Innovative, Energy-Efficient Lighting for New York State Roadways:

Opportunities for Incorporating Mesopic Visibility Considerations Into Roadway Lighting Practice

Final Report

Prepared By:
John D. Bullough and Mark S. Rea
Lighting Research Center
Rensselaer Polytechnic Institute

Prepared For:
New York State Energy Research and Development Authority
New York State Department of Transportation

April 2008

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ABSTRACT

The present report outlines activities undertaken to assess the potential for implementing research on visibility at mesopic light levels into lighting practices for roadways in New York State. Through measurements of light levels at several roadway lighting installations in New York's Capital District, and through analyses of visibility and human factors issues, and through economic analyses, the potential benefits for using "white" light sources in New York are discussed. Many of the benefits will be difficult for the New York State Department of Transportation (NYSDOT) to capitalize on because of the relatively few lighting installations designed and developed by NYSDOT. Nonetheless, there does appear to be potential for reducing lighting energy use and operating costs in rural and suburban roadway lighting installations, such as those located in residential areas, while maintaining unified luminance values related to visual performance under roadway lighting. Existing practices for roundabout lighting, mid-block crossing lighting, and work zone lighting might also be opportunities for further exploration of the potential benefits of unified photometry for roadway lighting in New York State.

ACKNOWLEDGMENTS

The authors gratefully acknowledge support for this project from the New York State Energy Research and Development Authority (NYSERDA) and the New York State Department of Transportation (NYSDOT) through Program Opportunity Notice 1028. Marsha Walton from NYSERDA and Humayun Kabir from NYSDOT served as project managers. Peter Morante, Leora Radetsky and Nicholas Skinner from the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute made valuable contributions to the study, as did Richard Drake, Priscilla Richards and Joseph Tario from NYSERDA; Jay Higle, Rochelle Hosley, Thomas Melander, Janice Methe, Loretta Montgomery and Barbara O'Rourke from NYSDOT; Maria Chau, Christine Thorkildsen and Roslyn Webber from the Federal Highway Administration; John Walter from National Grid; Gary Tatro from the New York State Thruway Authority; and Michael Franchini from the Albany County Department of Public Works.

INTRODUCTION

Lighting along roadways and highways serves a primary purpose of safety by supporting visibility of pedestrians, vehicles and other potential hazards for drivers. In New York State, an estimated 1.1 billion kWh of electricity per year is currently used for roadway lighting (EEI, 1962; World Almanac, 1990), equivalent to the burning of approximately 320,000 tons of coal, and corresponding to the production of about 740,000 tons of CO_2, 6200 tons of SO_2 and 2700 tons of NO_X compounds (EPA, 1993). While precise quantification of the potential safety benefits of roadway lighting is difficult (Elvik, 1995), lighting does appear in many cases to provide tangible reductions in nighttime crashes, particularly at intersections and in locations where pedestrians are commonly found (IESNA, 1989; CIE, 1992). Indeed, the New York State Department of Transportation (NYSDOT) Highway Lighting Policy includes criteria for lighting such locations with non-continuous lighting systems located only at intersections and crossings, as opposed to continuous lighting systems that delineate the entire lengths of roadways. Non-continuous roadway lighting installations may tend to be located more frequently in rural and suburban areas, where ambient light levels are low and where the recommended light levels to be used are lower than in busier, urban areas (IESNA, 2000).

This is important because at low, so-called ***mesopic***, light levels typical of those encountered in rural and in partially-lighted roadways (IESNA, 2000), the human visual system's spectral (color) sensitivity to light differs from that implied by photometric quantities and instrumentation (e.g., illuminance, luminance and the meters used to measure these quantities). As described below in the Background section, the visual system is relatively more sensitive to light in the short-wavelength ("blue-green") portion of the visible spectrum at many light levels experienced at night in roadway installations. This shift in spectral sensitivity is not presently accounted for in recommendations for lighting from the Illuminating Engineering Society of North America (IESNA), American Association of State Highway and Transportation Officials (AASHTO), nor by standards for lighting in New York State, and may be important because the predominantly-used light source on NYS roadways is high pressure sodium (HPS) lamps, which have a distinctly yellowish color appearance containing much long-wavelength light. The LRC has developed a system of ***unified photometry*** (Rea et al., 2004; Rea and Bullough, 2007) to provide quantitative comparisons of different light source spectral distributions at different light levels.

Among the light sources that could be candidates for use in roadway lighting installations to take advantage of the shift in spectral (color) sensitivity at low, mesopic, light levels are metal halide (MH) lamps, fluorescent lamps and light emitting diode (LED) sources. While MH lamps have been used to a limited extent in New York State and other locations within the United States for roadway illumination (ICF Consulting and LRC, 2001), fluorescent and LED roadway lighting systems are less common. Unlike MH, in which the same types of luminaires and pole-based systems are used as roadway lighting systems using conventional HPS lamps, fluorescent and LED sources, because of their different shapes and optical characteristics from MH and HPS lamps, offer opportunities to produce different distributions of light along roadways than these other sources.

As part of a project through a program opportunity notice (PON 1028) issued by the New York State Energy Research and Development Authority (NYSERDA) and the New York State Department of Transportation (NYSDOT), the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute proposed and conducted several activities to investigate potential benefits and opportunities for incorporating mesopic visibility considerations into roadway lighting practice in New York State, and to address the following statewide policy objectives set out by NYSDOT, NYSERDA and other organizations:

From the NYSDOT Draft Statewide Transportation Master Plan for 2030:

- Improving safety: By determining if/how lighting at roadway intersections and pedestrian-rich environments, known locations where benefits of lighting can be found, could be further improved to reduce pedestrian-related and other types of crashes at these locations.
- Promoting sound energy and environmental policies: Since lighting is not presently optimized for meeting visual responses of drivers, energy use could perhaps be made more effective (either by maintaining safety with reduced energy or by increasing safety with no change in energy use) by selecting appropriate lighting.

From the NYSERDA State Energy Plan:

- Supporting safe operation of transportation infrastructure: By utilizing technologies designed to more closely match driver needs, visibility and, hopefully, safety could be improved.
- Promoting a cleaner environment: By better balancing energy use for lighting with driver visual requirements, wasted energy could be minimized.

From the Center for Clean Air Policy (CCAP) Recommendations to the Governor on Greenhouse Gas Emissions:

- Reducing transportation-related emissions: Reduced energy use for roadway lighting, if viable in certain applications, would have corresponding reductions in the greenhouse gases (CO_2, SO_2, NO_X) described above.

This report to NYSERDA and NYSDOT outlines the project activities, findings and recommendations regarding implementation of roadway lighting from the LRC project team.

BACKGROUND

As described above in the Introduction of this report, many light level recommendations for roadway lighting in North America (IESNA, 2000; AASHTO, 2005) correspond to the so-called *mesopic* light level range, in which the human visual system uses both cone and rod photoreceptors to provide the input for vision. This statement would be of academic interest only, if it were not for the fact that these types of photoreceptors respond differently to different parts of the visible spectrum (e.g., to different colors of light).

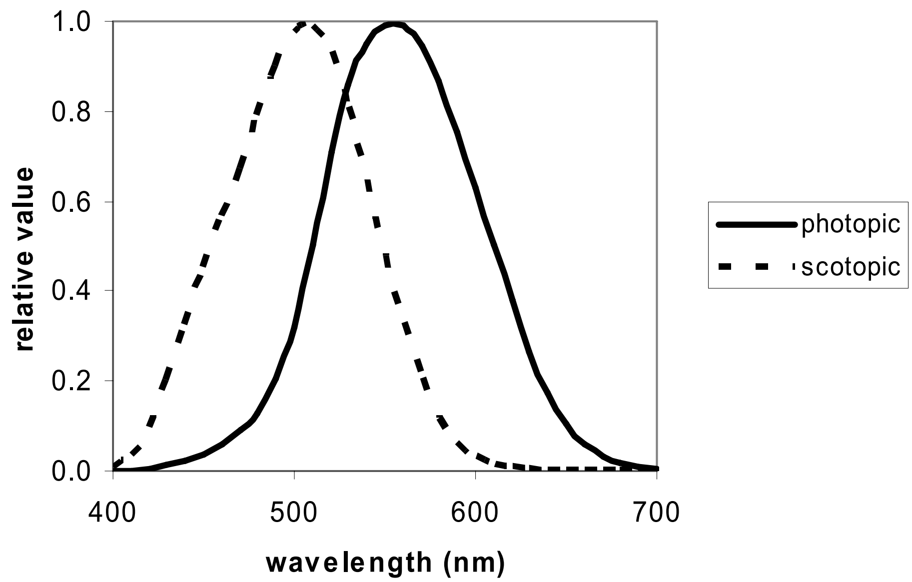


Figure 1. *Photopic and scotopic luminous efficiency functions, corresponding to cone-only and rod-only vision, respectively.*

At high light levels, corresponding to daytime and indoor conditions, the cone photoreceptors dominate vision, and have a peak sensitivity at a visible wavelength of 555 nanometers, corresponding to yellow-green light (Figure 1). Rods, however, are maximally sensitive at 505 nanometers, corresponding to ***blue-green*** light (Figure 1). What this means is that at low light levels, the visual system is actually more sensitive to lamps that produce more "bluish" light than to lamps that produce more "yellowish" light, when the measured light levels (e.g., in footcandles) are equal. Since high pressure sodium (HPS) lamps, with a yellowish-pinkish appearance are the predominantly used lamp for roadway lighting in New York State (ICF Consulting and LRC, 2001), this practice could contribute to less than optimal lighting conditions at intersections and locations where pedestrians are more frequently encountered, or to higher-than-necessary energy use at such locations.

