Vision and Exterior Lighting: Shining Some Light on Scotopic and Photopic Lumens in Roadway Conditions

Dr. Jack Josefowicz and Ms. Debbie Ha
November 2008

*This white paper, authored by Dr. Jack Josefowicz and Ms. Debbie Ha, has been reviewed by **Dr. Samuel M. Berman** and he concurs that the technical and scientific information therein is consistent with generally accepted knowledge in lighting and vision science.*

Summary

The human eye contains 2 major light sensitive photoreceptors, namely cones and rods each with its own spectral sensitivity, photopic sensitivity for cones and scotopic sensitivity for rods. At light levels typical of night time roadway lighting, both cones and rods can be active and both spectral sensitivities could apply. However for straight ahead viewing where the line of sight is directed to distant object detection and recognition, such as a pedestrian on a roadway, only cones are relevant. In that case, the photopic function is the operating sensitivity. The rod response, along with scotopic sensitivity, does not contribute to the important visual task of direct object recognition. Other visual tasks such as large area brightness perception, peripheral guidance and detection of objects not in the line of sight are affected by rod response and in that case both photopic and scotopic sensitivity functions need to be included to correctly characterize how light affects vision.

Overview

Objects are best seen and discerned in central vision i.e. when we directly view them straight ahead. In night time conditions, this primary visual task will generally benefit from the presence of an exterior lighting system. However, when we look straight ahead, the most important light coming from the viewed object activates the very center of the retina known as the fovea. The fovea is populated exclusively by cone photoreceptors and as a consequence of this anatomical condition (all cone and no rod receptors), the applicable spectral sensitivity for direct object recognition is always the photopic spectral function. This remains true even for the night time light levels typical of roadways.

Thus, to assure that a lighting system meets both IESNA and CIE recommendations for the vision functions of object detection and recognition, such as a pedestrian in a roadway, the recommended light levels should be specified in standard photopic photometric quantities.

In contrast to central viewing, the perception of spatial brightness involves light that stimulates all parts of the retina including both central and non-central regions. This applies to interior as well as the lit environments typical of night time roadway conditions. In night time conditions, rod and cone receptors will be active in the retina. As a result, both scotopic and photopic spectral sensitivities need to be considered together to adequately describe how light affects spatial brightness perception.

