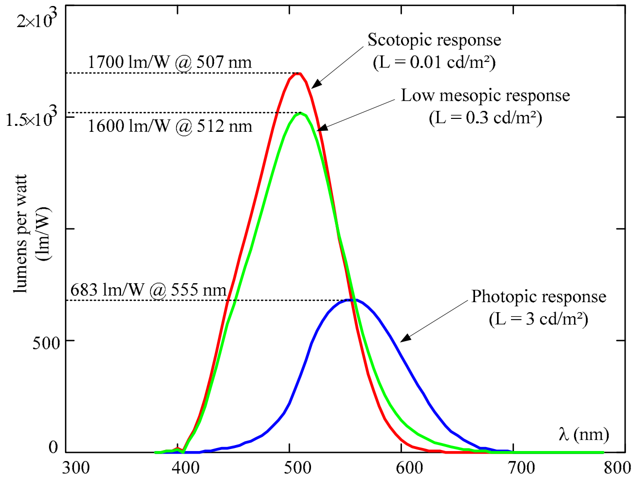

Figure 2. Eye response under different luminance conditions.

Table I shows relevant experimental data for the studied light sources. It includes the photopic and scotopic efficacy of each one, as well as the radiant efficiency, i.e., how much of the electrical power (watts) demanded by the source is actually being converted to radiant flux (also watts), either visible or invisible. Color-related information, such as correlated color temperature (CCT) and color rendering index (CRI) are also provided in this table.

Fig. 3 shows the spectral power distribution (SPD) obtained from the three types of sources measured: high pressure sodium (HPS) lamp, metal halide (MH) lamp and one power HB-LED (SPD similar to low power HB-LEDs).

TABLE I – EXPERIMENTAL DATA FROM INTEGRATING SPHERE

Measured Source	Luminous Efficacy:		Radiant Efficiency	Color-Related:	
	Photopic	Scotopic		CCT	CRI
High Pressure Sodium 70 W	77 lm/W	44.4 lm'/W	29.2%	1902 K	27.3%
Metal Halide 70 W	60.9 lm/W	107.2 lm'/W	26.6%	4497 K	69.8%
Low Power HB-LED 20 mA	46.2 lm/W	94.5 lm'/W	14.8%	5915 K	79.2%
Power HB-LED 350 mA	85.9 lm/W	167.8 lm'/W	27.3%	6217 K	70.5%

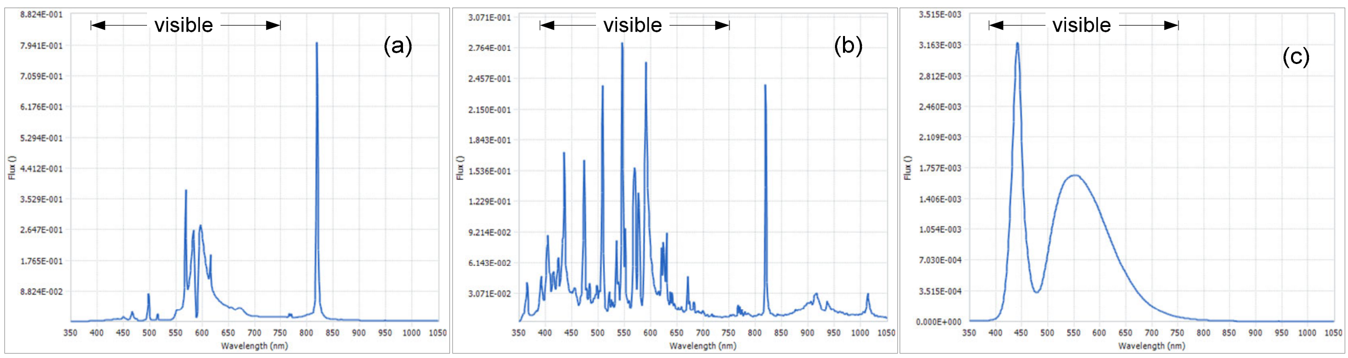

Figure 3. Spectral power distributions for (a) HPS 70 W, (b) MH 70 W and (c) power HB-LED 350 mA, obtained in integrating sphere. The visible spectrum range is shown (380-750 nm). Wavelength aperture was 350-1050 nm.

It is possible to see from Figure 3 that the power HB-LED emits no radiation at Near Infrared (NIR, 800-1400 nm), as opposed to the other two high intensity discharge technologies, which show even high peaks at some wavelengths that will produce no visible response at all.