A series of laboratory and field studies have been conducted by the LRC (e.g., Rea et al., 2004; Rea and Bullough, 2007) and other laboratories (e.g., see the summary published by IESNA, 2006) to investigate and quantify the improvements in visibility that are associated with using light sources that are spectrally (color) tuned for mesopic vision, but presently, there are no specific standards or recommendations for lighting that would incorporate these scientific findings.

One convenient way to describe a light source's potential to provide effective visibility at light levels in the mesopic range is the scotopic/photopic (S/P) ratio (Berman, 1992), which is defined as the light output of a lamp characterized in terms of rod-only vision (i.e., scotopic) divided by the light output characterized in terms of cone-only vision (i.e., photopic). The latter term in this ratio is the conventional method for characterizing light output, as described above. Lamps with higher S/P ratios will be expected to be more visually effective than those with lower S/P ratios at mesopic light levels, when the photopic light levels are equal. Stated another way, a light source with a higher S/P ratio might be able to be used at a lower photopic light level than another lamp with a lower S/P ratio, while still providing equivalent visual effectiveness.

Source	**Photopic efficacy, lm/W**	**Mesopic efficacy, lm/W**	**Scotopic efficacy, lm/W**
HPS (400 W, S/P = 0.63)	127 (100%)	98 (100%)	80 (100%)
MH (1000 W, S/P = 1.69)	107 (85%)	159 (163%)	182 (226%)
Incandescent (2815 K, S/P = 1.38)	15 (12%)	19 (19%)	20 (25%)
Clear mercury (400 W, S/P = 1.27)	52 (41%)	62 (64%)	67 (83%)
Xenon (1000 W, S/P = 2.26)	30 (24%)	56 (57%)	68 (84%)
Low pressure sodium (180 W, S/P = 0.23)	180 (142%)	89 (91%)	41 (51%)
Cool white fluorescent (F40, S/P = 1.52)	77 (61%)	105 (107%)	117 (145%)
Triphosphor fluorescent (32 W, T8, 3500 K, S/P = 1.37)	85 (67%)	107 (109%)	116 (144%)
Sulfur (1375 W, S/P = 2.26)	94 (74%)	176 (180%)	213 (265%)

Table 1. *Photopic, mesopic (equivalent to 0.1 cd/m² of HPS) and scotopic luminous efficacy of several light sources.*

Table 1 lists the S/P ratio and luminous efficacy (lumens per watt, lm/W) for several light sources at a range of different light levels spanning the visual range (photopic, mesopic, scotopic). This table demonstrates the relative influence of light level and spectrum in defining a light source's relative visual effectiveness in the mesopic range. At higher levels, differences between light sources with different S/P ratios decrease until they are nonexistent at photopic light levels.

REVIEW OF NYS LIGHTING POLICIES AND STANDARDS

New York State Policies and Standards
State agencies dealing with roadway lighting in New York include NYSDOT, the New York State Thruway Authority (NYSTA) and the New York State Bridge Authority (NYSBA). These agencies, with few exceptions, use the NYSDOT specifications for lighting.

The NYSDOT publishes several standards documentations relating to roadway lighting:

- Policy on Highway Lighting (NYSDOT, 1979)
- Highway Design Manual (NYSDOT, 1995)
- Standard Specifications (NSYDOT, 2006)

The Policy on Highway Lighting serves primarily as NYSDOT's warranting procedure for deciding when to install roadway lighting. For example, lighting is considered for locations that exhibit high night-to-day crash ratios (when nighttime crashes form a larger-than-expected proportion of crashes relative to the proportion of traffic occurring at night), when highway interchanges are closely spaced together, and when large pedestrian populations are likely to be present. While NYSDOT generally pays for the design and installation of lighting, operation and maintenance is supposed to be paid for by the municipality in which the lighting is to be located. The Policy was developed in 1979.

The Highway Design Manual discussed issues related to the planning of lighting installations by NYSDOT. Specifically, the Manual stipulates that illuminance criteria (as opposed to luminance criteria) are to be used in the calculation and specification of light levels. This is important because the recommended practices of the Illuminating Engineering Society of North America (IESNA), on which the American Association of State Highway and Transportation Officials (AASHTO) lighting guidelines are based, allow either illuminance or luminance to be used. The Manual further states that HPS lamps are preferred for roadway lighting, in semi-cutoff luminaires (usually having the characteristic "cobrahead" shape). When so-called "ornamental" lighting is to be used, any extra costs for equipment in addition to maintenance and operation are to be borne by the municipality in which the lighting will be located. The Manual was last updated in 1995.

The NYSDOT Standard Specifications that address lighting are mainly concerned with issues regarding durability of equipment and electrical safety. It does list performance criteria required for lamps and includes both HPS and mercury vapor lamps (the latter type is often used in overhead highway sign lighting, although the ballasts for these lamps are being phased out by federal energy efficiency legislation, which will effectively phase out use and availability of these lamps as well). The Specifications were last updated in 2006.

Municipal Codes

A number of municipal codes for cities in New York State were reviewed in order to assess whether they address roadway and outdoor lighting of differing spectral characteristics. These cities include the 32 listed below:

- Auburn
- Batavia
- Beacon
- Binghamton
- Buffalo
- Canandaigua
- Geneva
- Glen Cove
- Hudson
- Ithaca
- Jamestown
- Kingston
- Lackawanna
- Lockport
- Middletown
- Mount Vernon
- Newburgh
- New Rochelle
- Ogdensburg
- Olean
- Oneida
- Oneonta
- Peekskill
- Port Jervis
- Poughkeepsie
- Rensselaer
- Rochester
- Rye
- Saratoga Springs
- Troy
- Watertown
- Yonkers

Many of the codes had no specific mention of roadway lighting, although almost all of them discussed public or outdoor lighting in general (e.g., parking lot lighting). Nearly every municipal code explicitly listed some limit on glare or light trespass to adjacent properties including public roadways. Three of them provided for maximum allowable illuminances on adjacent properties. Four cities required *minimum* light levels for certain types of outdoor/public lighting installations.

Four cities included restrictions on the luminaires used for outdoor/public lighting, either mentioning requirements for full cutoff (IESNA, 2000) or fully shielded luminaires, or including restrictions against using "yard light" or "barn light" luminaires. Three cities included requirements or restrictions pertaining to the lamps used for outdoor/public lighting. Such requirements included specification of lamp types as HPS lamps, maximum site wattages based on area of the property in question, and requirements for luminaire shielding that depend upon the light output/wattage of the lamp(s) to be used. The characteristics of poles in terms of height and materials were also addressed by five of the city codes; four times in terms of height, and once in specifying a specific material to be used for outdoor/public lighting in certain sections of the city.

Finally, two of the codes addressed implementation issues associated with lighting. One stipulated that in subdivisions, all lighting costs would be paid by the subdivider or developer. One city required a specific department to deal with complaints about outdoor/public lighting.

Appendix 1 contains the text from municipal codes that refer to outdoor/public lighting.

SURVEY OF TRANSPORTATION OFFICIALS

A short questionnaire regarding awareness and implementation of issues related to mesopic visibility, unified photometry and roadway lighting was developed and distributed to members of the AASHTO Subcommittee on Design from each state (members represent a state transportation/highway department). Twenty states responded:

- Alabama
- Arkansas
- Arizona
- Colorado
- Georgia
- Iowa
- Illinois
- Massachusetts
- Michigan
- Mississippi
- Missouri
- North Carolina
- Ohio
- Oregon
- South Carolina
- South Dakota
- Tennessee
- Texas
- Utah
- Wyoming

The first survey question asked if the respondent's agency was familiar with recent research in vision at mesopic light levels and with the concept that "bluer" or "whiter" light might be more visually effective at night than "yellowish" light at low light levels. Slightly more than half (60%) were familiar with such research. Of these, three respondents (25% of those answering "yes" to the first question) had considered revisions to their lighting practices based on this research.