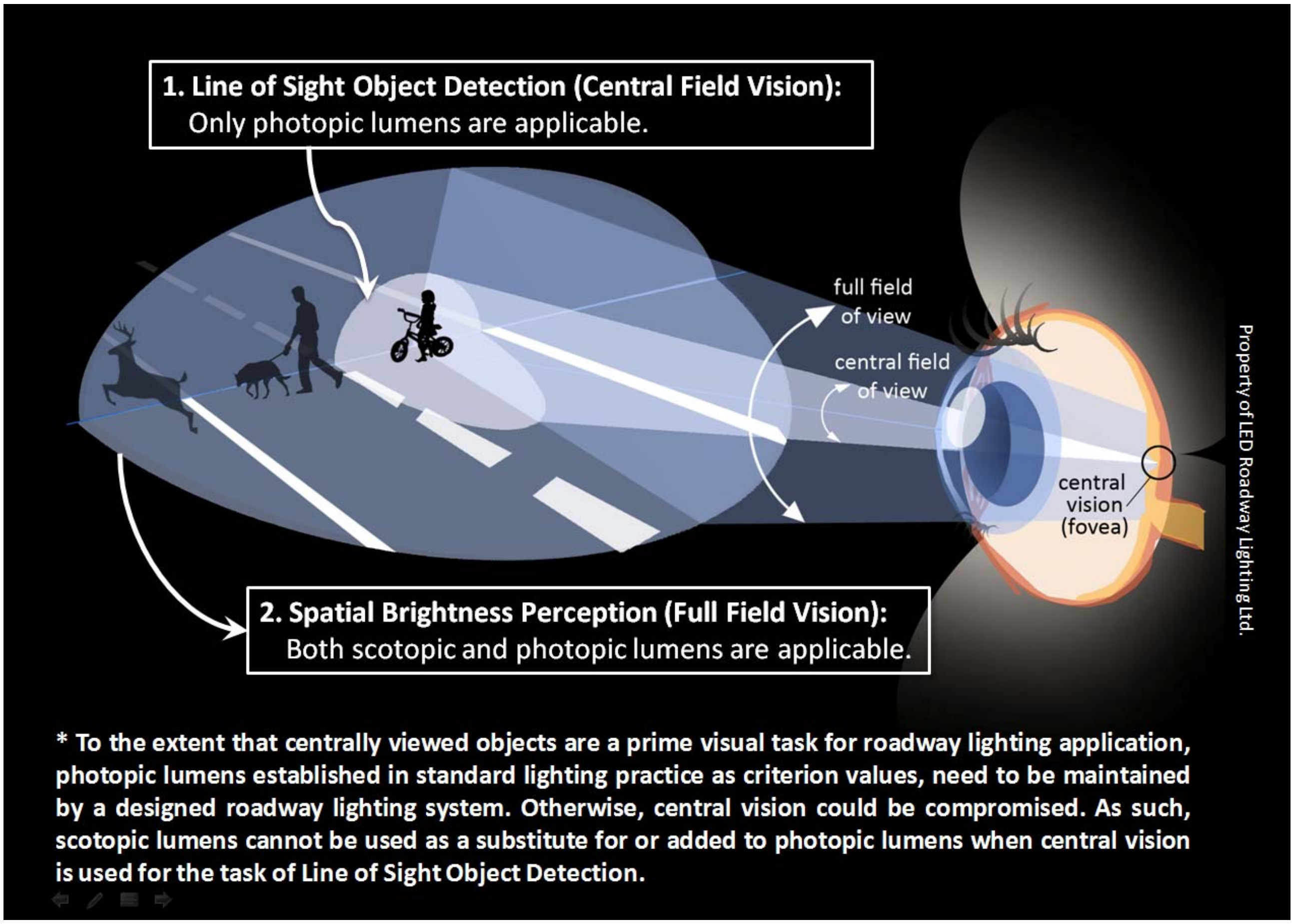

Figure 1: Line of Sight Object Detection & Spatial Brightness Perception on a Roadway

Background

Photoreceptors (i.e. human light sensors) are located at the back surface of the eye [1]. This light sensitive structure is called the retina. The surface of the retina is composed of both rods (~120 million) and cones (~7 million)[2]. Rods and cones are the primary means through which the eye receives optical signals that are subsequently transferred to the brain [2]. There, the signals are converted to visual images that are perceived. The perception of color is accomplished via the cones that are tuned to respond to light in a wavelength range of between blue light (450 nm) and red (675 nm) light [3] combining to provide a peak for achromatic spectral sensitivity at 555nm. During daytime conditions and high lighting levels, only cones are activated giving the human eye Photopic vision [1][2]. In pitch-black night time and very low lighting levels such as starlight, only rods are activated. Rod receptors are sensitive to wavelengths from violet light (400 nm) to orange light (610 nm)giving the human eye Scotopic vision [1][2]. There is an intermediate luminance level (3 candelas/m^2 to 0.01 candelas/m^2) referred to as Mesopic vision, where both rods and cones contribute to vision by varying degrees [1][2]. Much of the lighting for roadways, parking lots, and other exterior locations fall within the Mesopic range. In fact, the Illuminating Engineering Society of North America (IESNA) recommends a photopic luminance of between 0.3 and 1.2 candelas/m^2 for roadway lighting [4].

In Figure 2, the graph shows the eye's two luminous efficiency functions at various wavelengths (colours) of light normalized by the international definition of the lumen, i.e., 683 lumens at 555 nm. The cone achromatic channel for photopic vision, called the photopic spectral sensitivity function (the calibrating function applied to calibrate all light meters) has a maximum sensitivity at the green colour of 555nm. Rods, for scotopic vision, have their maximum spectral sensitivity as shown by the peak of the Scotopic sensitivity function at the blue-green colour of 507nm. The different peak heights of the two sensitivity functions shown in Figure 2 are a consequence of the fixed and internationally accepted normalisation of 683 lumens at 555 nm and are not related to innate differences in rod or cone light sensitivity.