III. Roadway Characteristics and Classification

The case study presented in this paper was conducted in the surrounding roadway of the School of Engineering of the Federal University of Juiz de Fora (UFJF), in Brazil. Its PL system is composed of 250W high pressure sodium lamps (HPS), with conventional electromagnetic ballasts and their respective luminaires mounted on top of 10 meter (m) high poles, with an average distance of 35m from each other. The single outreach arm of the poles has approximately 2.3m and features a horizontal slope of around 10 degrees. The distance of the pole to the roadway is about 0.45 m, being the single-lane roadway 8m in width.

According to ABNT NBR 5101 – 1992 [8], the current Brazilian standard for public lighting, the roadway can be classified as "main urban roadway", on C1 group, in which are included avenues and paved streets or sidewalks, where there is predominance of commercial buildings, as well as pedestrian traffic. For this group with low car and pedestrian traffics, the standard requires a minimum average illuminance level of 5 lux on the work plane (E_{avg} = 5 lux) and an uniformity factor of 20% (U_0 = 0.2), which is defined as the ratio between the minimum illuminance obtained in the measurement grid (E_{min}) and E_{avg}. Yet, according to [8], the illuminance measurement grid must be composed of 110 measurement points divided into 11 transversal rows of 10 points equally spaced, with a length equals to the distance between two consecutive poles.

It is important to note that Brazilian PL standard is considered outdated and does not take into account luminance levels (although this is being revised nowadays). But it will be considered in this paper since there is no current alternative for setting minimum PL requirements.

The aforementioned roadway is to receive a lighting system based on LED luminaires. This pilot study aims *in situ* monitoring of the operation of the devices and raises question on the comparison between LEDs and other technologies currently employed. The preliminary results here presented were obtained during the evaluation process for selecting the products which should be installed.

IV. Case Study

A. High Pressure Sodium

At first, some photometric measurements were carried out *in loco* for the current PL system, which currently employs 250W HPS lamps.

The cost of each point, considering just the luminaire, electromagnetic ballast, starter ignitor, power factor correction capacitor and the lamp itself is around US$ 150.00.

Throughout the surrounding roadway, there are 56 fixtures, resulting in an installed power of 15.68kW (lamp plus 30W loss for each ballast), with a 0.92 power factor, assuming a good behavior of power factor capacitors.

Therefore, the total cost of the PL points is US$ 8,400.00. Estimated lifespan of HPS lamps is 20,000 hours [9] and the color rendering index (CRI) considered is 27%, obtained experimentally from Table I.

Illuminance measurements were carried out on the stated grid, considering a pole between other two with identical luminaires as being the central reference. Measured relevant data are compiled in Table II. Figure 4 shows the point-to-point illuminance plotted over the grid for this first measurement.

B. Low Power HB-LEDs

As mentioned before, one of the lighting solutions considered in this study employs low power HB-LED modules. These luminaires were installed on three consecutive poles in such a way the central unit is far enough from other surrounded light sources (negligible influence).

The HB-LED luminaire is composed of 1,728 LED lamps, properly associated, draining approximately 97.53 W from electrical grid, with good power factor (0.96). Total harmonic distortion (THD) of input current was measured 22.4%. The cost of each luminaire is US$ 1,653, and the manufacturer-alleged lifespan is 70,000 hours. Colorimetric and photometric measurements for the LEDs alone are those presented also in Table I – Low power HB-LED 20 mA.

On the roadway, illuminance measurements were also performed, under the same guidelines as those for the HPS 250W luminaires aforementioned, and the data are shown in Table II. The spatial distribution of illuminances over the measurement grid is plotted in Figure 5.

C. Power HB-LEDs

The second model of LED luminaire installed for experimental purposes is composed of 48 power HB-LEDs, series-associated, half of which are collimated for altering and enhancing the light distribution of the power LEDs. Its input power was measured 120 W, with an input current THD of 3.33% and a power factor of 0.99. The unitary cost of such luminaire is US$ 1,690.

One individual power LED was also tested at the integrating sphere, being its photometric, colorimetric and spectrometric results those presented in Table I – Power HB-LED 350 mA, and its SPD that presented in Figure 3-c.

Once more, three identical luminaires were placed on three consecutive poles and photometric measurements on the grid were taken. These results are compiled in Table II and the spatial distribution of illuminances is shown in Figure 6.

V. Comparison Based on Classical Photometry

Based on the illuminances measured for the three luminaires, one can infer that the three technologies meet the Brazillian standard requirements. But the HPS luminaire shows an average illuminance value around two times higher than the other two. Thus, the 250 W HPS would be expected to produce a better luminosity sensation, considering the classical photometry and the lux defined under photopic conditions.