Another survey question asked respondents what factors were used to determine what lamps are used in roadway lighting. The two most commonly identified factors were lamp efficacy/energy efficiency by 60% of respondents and life/maintenance by 55% of respondents. Other factors that were cited by respondents included initial cost, color, availability, amount of pedestrian activity, distribution required, and type of facility to be lighted, but each of these factors was identified as important by many fewer respondents (less than 20%). 75% of respondents reported that they always (or nearly always) used HPS lamps in every case.

Survey participants were asked if published demonstrations could influence decisions made by their agencies regarding the selection of lamp types. 40% responded in the affirmative, that such demonstrations, particularly showing that new lighting technologies improved visibility or safety. The majority (60%) reported that until/unless AASHTO/IESNA standards change, neither would the lighting practices in their states. Every respondent reported that their agency uses either the AASHTO roadway lighting guidelines, the IESNA recommendations for roadway lighting, or both documents as the bass for their state's lighting practices.

FIELD MEASUREMENTS OF NYS ROADWAY LIGHTING INSTALLATIONS

As described above, the impact of differing spectral power distributions on visibility for roadway lighting depends upon the light level, with increasingly large effects at lower light levels. This leads to the hypothesis that any spectral effects of lighting would be more likely to be possible at rural and residential locations than at urban locations.

In addition, certain types of installations are less common and the lighting for these might not be representative of the type of surrounding location (e.g., urban versus rural). These installation types include roundabouts and mid-block crossings.

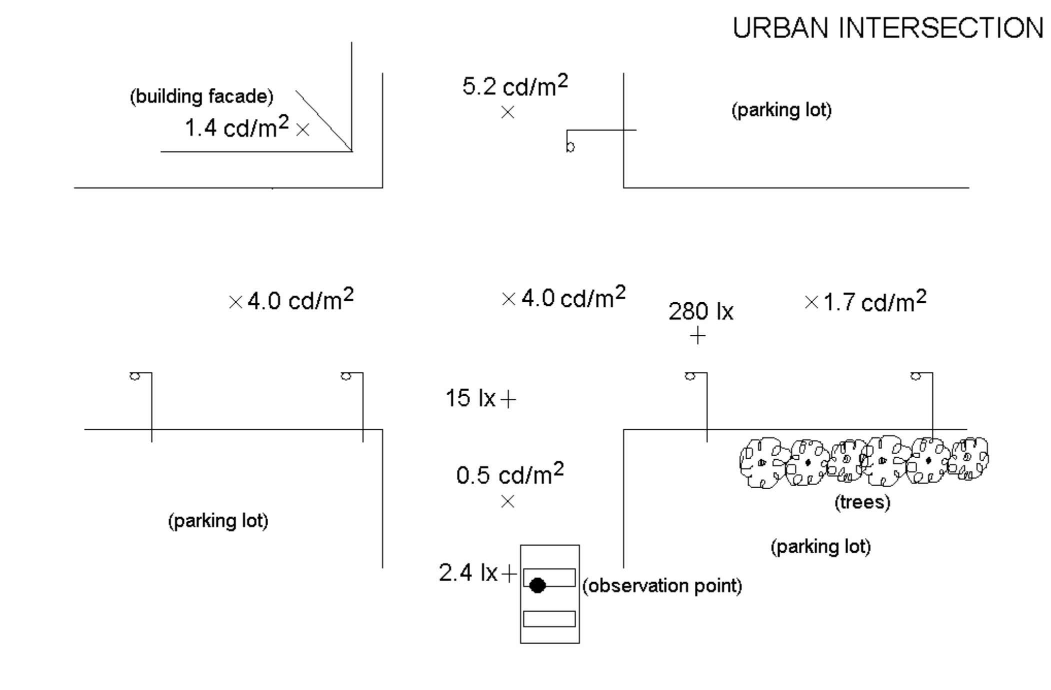
The project team performed limited site measurements at ten roadway lighting sites in the Albany/Troy region of New York State in order to assess the extent to which roadway light levels are found within the mesopic region. In each installation, the light source used was high pressure sodium. Except where noted below, lighting was provided by semi-cutoff or full cutoff "cobrahead" luminaires. The following types of sites were measured:

- Urban intersection
- Urban intersection with post-top lighting
- Urban pedestrian crossing
- Urban roadway segment
- Suburban intersection
- Suburban mid-block crossing with post-top lighting
- Suburban curved roadway segment
- Suburban roundabout
- Rural intersection
- Rural roadway segment

Because these sites are in-use roadway locations, closing off traffic in order to perform a full grid of measurement points as recommended by the IESNA (Rea, 2000) was not practical. Instead, luminance measurements were made from within a parked vehicle in the location indicated in the sketches, as well as a sample of horizontal illuminances measured on the pavement surface. In two of the locations it was not practical to measure horizontal illuminances. He et al. (1997) used a similar sampling procedure to characterize light levels for roadways.

Figures 2 through 11 show sketches of each location and measurement values, along with aerial photographs (generated using Google Earth™) of the sites.

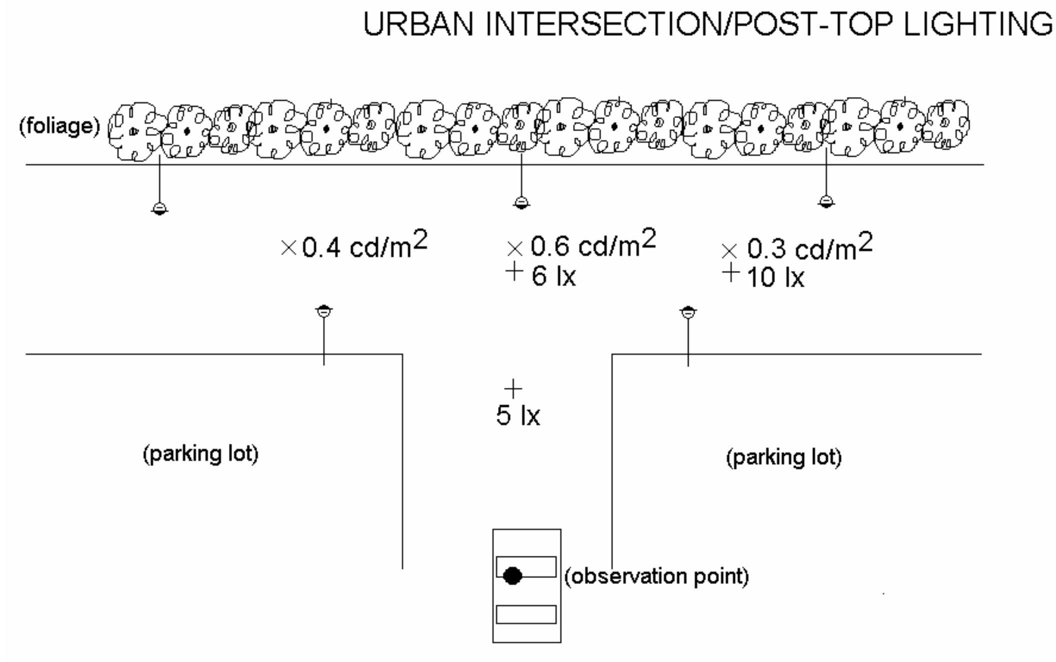
a)



b)

Figure 2. *a) Sketch of urban intersection and measurement values (+: horizontal illuminance; ×: luminance taken from observation point). b) Aerial photograph of site.*

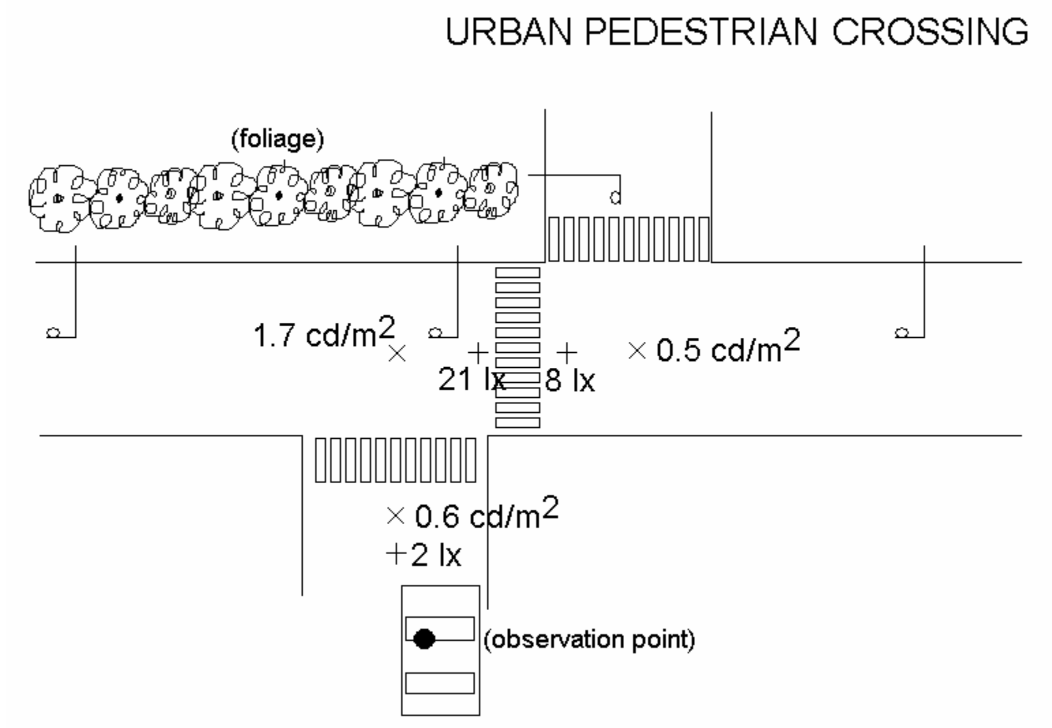
a)



b)