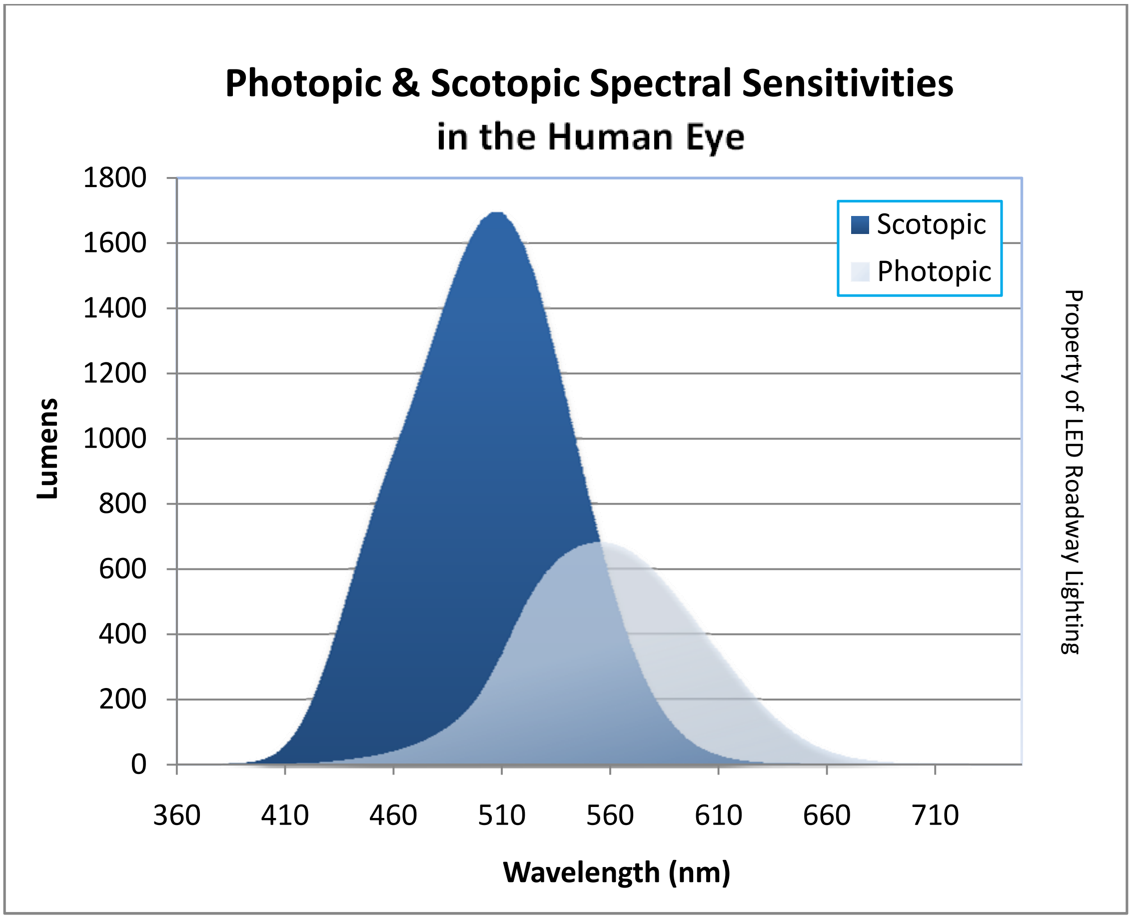

Figure 2: Photopic & Scotopic Spectral Sensitivities of the Human Eye: Adapted from [3]

Vision Tasks on a Roadway at Night

While commuting on a roadway, visual function can be separated into at least four distinct tasks— Direct (Line of Sight) Viewing along with Object Detection and Recognition, Spatial Brightness Perception, Guidance along with Off-Axis Object Detection and Movement Detection.

(a) **Line of Sight Viewing with Object Detection (Central Vision is Predominate):** At mesopic light levels, this task is essentially independent of brightness of the surrounding environment and focuses only on the identification of objects viewed straight ahead. In the human eye, this task is attended by the fovea, located in the central part of the retina [Figure 3] where vision is the most precise [1]. Only cones are present in the fovea [Figure 4] making the Photopic Sensitivity Function the sole spectral contributor for Line of Sight Viewing and direct Object Detection tasks. This presumption based on the anatomy of the retina has been confirmed for roadway light levels by the studies of He et.al [5]. In that study, a spot of light was flashed in the visual field of several subjects and their reaction response times were measured. This response was studied for light level adaptation conditions typical of night time lit environments. When the spot was presented foveally at these mesopic light levels, photopic luminance alone predicted the measured behaviour. However, when the spot was presented away from the line of sight or visual axis at mesopic light levels, both scotopic and photopic quantities were required to properly correlate the reaction time data.