Nevertheless, it should be taken into account that the photopic efficacy is greater for HPS and, yet further, this luminaire has a power two times greater than the highest power of the two LED luminaires studied (120 W). Therefore, it was already expected that the illuminance levels would turn out greater.

But since luxmeters are calibrated to respond under photopic conditions of illumination, a parallel analysis adapting classical photometry could be derived in order to actually compare both technologies under the more realistic condition of the roadway, considering the scotopic-adapted eye response curve.

TABLE II – PHOTOMETRIC RESULTS

Luminaire	E_{med}	E_{min}	E_{max}	U_0
HPS	22.0 lux	7.5 lux	34.6 lux	0.34
Low Power HB-LEDs	9.1 lux	3.9 lux	21.7 lux	0.42
Power HB-LEDs	8.8 lux	3.2 lux	13.9 lux	0.36

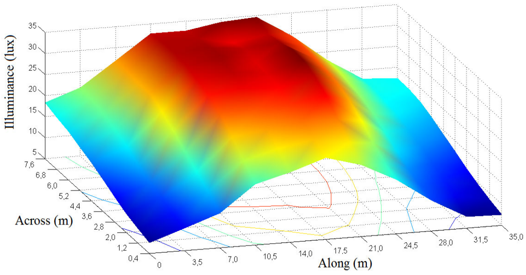

Figure 4. Spatial distribution of illuminances for HPS 250 W luminaire.

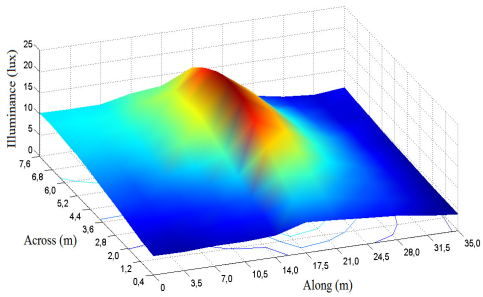

Figure 5. Spatial distribution of illuminances for low power HB-LED luminaire.

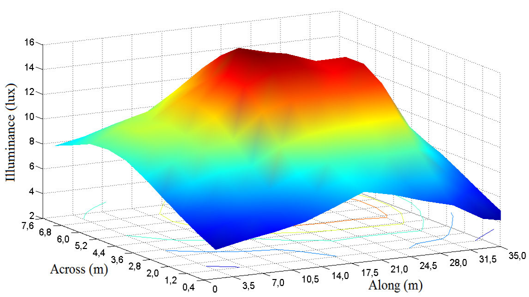

Figure 6. Spatial distribution of illuminances for power HB-LED luminaire.

It is important to stress, though, that the color sensation and the color rendering are far better for the LED luminaires than for HPS lamps. Yet, power consumption is lower, and energy savings could justify the broad adoption of this technology. These hypotheses will be further analyzed.

VI. COMPARISON UNDER DYNAMIC RESPONSE OF HUMAN VISION

The luminous flux (lumen – lm) is the photometric unity used to correlate the radiant flux (expressed in watts) to the radiation effectively perceived by the human observer (i.e., light). The luminous efficacy of a radiation (or light source) is defined as an inverse ratio between the radiant flux emitted (or input power, in the case of an electrical source of light) and the amount of flux from this radiation that can be perceived as light, i.e., the human eye-weighted part of the radiant flux, that is the luminous flux (lumens). Therefore, it readily assumes the unity of lumens per watt (lm/W). It is evident that energy being emitted outside the visual spectrum range reduces luminous efficacy, because it will produce no eye stimulus whatsoever.

Considering that two extremes of sensibility are observed in human eye (photopic and scotopic), dependent on luminance conditions, it is appropriate to say that the efficacy is also dependent on these visual conditions.

As shown in Figure 2, the human eye responds more to some wavelengths than to others. For example, a pure monochromatic radiation of wavelength equals 555 nm (yellowish-green) would be perceived as a 683 lm flux for each irradiated watt, i.e., its efficacy would be 683 lm/W under photopic conditions. Thus, the efficiency of this radiation would be 100%, since this is the highest value that the eye can perceive for each watt irradiated in this visual condition.

Analogously, a pure radiation of 507 nm (bluish-green) would be perceived by the human eye, under scotopic conditions, as the highest flux possible, i.e., 1,700 lm for each irradiated watt. This would correspond to the 100% efficiency of radiation under scotopic visual response.