Figure 3. *a) Sketch of urban intersection with post-top luminaires and measurement values (+: horizontal illuminance; ×: luminance taken from observation point). b) Aerial photograph of site.*

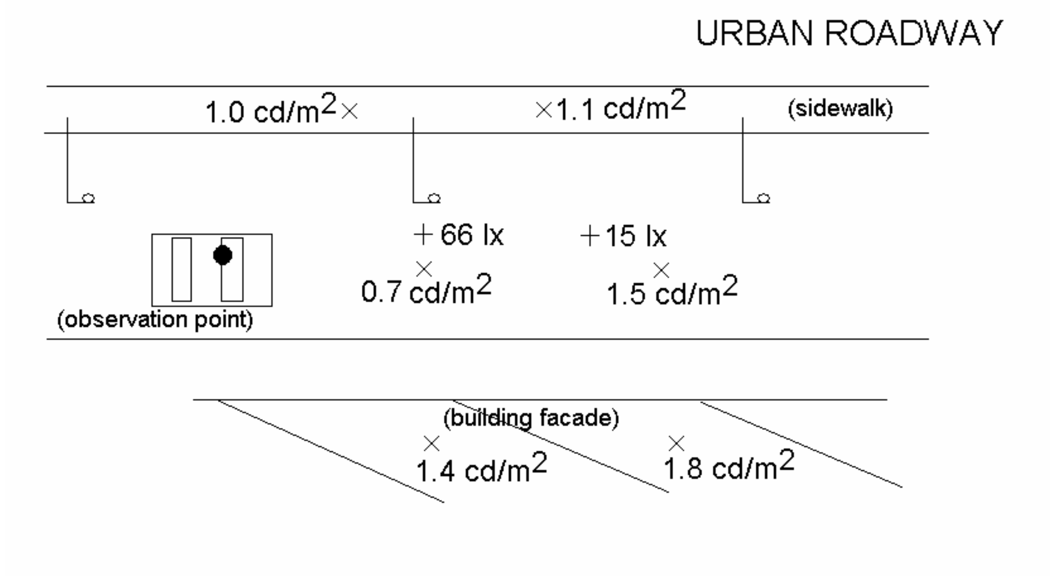
a)



b)

Figure 4. *a) Sketch of urban pedestrian crossing and measurement values (+: horizontal illuminance; ×: luminance taken from observation point). b) Aerial photograph of site.*

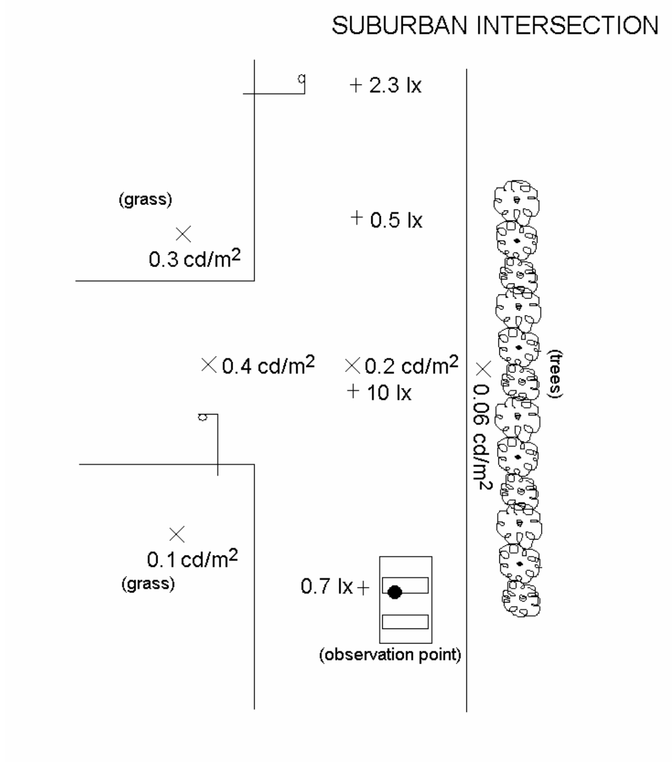
a)



b)

Figure 5. *a) Sketch of urban roadway segment and measurement values (+: horizontal illuminance; ×: luminance taken from observation point). b) Aerial photograph of site.*

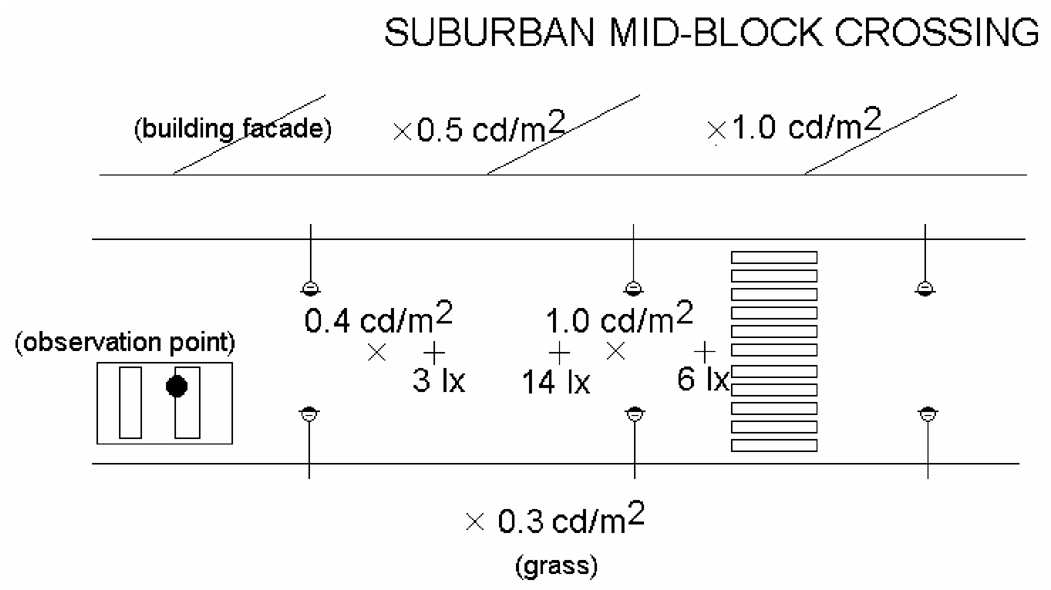
a)



b)

Figure 6. *a) Sketch of suburban intersection and measurement values (+: horizontal illuminance; ×: luminance taken from observation point). b) Aerial photograph of site.*

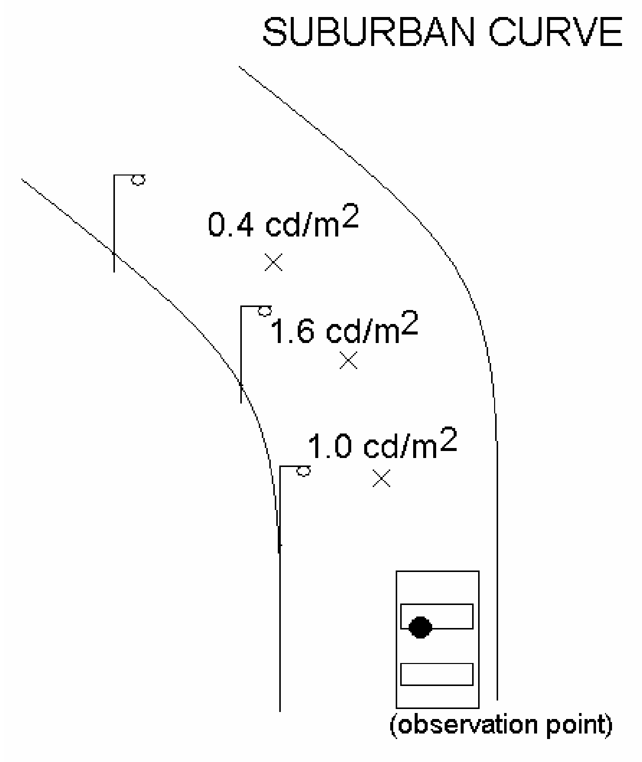
a)



b)