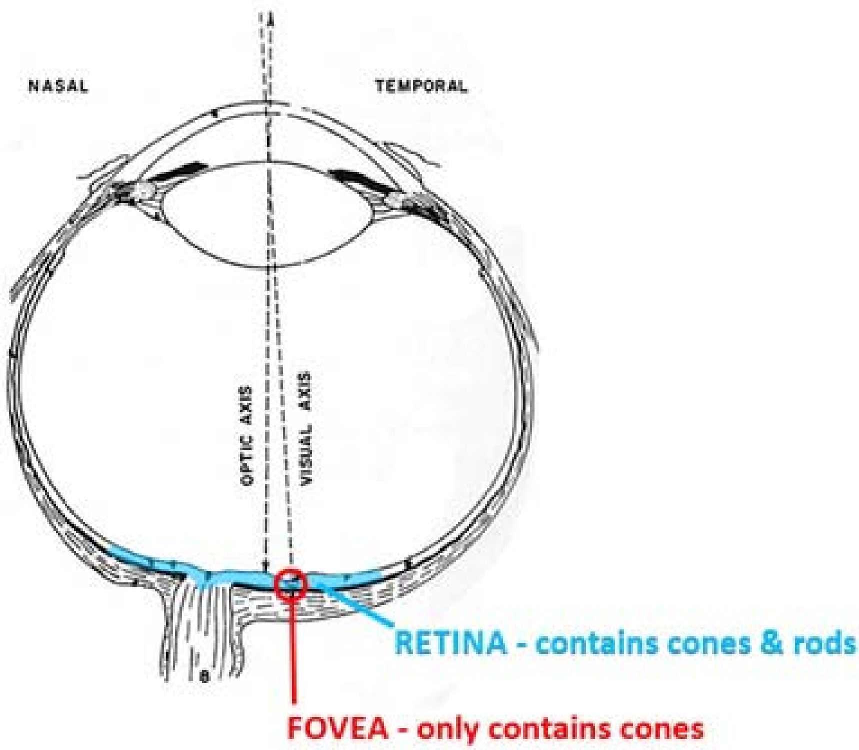

Figure 3: Schematic of Right Eye. Adapted from [1]