It is, therefore, proposed that the radiation should be weighted by the luminosity function (eye response curve) adequate to the luminance condition: for example, the pure 507 nm radiation aforementioned would yield only 278 lm/W at photopic conditions, but yields 1,700 lm/W under scotopic conditions. That does not mean that the radiation is more efficient under scotopic vision; it means that the effective scotopic flux is different from the photopic flux for this radiation [3]. That implies that the luminous sensation produced by the radiation composed by this wavelength is more sensitizing to the human eye on scotopic condition than it is under photopic regime.

Based on this statement, an adaptive photometrical comparison should be derived. The lux measured for the luminaires installed over the roadway is naturally weighted by the photopic luminosity function. It is suggested that an adaptation for the lux dimension could follow from the source efficacies compiled in Table I.

As mentioned before, with the help of a luminance meter, luminance was measured on the roadway studied, being L_R = 0.03 cd/m². The luminosity function that represents this luminance condition is the one plotted in Figure 2, a low mesopic curve obtained by propoer mesopic model [6]. It is clear in Figure 2 (and also in Fig. 1) that the low mesopic condition for a 0.03 cd/m² luminance is very close to the pure scotopic response (0.01 cd/m²), being their curves (luminosity functions) almost coincident. Therefore, it is possible to infer that considering pure scotopic conditions at the roadway for adapting the photometry will not imply in great deviation from the mesopic-reality of the eye response and the scotopic photometric-adapted values will be fairly representative. As a matter of fact, the error using the scotopic response is lower than when using the photopic one, when the condition is low mesopic.

For adapting the measured lux, one can start by the classical photopic definition of this photometric unit of illuminance, (1), using the photopic lumen (lm).

$$lux = lm / m^2 \tag{1}$$

Analogously, (2) can be used to define the adapted lux, so-called “effective scotopic lux”, or lux’, using the scotopic flux (lm’) of the radiation in its definition.

$$lux' = lm'/ m^2 \tag{2}$$

The ratio between the two analogous units can be derived for finding the relationship (3).

$$\frac{lux'}{lux} = \frac{lm'/ m^2}{lm / m^2} \Rightarrow \frac{lux'}{lux} = \frac{lm'}{lm} \tag{3}$$

Then, (3) can be rearranged, by dividing and multiplying by W^{-1}, as in (4), in order to obtain a relationship that is only dependent on the efficacies values of each source.

$$\frac{lux'}{lux} = \frac{lm'}{lm} \cdot \frac{W^{-1}}{W^{-1}} \Rightarrow \frac{lux'}{lux} = \frac{lm'/W}{lm / W} \tag{4}$$

Finally, (5) can be derived and used as the adaptation necessary to translate photometric data obtained with photopic-calibrated equipment (such as the luxmeters) into equivalent scotopic data, for each kind of technology, as long as the ratio lm’/lm is known for the light source studied.

$$lux' = \frac{lm'/W}{lm/W} lux \tag{5}$$

Using the efficacies obtained experimentally with the integrating sphere and presented at Table I, a ratio of $k = (lm'/W)/(lm/W)$ can be calculated for each of the technologies of light source. These values are presented at Table III. They can then be used to convert the photopic lux into the effective scotopic lux, shown in Table IV for the average measured illuminances of each luminaire tested, as a way of adapting the photometry to the roadway quasi-scotopic conditions.

TABLE III – VALUES OF k CALCULATED FOR EACH LIGHT SOURCE TYPE

Source Technology	Photopic efficacy (lm/W)	Scotopic efficacy (lm’/W)	k
High Pressure Sodium	77 lm/W	44.4 lm’/W	0.577
Low Power HB-LED	46.2 lm/W	94.5 lm’/W	2.05
Power HB-LED	85.9 lm/W	167.8 lm’/W	1.95

TABLE IV – SCOTOPIC-ADAPTED PHOTOMETRIC RESULTS OF LUMINAIRES

Luminaire Technology	E_{avg} (lux)	E'_{avg} (lux’)
HPS 250 W	22 lux	12.7 lux’
Low Power HB-LED	9.1 lux	18.7 lux’
Power HB-LED	8.8 lux	17.2 lux’

Table IV shows that both LED luminaires are somehow equivalent, and have a higher adapted illuminance as compared to the HPS luminaire when considering the scotopic condition, according to the analysis proposed here.

VII. COST COMPARISON AND PAYBACK

It is also possible to calculate the payback for installing each of the LED solutions presented, substituting the current 250 W HPS system. This payback calculation will be performed considering only one light point, and can be extended for the whole set of luminaires that should be installed. The payback (in years) is then calculated using (6), dividing the LED luminaire price by the financial amount that can be saved per year. To estimate this amount, it is necessary to know the difference between the input powers of the HPS and LED luminaires, using daily usage to determine the energy saved yearly (i.e., power difference multiplied by 12 hours/day and multiplied by 365 days/year). Then, multiplying the saved watt-hours by the cost of energy (USD per watt-hour), the saved resources per year is obtained.