Figure 7. *a) Sketch of suburban mid-block crossing and measurement values (+: horizontal illuminance; ×: luminance taken from observation point). b) Aerial photograph of site.*

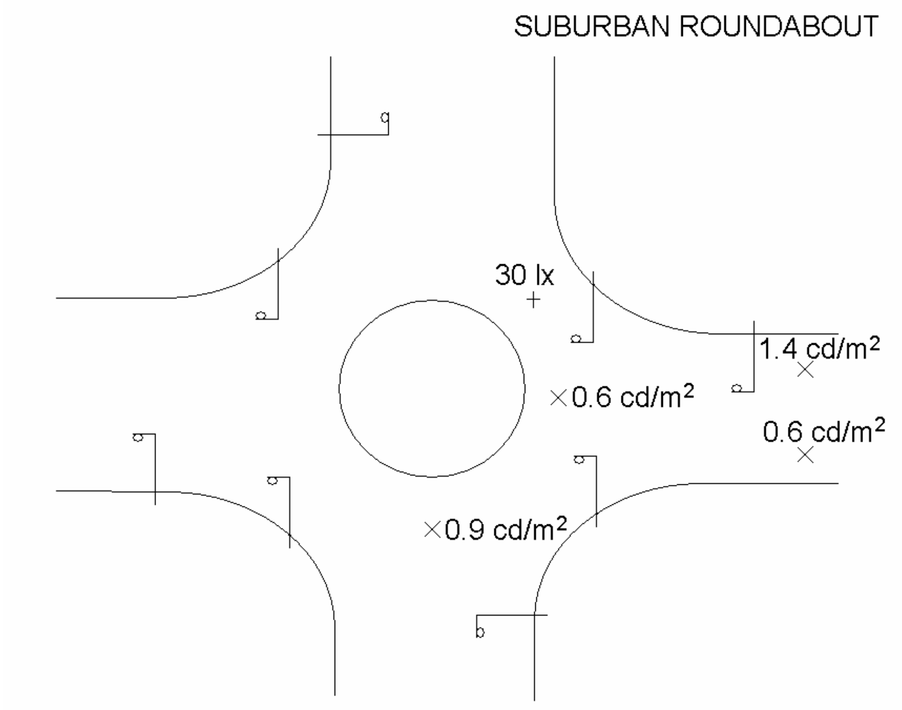
a)



b)

Figure 8. *a) Sketch of suburban curved roadway segment and measurement values (+: horizontal illuminance; ×: luminance taken from observation point). b) Aerial photograph of site.*

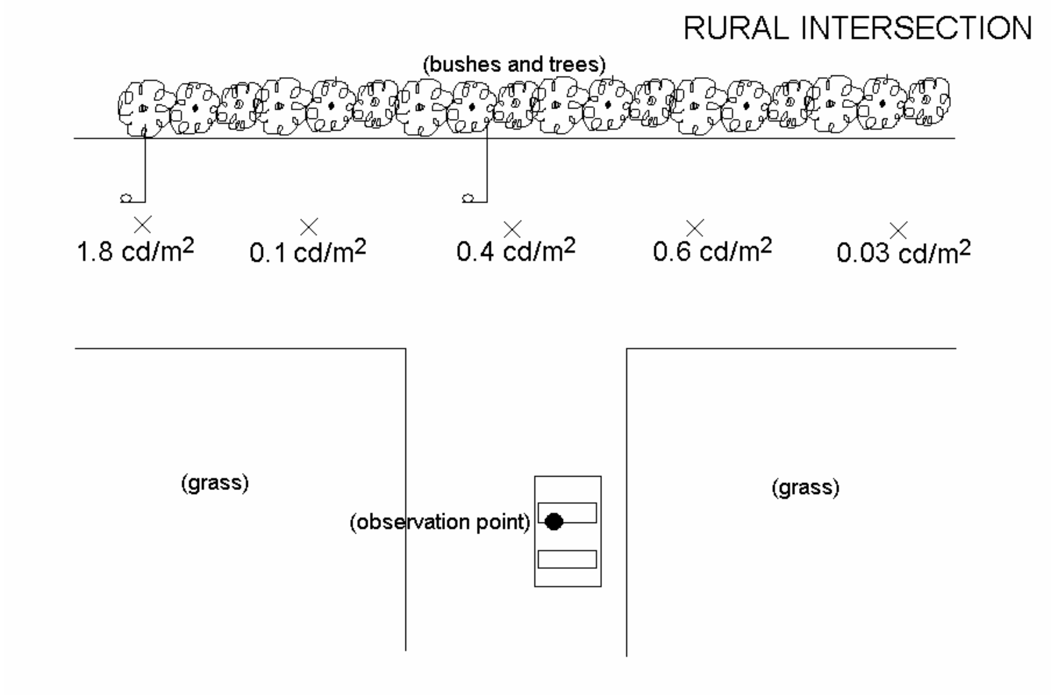
a)



b)

Figure 9. *a) Sketch of suburban roundabout and measurement values (+: horizontal illuminance; ×: luminance taken from observation point). b) Aerial photograph of site with present roundabout drawn in.*

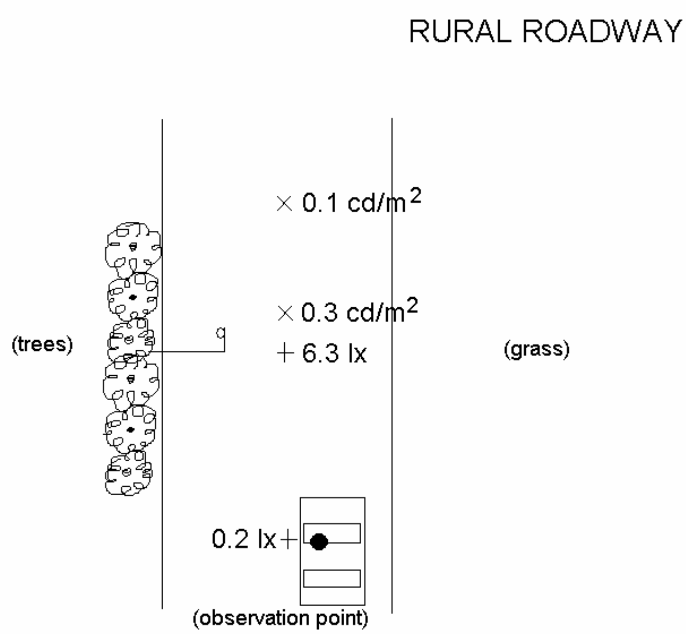
a)



b)

Figure 10. *a) Sketch of rural intersection and measurement values (+: horizontal illuminance; ×: luminance taken from observation point). b) Aerial photograph of site.*

a)



b)

Figure 11. *a) Sketch of rural roadway segment and measurement values (+: horizontal illuminance; ×: luminance taken from observation point). b) Aerial photograph of site.*

HUMAN FACTORS ANALYSES

In order to assess the relative role of mesopic vision in roadway lighting installations, the light levels measured for each category were assessed to determine whether the luminances from the installed lighting were within the range corresponding to a combined role of rods and cones in the eye.

In order to make use of as many of the lighting measurements as possible, the illuminance values were used to estimate luminances (assuming Lambertian reflectance characteristics of pavement and pavement reflectances of 0.1 [Zhang, 2006]) using the following equation:

$$L = E\rho/\pi$$

where L is the luminance (in cd/m²), E is the illuminance (in lux), ρ is the reflectance, and π is equal to 3.1416.