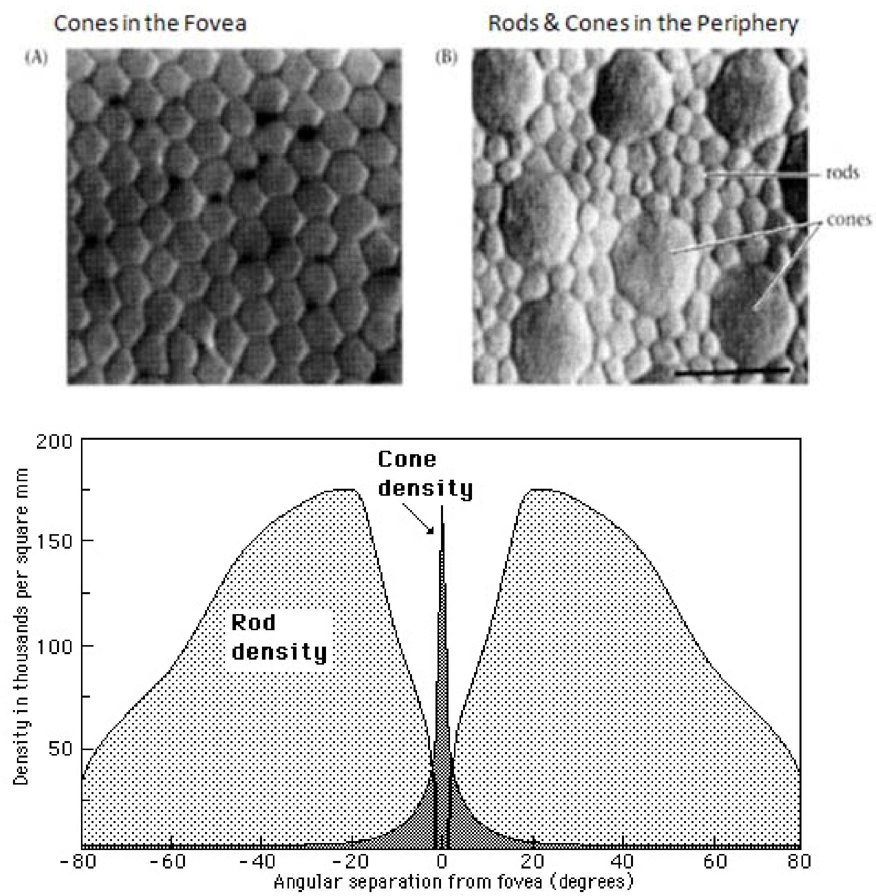

Figure 4: Rod and Cone Density on the Retina [2]

(b) **Spatial Brightness Perception (Full Field Vision):** This percept relates to how light is perceived in a broadly lit spatial area. At night, this can relate to how secure we feel in it. Spatial Brightness Perception is initiated by both rod and cone photoreceptors throughout the entire retina, and thus will require both scotopic and photopic photometric quantities to accurately describe the perceptions [6][7].

(c) **Non Central Vision for Guidance and Detection of Targets Located Off the Visual Axis:** This task refers to the acquisition of visual information not in the line of sight along with the detection of objects that are not located in the direct central field of view (line of sight) but are off to the sides. In Mesopic conditions, both rods and cones will contribute to both guidance and off-axis target detection [3].

(d) **Movement Detection:** The ability to detect movement both centrally and peripherally is an important visual task that is especially useful for night time driving and security observations [8]. Although central movement detection is known to be primarily governed by photopic spectrum [9], little is known quantitatively about the spectral component of non-central movement detection especially in mesopic conditions. However it has been determined [10] that at mesopic light levels, non-central movement detection is better with more bluish light as compared to more reddish light both set at the same photopic level. This result indicates that rod response is also involved in non-central movement detection.

A Concern for Lighting Practice

For street and roadway lighting applications where mesopic vision may apply [3], it is incorrect to obtain the net response of the eye to brightness or any other vision experience by summing the photopic and scotopic light associated with a light source. The light initiated signals from the rods and cones are combined in the visual cortex of the brain to produce perception. The manner by which they are combined depends on the specifics of the task as well as the light level. For example, at light levels at the upper end of the Mesopic range, rod contributions to brightness perception will be negligible compared to cone signals; whereas at the low end of the Mesopic range, the situation would be reversed.

A reduction in photopic light levels below standard lighting specifications, on the basis that scotopic lumens can be added to photopic lumens, ignores the fact that only photopic lumens are involved with direct line of sight object recognition, where primarily cone receptors in the fovea are activated. **For good lighting practice applied to street, roadway, and highway lighting applications, it is essential not to deviate from the IES (Illuminating Engineering Society) RP-8-00 specifications [11] or CIE (International Commission on Illumination) 115-2005 specifications [4] that define photopic light levels.** These specifications are based on the determination of the minimum amount of photopic lumens required for safety and security in Direct Object Recognition applications, such as a pedestrian crossing a roadway.

Comparing LED and HPS Spectral Power Densities and Lumen Outputs

The scotopic and photopic lumens incorporated by the human eye associated with a luminaire with a given spectral power density is determined by weighting that spectral power density with the photopic or scotopic spectral sensitivity. The integrated result over the range of visible wavelengths of the weighted spectral power density curve yields the photopic and scotopic lumens respectively [1][2]. Furthermore, the ratio of scotopic to photopic light for a particular light source (S/P value) is independent of absolute light level to the extent that the spectral power density remains constant [6].

When such a calculation is carried out for the comparison of a typical HPS lamp with the whiter light LED source, the result obtained shows that these LEDs [Figure 7] can have significantly higher S/P values as compared with the typical HPS [Figure 6]. The examples of Figure 6 and Figure 7 show that the S/P value for the LED source is about a factor 2.65 greater than the HPS source.

This characteristic may be used to an efficacy advantage in situations where there is a benefit for lighting with relatively more scotopic content such as for area brightness perception or off-axis detection. **However, where maximum safety and hence direct straight-on object recognition is critical, such as Line of Sight Object Detection of a pedestrian crossing a street, only photopic lumens should be considered.**

In Figure 5, the graph shows LRLL results for a comparison of a conventional 100W HPS cobra head fixture to LRLL Model A100 LED fixture [12] with equivalent total integrated areas under their spectral power densities. This was measured in a two metre diameter *Sphere Optics* integrating sphere and generated with the *SLM-800* integrating sphere program.