Considering the 30W loss of the electromagnetic ballasts, an electricity rate of US$ 7,65/kWh and the LED luminaire pieces aforementioned, the payback for substituting the current public lighting system for each one of the presented LED solutions is calculated, and shown in Table V. This payback takes into account the power saved yearly by substituting the current system, ignoring possible maintenance costs of all technologies, as a simplification.

This analysis demonstrates a very short period of payback. This is probably because the current HPS system is well oversized. Therefore, the power difference between the LEDs and the HPS solutions is very high, making a huge difference of saved energy in a year basis.

However, it is interesting to show this result because there are probably many PL installations that are also oversized, perhaps due to intrinsic low scotopic efficacy of HPS. Thus, LED could be affordable in such systems.

$$Payback\ (years) = \frac{LED\ luminaire\ price\ (USD)}{Resource\ saved\ yearly\ (USD/\ year)} \tag{6}$$

TABLE V – PAYBACK FROM POWER SAVINGS ONLY

Luminaire Technology	**MS (US$/year)**	**Payback**	
		Years	**Months**
Low Power HB-LED	6,165.29	0.27	3.22
Power HB-LED	4,690.98	0.26	3.12

VIII. ALTERNATIVE HPS SYSTEM HYPOTHESIS

To consider a situation where the system employing HPS luminaires is not oversized, a simulation using Dialux software was performed, using 150 W HPS luminaires, which produce 14,500 lm. The roadway conditions are the same. Table VI shows the results obtained, while it can be seen that the Brazilian standard is met under photopic conditions.

TABLE VI – 150 W HPS DIALUX SIMULATION RESULTS

E_{med}	E_{min}	E_{max}	U_0
8.5 lux	1.7 lux	30.0 lux	0.2

The payback periods of the LED solutions, for this case, considering a 10 W ballast loss, are shown in Table VII.

TABLE VII – PAYBACK CONSIDERING 150 W HPS SYSTEM

Luminaire Technology	**MS (US$/year)**	**Payback**	
		Years	**Months**
Low Power HB-LED	2,144.48	0,77	9,25
Power HB-LED	670,14	2,52	30,26

It's possible to see that the period of payback, in this case, is longer than when a 250 W HPS oversized solution is used, nevertheless, the utilization of SSL in PL is probably economically viable. According to the table VII, the Low Power HB-LED will be paid faster than the other type of LED luminaire.

But, under a closer inspection, considering the *k* factor for HPS from Table III, the average illuminance on the working plane would be 4.9 lux' for the scotopic-adapted eye, which is bellow the standard requirement. This suggests that, perhaps, HPS 150 W is, indeed, not quite adequate as a PL lamp for this roadway, under scotopic-adapted analysis. In this case, an HPS solution, to be in accordance with minimum requirements, should be of greater power, thus making LED luminaires, once more, the more energy-efficient solution.

IX. CONCLUSION

This paper presented a new way to compare technologies used in street lighting, taking into account the issue of human visual perception.

It is important to emphasize that this analysis does not prove that LEDs are a better and brighter source of light than HPS for public lighting, but rather suggests that a more careful inspection should take place in order to decide whether it is more viable to use LED luminaires or reducing the installed power of current HPS systems.

The scotopic-adapted lux proposed here is a powerful tool to be used under dim light situations, such as in this roadway. It was shown that the luminance levels measured in loco places the corresponding sensitivity curve under low mesopic response, and indeed very close to the scotopic response of the human eye, thus justifying a more precise analysis such as the one proposed by this paper. This suggests that, if two different luminaires, one with HPS lamps and the other employing LEDs, were able to provide the same work plane level of illuminance, the luminosity sensation with solid state technology would be better. Unfortunately, the current HPS system is way oversized, thus giving a bright impression while spending too much energy.

As already mentioned, the proposed replacement of the current HPS system of PL is economically viable because payback occurs before ending the lifespan of the LED luminaires themselves.

Analyzing only the fixtures that use LED technology, it is possible to see that the low power HB-LED luminaire photometric results were better than power HB-LED luminaire results, compared side-by-side. However, the luminaire that employs power HB-LEDs presented more compatible electrical parameters.

But it should be taken into account that the preliminary conclusions presented in this work are solely about these two luminaire models, and other fixtures should be evaluated for more conclusive results over the whole arising LED technology in the market.

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