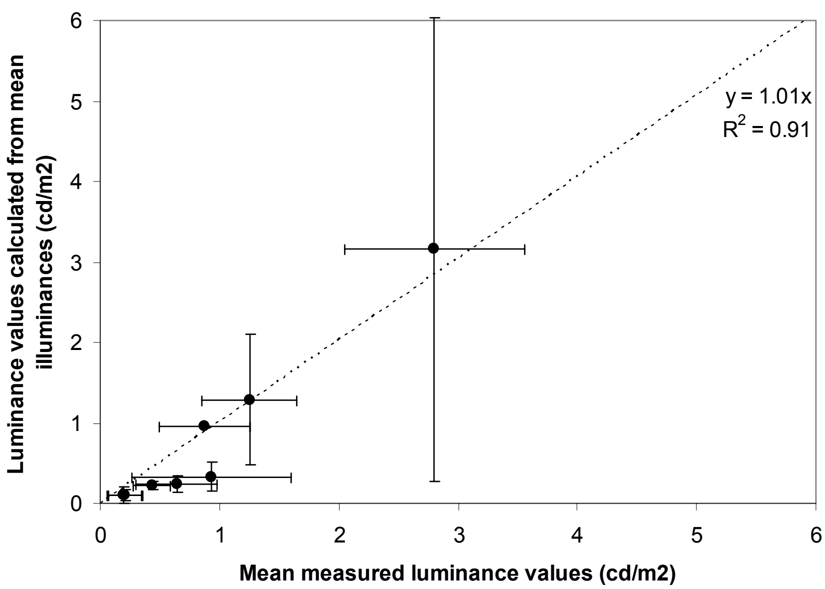


Figure 12. *Comparison of the mean luminances measured for each location with the calculated luminances (from the mean illuminances) for each location. Error bars indicate the standard error of the mean for the luminance values at each location.*

The mean luminance measurement values and the mean luminance values calculated from the illuminances for each location were highly consistent and correlated with one another (r^2 = 0.91), indicating that the assumption of Lambertian reflectance of 0.1 was probably a reasonable estimate.

A convenient way to characterize the relative role of rods and cones in the eye at a particular light level is through a parameter called X (Rea et al., 2004). Referring to the photopic and scotopic luminous efficiency functions in Figure 1, X is the relative proportion of photopic (cone) luminous efficiency and (1 - X) is the relative proportion of scotopic (rod) luminous efficacy. At photopic light levels, X = 1 (cone-only vision). At scotopic light levels, X = 0 (rod-only vision). At mesopic light levels, X is between 0 and 1, and the resulting luminous efficiency function is one that lies between the photopic and scotopic functions in Figure 1 (see Figure 13, which illustrates luminous efficiency functions corresponding to values of X of 0.25, 0.5 and 0.75). When two lighting installations using different lamp spectra have the same resulting value of X, they will have the same unified luminance and therefore, result in the same mesopic visibility.

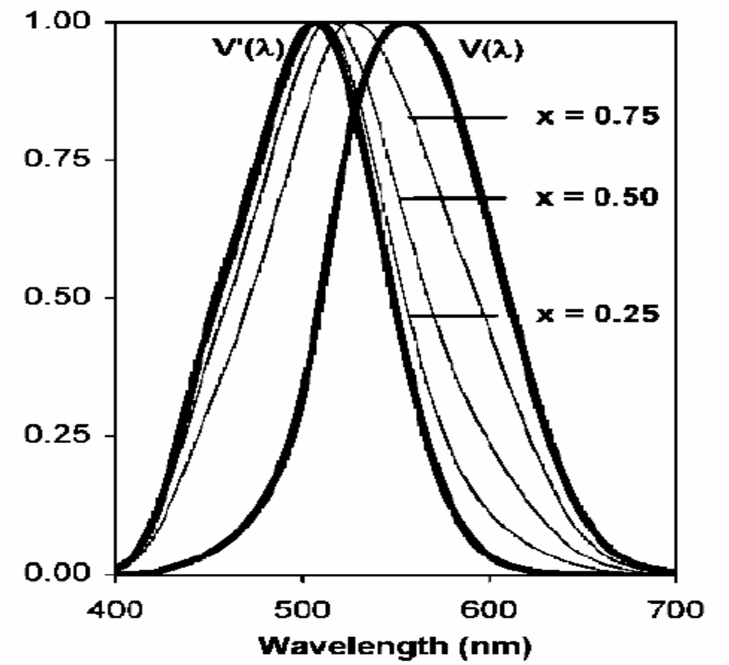


Figure 13. *Photopic [V(λ), X = 1] and scotopic [V'(λ), X = 0] luminous efficiency functions, and luminous efficiency functions corresponding to values of 0.25, 0.5 and 0.75 for X.*

Table 1 summarizes the mean luminance and illuminance values for each location, and provides an estimate, for each site, of how many luminance values resulted in values in the photopic, high mesopic (X ≥ 0.5) and low mesopic (X < 0.5) ranges.

Location type	Mean luminance (cd/m²)	Mean illuminance (lx)	Percent photopic (X=1)	Percent high mesopic (X≥0.5)	Percent low mesopic (X<0.5)
Urban intersection	2.8	99	67%	22%	11%
Urban intersection (post-top)	0.4	7	17%	50%	33%
Urban pedestrian crossing	0.9	10	50%	17%	33%
Urban roadway	1.3	41	88%	13%	0%
Urban overall			*59%*	*24%*	*17%*
Suburban intersection	0.2	3	0%	33%	67%
Suburban midblock crossing (post-top)	0.6	8	25%	50%	25%
Suburban curve	1.0	n/a	67%	33%	0%
Suburban roundabout	0.9	30	100%	0%	0%
Suburban overall			*36%*	*32%*	*32%*
Rural intersection	0.6	n/a	40%	20%	40%
Rural roadway	0.2	3	0%	25%	75%
Rural overall			*22%*	*22%*	*56%*

Table 2. *Summary of light level (luminance and illuminance) measurements; also shown for each location and area type (urban, suburban and rural) are the percentages that each of the values were in the photopic, high mesopic and low mesopic ranges.*

From the values in Table 2 several trends are evident. The proportion of luminance values in the photopic (X = 0) range is largest for urban locations and decreases as the area type shifts to suburban and then rural locations. The reverse trend is seen with the low mesopic (X < 0.5) luminance values; the majority of values in the rural locations are in this low range, but relatively few are in this range in urban areas.

The urban intersection lighted with post-top luminaires is perhaps anomalous in comparison to the other urban locations. Part of the reason for this may be the distribution of light produced by the post-top luminaires compared to those produced by "cobrahead" types of luminaires. The former luminaire types may produce higher levels of vertical illumination and relatively lower levels of horizontal illumination than the latter, which would result in higher pedestrian luminances but lower luminances of pavement surfaces.

The suburban intersection also had relatively lower luminance and illuminance values than the other suburban locations. This location was in a primarily residential area with low speed limits and away from major roads. In contrast, the roundabout, although located in a suburban area, had relatively high light levels, consistent with NYSDOT practice for lighting these quite novel roadway features in New York State (see Roundtable Summary below).

In general, however, the measurement results from the installations illustrated in Figures 2 through 11 do indicate that lighting practices in New York State, at least in the Albany/Troy region, do result in light levels in the mesopic visual range. Thus, it could be assumed that the visual systems of drivers in these installations (especially in suburban and rural locations) are relatively more sensitive to short-wavelength ("blue" or "white") light than would be implied by the light level readings themselves. This finding implies that alternative light source spectral power distributions could be used to improve visibility while maintaining (photopic) light output, or possibly, to reduce energy use while maintaining constant levels of mesopic visibility, (e.g., constant unified luminances).

Assuming representative values of X of 0.75 for high mesopic and of 0.25 for low mesopic light level ranges, it is possible to calculate weighted-average values of X for a subset of the lighting installations in Table 2 (excluding the urban locations and the roundabout, where the predominant light level range is photopic). From these values of X it is possible to calculate, for HPS (with an S/P ratio of 0.6) and two different light sources (MH lamps with an S/P ratio of 1.6, and 7500 K correlated color temperature [CCT] fluorescent/induction lamps with an S/P ratio of 2.75) the light level needed to obtain the resulting value of X. Table 3 lists these values; they imply that using lamps with higher S/P ratios, lower light levels could be used to achieve equivalent visibility as high pressure sodium.

Location type	**X**	**HPS luminance (cd/m^2)**	**MH luminance (cd/m^2)**	**Fluor./induction luminance (cd/m^2)**
suburban intersection	0.42	0.27	0.21	0.15
suburban mid-block crossing	0.69	0.44	0.38	0.33
suburban curved roadway segment	0.92	0.56	0.54	0.52
rural intersection	0.65	0.41	0.35	0.30
rural roadway segment	0.38	0.26	0.19	0.14

Table 3. *Weighted-average values of X for the suburban and rural locations where light level measurements (under HPS lamps) were made. Also shown are the photopic luminances required to obtain the same values of X with MH lamps (S/P = 1.6) and fluorescent/induction lamps (S/P = 2.75).*

ECONOMIC AND ENERGY ANALYSES

The human factors/visibility analyses in the previous section of this report, culminating in Table 3, imply that lower light levels could be used with "whiter" light sources in order to obtain equivalent mesopic visibility (e.g., to obtain equivalent unified luminances). Of course, the characteristics of HPS lamps most commonly used for roadway lighting differ considerably from those of other light sources that might be used as alternatives for roadway lighting. These characteristics include:

- Lamp life
- Lamp lumen output
- Lamp wattage
- Lamp cost
- Luminaire cost

For example, even if a light source has a high S/P ratio, if it is very expensive, or if it is short-lived, or if its lumen output is very low, it might not be a practical choice in a roadway lighting installation because of economic considerations.