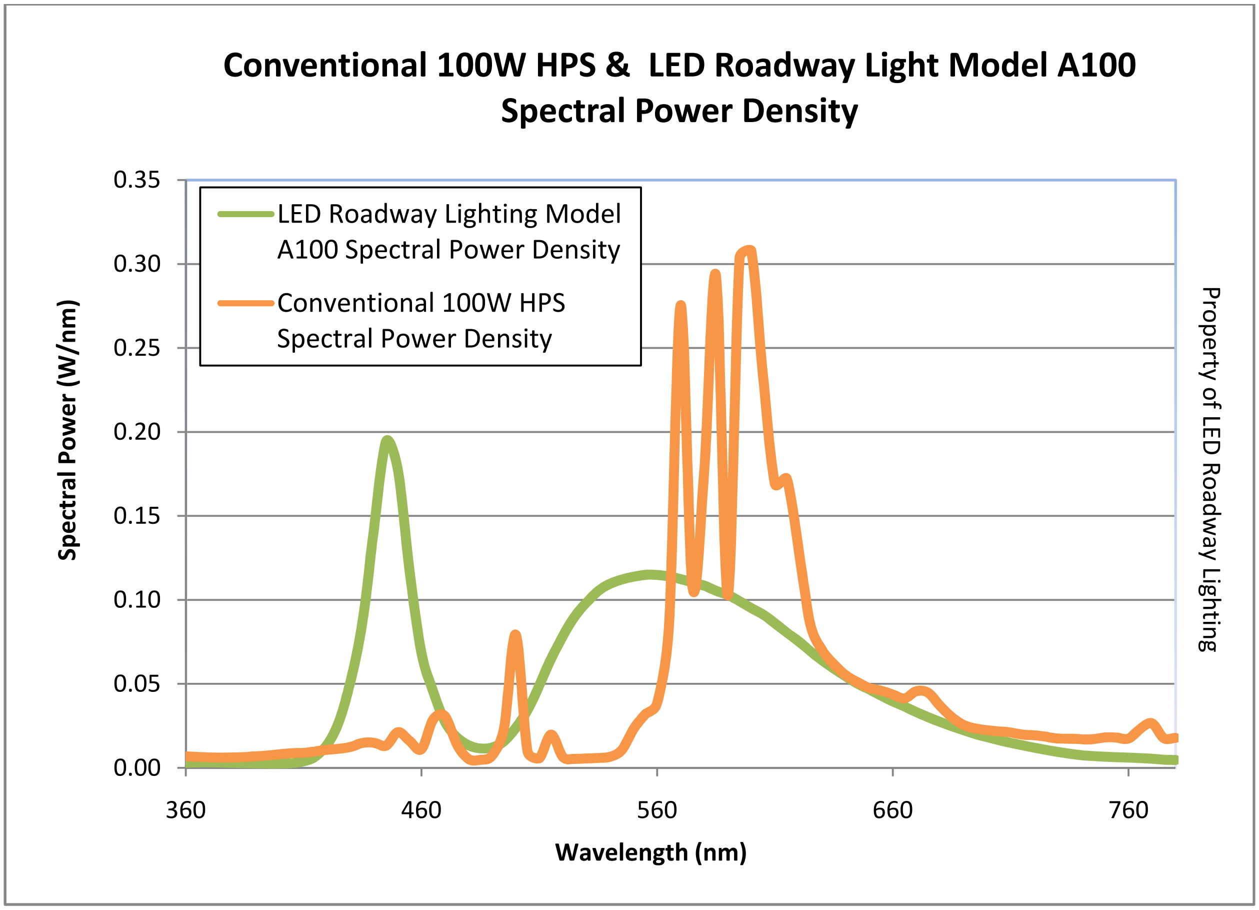

Figure 5: Conventional 100W HPS & LED Roadway Lighting Model A100 Spectral Power Density. Data from LED Roadway Lighting Limited (LRLL)[12].