In order to compare the energy and economic performance of the two "white" light sources (MH and induction) listed in Table 3 to that of HPS, life-cycle cost analyses were performed to assess the annualized cost of installation, maintenance and operation (both individually and together) for the suburban and rural lighting scenarios listed in Table 3. Again, the urban locations and the roundabout location were excluded from this analysis because of the preponderance of light levels in the photopic light level range found for these types of installations. For the rural roadway segment scenario, an additional light source (lighting emitting diode [LED], having an S/P ratio of 1.97) was included as an alternative, using performance data from a recent demonstration report of LED street lighting in Oakland, CA (Cook et al., 2008). Using the same method as in Table 3 to calculate the required (photopic) luminance from the LED source needed to provide the same unified luminance as the HPS source for the rural roadway segment application, a photopic luminance of 0.17 cd/m² is required from the LED source to obtain equal unified luminance as 0.26 cd/m² under HPS.

For the analyses, the following characteristics were assumed for each light source:

- HPS: 100 W, 28 W ballast power, mean light output = 8550 lumens, life = 24,000 hours, lamp cost = $43, luminaire cost = $80
- MH: 100 W, 30 W ballast power, mean light output = 7000 lumens, life = 15,000 hours, lamp cost = $50, luminaire cost = $80
- Induction: 85 W (including ballast power), mean light output = 6000 lumens, life = 60,000 hours, lamp cost = $200, luminaire cost = $200
- LED: 78 W (including ballast power), mean light output = 4530 lumens, life = 100,000 hours, lamp cost = $0 (because it is integrated into the luminaire), luminaire cost = $610

Table 4 lists the results of the economic analyses, assuming (per Leslie and Rodgers, 1996) a projected economic horizon of 20 years, an annual discount rate of 8%, operation of 12 hours/day, electricity costs of $0.08/kWh. The analyses take into account the installation costs, operation costs in terms of electricity, and maintenance costs in terms of lamp replacement. It is assumed that lamp replacement (or luminaire replacement, for the LED light source) occurs immediately following lamp failure.

Location	**Suburban intersection**			**Suburban mid-block crossing**			**Suburban curved roadway**			**Rural intersection**			**Rural roadway segment**			
Lamp type	*HPS*	*MH*	*Induction*	*HPS*	*MH*	*Induction*	*HPS*	*MH*	*Induction*	*HPS*	*MH*	*Induction*	*HPS*	*MH*	*Induction*	*LED*
Initial costs																
Number of luminaires	2	1.9	1.6	6	6.3	6.4	3	3.5	4.0	2	2.1	2.1	1	0.9	0.8	1.2
Cost per luminaire	$80	$80	$200	$80	$80	$200	$80	$80	$200	$80	$80	$200	$80	$80	$200	$610
Total luminaire cost	$160	$152	$316	$480	$504	$1284	$240	$283	$792	$160	$166	$416	$80	$71	$152	$720
Lamps per luminaire	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Total number of lamps	2	1.9	1.6	6	6.3	6.4	3	3.5	4.0	2	2.1	2.1	1	0.9	0.8	1.2
Total lamp cost	$86	$95	$316	$258	$315	$1284	$129	$177	$792	$86	$104	$416	$43	$45	$152	$0
Number of poles	2	1.9	1.6	6	6.3	6.4	3	3.5	4.0	2	2.1	2.1	1	0.9	0.8	1.2
Pole cost	$1275	$1275	$1275	$1275	$1275	$1275	$1275	$1275	$1275	$1275	$1275	$1275	$1275	$1275	$1275	$1275
Total pole cost	$2550	$2423	$2015	$7650	$8033	$8186	$3825	$4514	$5049	$2550	$2652	$2652	$1275	$1135	$969	$1505
Total equipment cost	$2796	$2670	$2647	$8388	$8852	$10754	$4194	$4974	$6633	$2796	$2922	$3484	$1398	$1250	$1273	$2224
Labor	$2796	$2670	$2647	$8388	$8852	$10754	$4194	$4974	$6633	$2796	$2922	$3484	$1398	$1250	$1273	$2224
Total installation cost	$5592	$5339	$5293	$16776	$17703	$21507	$8388	$9947	$13266	$5592	$5845	$6968	$2796	$2501	$2546	$4449
Annual costs																
Capital recovery factor (8% discount/20 years)	0.10185	0.10185	0.10185	0.10185	0.10185	0.10185	0.10185	0.10185	0.10185	0.10185	0.10185	0.10185	0.10185	0.10185	0.10185	0.10185
Annualized installation cost	$570	$544	$539	$1709	$1803	$2190	$854	$1013	$1351	$570	$595	$710	$285	$255	$259	$453
Average daily use (hours)	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
Annual operating time (hours)	4380	4380	4380	4380	4380	4380	4380	4380	4380	4380	4380	4380	4380	4380	4380	4380
Average rated lamp life (hours)	24000	15000	60000	24000	15000	60000	24000	15000	60000	24000	15000	60000	24000	15000	60000	100000
Lamps used per year	0.37	0.55	0.12	1.10	1.84	0.47	0.55	1.03	0.29	0.37	0.61	0.15	0.18	0.26	0.06	0.05
Relamping labor per lamp	$23	$23	$23	$23	$23	$23	$23	$23	$23	$23	$23	$23	$23	$23	$23	$23
Lamp replacement cost per lamp	$66	$73	$223	$66	$73	$223	$66	$73	$223	$66	$73	$223	$66	$73	$223	$633
Annual maintenance cost	$24	$41	$26	$72	$134	$105	$36	$75	$64	$24	$44	$34	$12	$19	$12	$33
Input power (watts)	128	130	85	128	130	85	128	130	85	128	130	85	128	130	85	78
Annual energy use (kWh)	1121	1082	588	3364	3587	2390	1682	2016	1474	1121	1184	774	561	507	283	403
Electricity cost per kWh	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08
Annual energy cost	$90	$87	$47	$269	$287	$191	$135	$161	$118	$90	$95	$62	$45	$41	$23	$32
Annual operating cost	$114	$127	$73	$341	$421	$296	$171	$237	$182	$114	$139	$96	$57	$60	$35	$65
Total annualized cost	$683	$671	$612	$2050	$2224	$2486	$1025	$1250	$1534	$683	$734	$806	$342	$314	$294	$518

Table 4. *Economic analyses comparing annualized costs for suburban and rural roadway lighting installations providing equivalent mesopic visibility as the HPS installations outlined in Table 3.*

Together, these analyses show the relative importance of issues such as initial costs, lamp life, and mesopic visibility on the overall annual costs associated with roadway lighting. For example, Figure 14 illustrates the total annualized costs for the three lamp alternatives for the suburban mid-block crossing, one of the installations with light levels in the high mesopic range (on average, X = 0.69). The HPS installation is less expensive than either of the "white" light source options, even though one of these options results in lower operating costs (Figure 15; primarily because of reduced energy costs), while the other has higher operating costs than HPS as well.

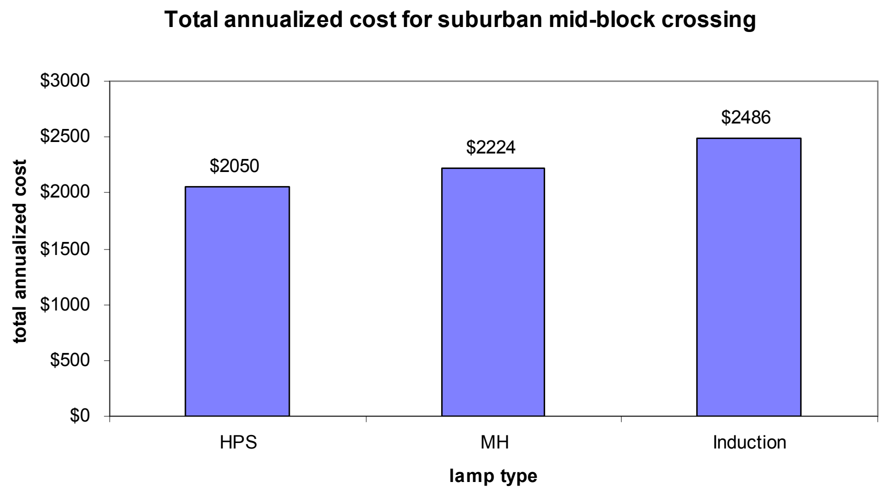


Figure 14. *Total annualized costs for HPS, MH and induction lamp suburban mid-block crosswalk lighting installations.*