Figure 6 below shows the lumen spectrum for a conventional 100W HPS streetlight with 6650 lumens total fixture output (9500 initial lamp lumens with a fixture optical efficiency of 70%) The HPS spectral power density shown has been weighted at each wavelength by the photopic and scotopic visual sensitivities as incorporated by both the cones (photopic) and rods (scotopic) in the eye. Similarly, Figure 7 also shows the same type of lumen spectrum for LRLLs Model A100 streetlight, which is designed to be a more energy efficient replacement for the conventional 100W HPS streetlight producing the same net fixture lumen output of 6650lm. Because of its larger S/P value, the LED light output provides considerably more scotopic content. However, as previously discussed for street and roadway lighting, only photopic output should be considered for IES and CIE roadway safety specifications.

On the other hand, since the photopic lumen output of both lights is the same, energy efficiency can be compared on the basis of fixture lumen output per 'plug' watt (lm/W), also called efficacy. A 'plug' watt is the total electrical power input into the fixture. At a fixture output of 6650 lumens, the LED Roadway Lighting Model A100 has a fixture efficacy as high as 94 lm/W [12] (with inclusion of the power supply) whereas a conventional 100W HPS producing the same output lumens has a fixture efficacy of 48.5 lm/W (with inclusion of a standard magnetic ballast with a power supply efficiency of 73%[13][14]). This means that for the same light output, the Model A100 is almost twice as efficacious when compared to the HPS.

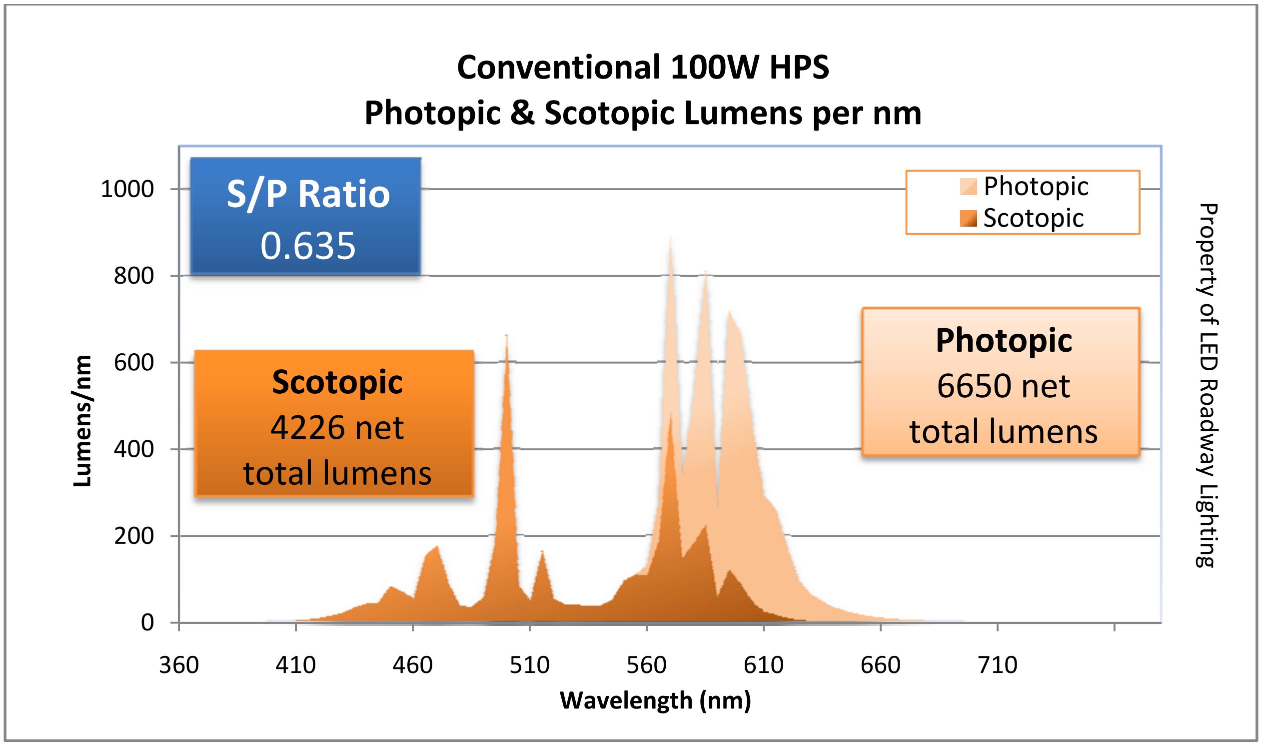

Figure 6: Conventional 100W HPS Photopic & Scotopic Lumens per nm as incorporated by the Human Eye: The spectral power density of the HPS light output was weighted by the photopic and scotopic spectral sensitivities. Data from LED Roadway Lighting Limited (LRLL)[12].

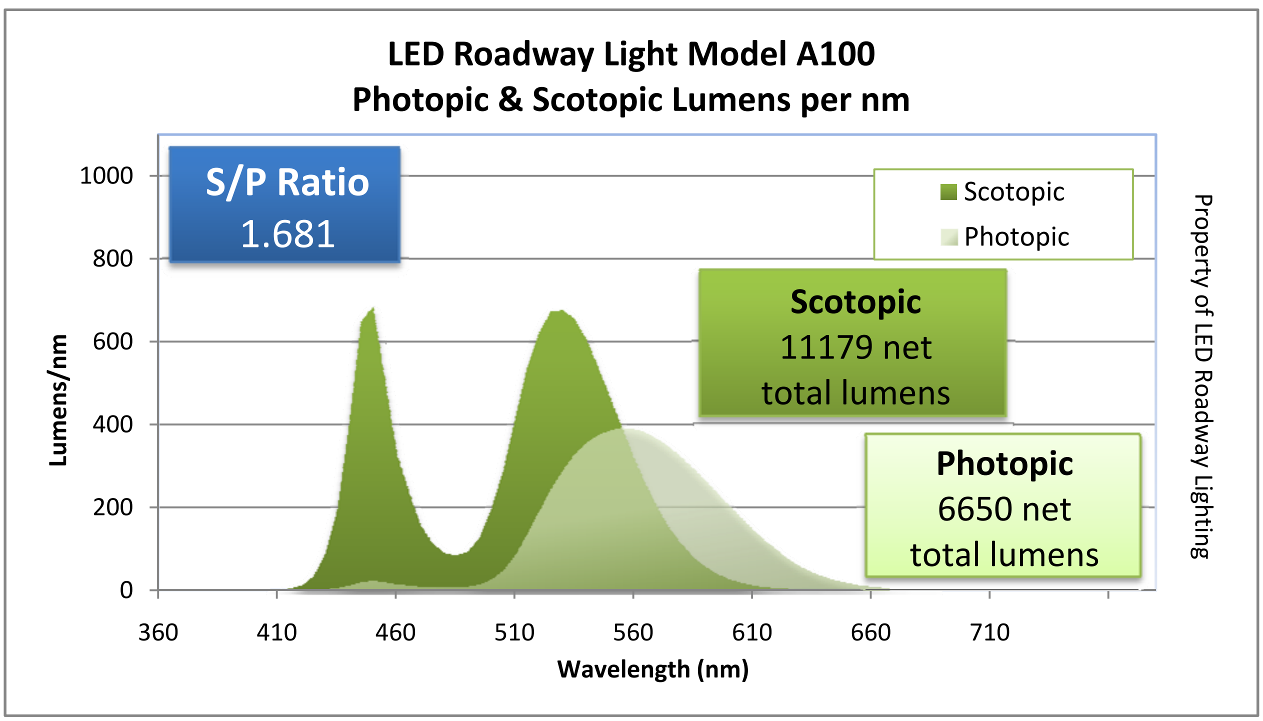

Figure 7: LED Roadway Lighting Model A100 Photopic & Scotopic Lumens per nm as incorporated by the Human Eye: The spectral power density of the LED Roadway Light Model A100 light output was weighted by the photopic and scotopic spectral sensitivities. Data from LED Roadway Lighting Limited (LRLL)[12].

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[13] **Nova Scotia Power Inc.** P.O. Box 910, Halifax, NS, Canada B3J 2W5

[14] **O'Neil F.C. Scriven & Associates Ltd** (Street Lighting Consultants). 5450 Cornwallis Street, Halifax, NS, Canada B3K 1A9.

Please direct all questions & comments to:

35 Ash Lake Court, Bayers Lake Business Park
Halifax, NS, Canada, B3S 1B7
Phone: +1 (902) 450-0555
Fax: +1 (902) 450-5097
Email: sales@ledroadwaylighting.com