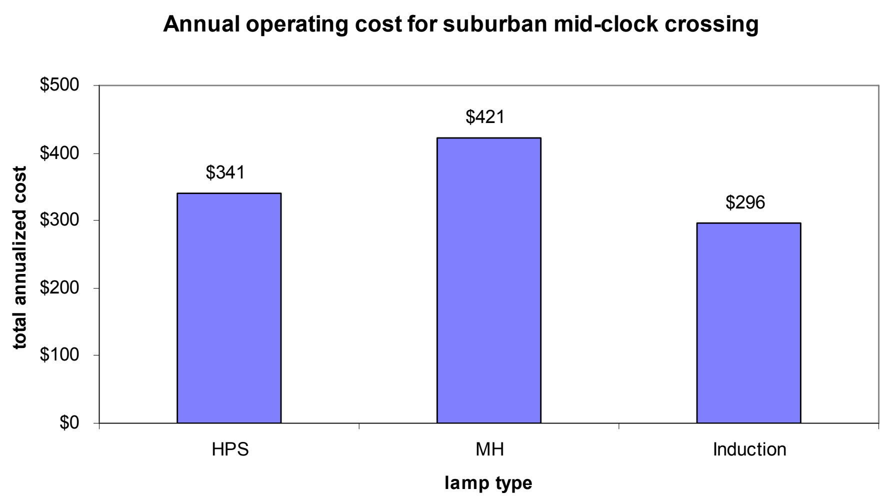


Figure 15. *Annual operating costs for HPS, MH and induction lamp suburban mid-block crosswalk lighting installations.*

In comparison, looking at the rural roadway segment lighting installation, which has light levels averaging in the low mesopic range (X = 0.38), both installations have lower total annualized costs (including installation costs; Figure 16) as well as lower operating costs (considering only energy and maintenance; Figure 17).

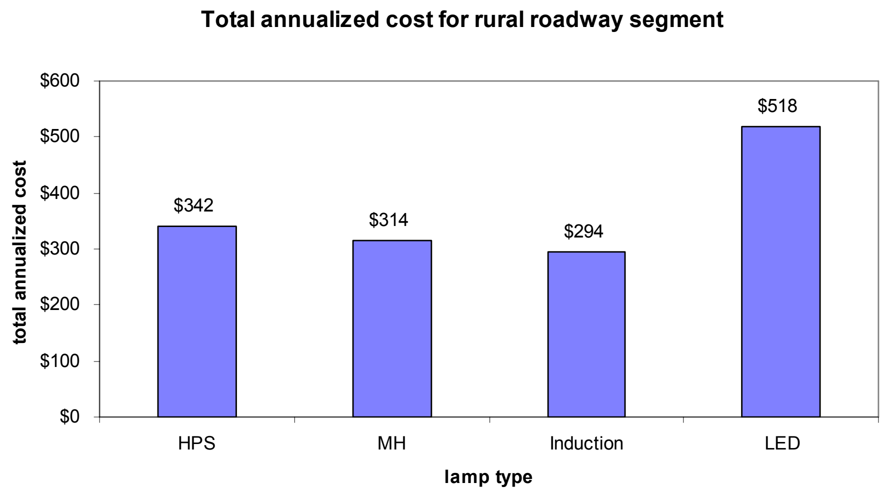


Figure 16. *Total annualized costs for HPS, MH, induction lamp and LED rural roadway segment lighting installations.*

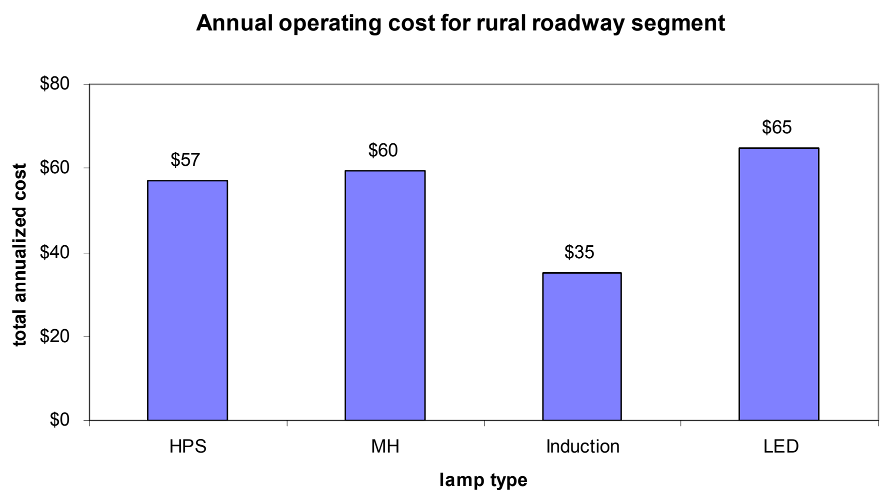


Figure 17. *Annual operating costs for HPS, MH and induction lamp rural roadway segment lighting installations.*

These analyses do indicate however, that using equivalent mesopic visibility (or unified luminance) as a criterion for roadway lighting can result in reduced energy use compared with conventional lighting approaches using HPS lamps.

An important consideration in interpreting these analyses is whether lighting is being considered in the design phase or whether retrofit installation of lighting is being considered. Equipment costs, particularly for the induction lamp and corresponding luminaires, but also for poles and the labor costs associated with installing new lighting, make up the majority of the annualized costs, as seen in Table 4 and in Figures 14 through 17.

ROUNDTABLE SUMMARY

On December 7, 2007 the LRC hosted a roundtable meeting to present preliminary results of the project and to discuss the potential for new lighting practices based upon research into mesopic visibility. Attending the meeting were individuals from NYSERDA, NYSDOT, FHWA, National Grid, and the LRC. In addition, information regarding the meeting was shared with individuals from NYSTA, from the Albany County Department of Public Works, and from Synthesis LLP, a landscape architecture firm in New York State, who had planned to attend the roundtable but were unable to.

J. Bullough/LRC, co-principal investigator for the project, chaired the meeting and welcomed the attendees. M. Walton/NYSERDA and H. Kabir/NYSDOT who served as the managers for this jointly sponsored project also welcomed the attendees who then introduced themselves to the group.

M. Rea/LRC presented the background, theory and implications of the unified system of photometry that specifically addresses light measurement in the mesopic region. P. Morante/LRC discussed three lighting case studies that employed the unified system of photometry and measured people’s reactions to the lighting. J. Bullough/LRC discussed policies, practices (measurements of actual locations) and economics associated with lighting systems designed according to the unified system of photometry. Appendix 2 contains copies of the presentations.

Following the presentations, J. Bullough/LRC asked the audience "Where do we go next?"

In general, NYSDOT does not design and engineer a lot of fixed lighting for illumination purposes. When fixed lighting is designed, it is usually turned over to a municipality for operation and maintenance. Where NYSDOT does own and operate fixed lighting, it is usually designed to provide relatively high levels of illumination, that is, levels outside the mesopic region. Finally, NYSDOT follows prescribed lighting practices used in other states, so taking advantage of any economic benefits implied by the unified system of photometry would not be possible except as a demonstration project. Since there are no standard practices for lighting roundabouts, since New York and other states are designing more roundabouts to ease traffic congestion, and since NYSDOT will own and operate these lighting systems there may be an opportunity to use the unified system of photometry in developing new lighting standards for roundabouts, particularly if light levels in the peripheral regions of roundabouts are practical.

B. O'Rourke/NYSDOT mentioned that NYSDOT is concerned with misadaptation of the visual system in, for example, work zones, where drivers transition between lighted and unlighted areas. Also, B. O’Rourke noted that NYSDOT can conduct demonstration projects as long as they have a plan to evaluate them. Cost issues related to maintenance and replacement are important to municipalities. She mentioned roundabouts, mid-block crossings and work zones as possible opportunity areas for using the unified system of photometry in a demonstration context.

M. Walton/NYSERDA asked if existing luminaires could be used in some applications of "mesopic-friendly" lighting. An issue from NYSDOT seems to be that there is still uncertainty about mesopic vision and this uncertainty will be a barrier. How can LRC help reduce uncertainty?

P. Morante/LRC mentioned that Groton, CT was pleased with the results of the lighting demonstration in their city and will likely move forward with lighting based on unified photometry. Similar demonstrations can help reduce uncertainty and provide greater confidence in using the unified system of photometry. J. Walter/National Grid mentioned that utilities can sometimes be cautious about implementing new technologies into their offerings until they are confident they will be able to be used successfully.

B. O'Rourke/NYSDOT felt that there were exciting opportunities for new lighting designs.

J. Tario/NYSERDA emphasized that it is important to have the right timing for the evidence to accumulate, before standards become so rigid or inflexible that there is often little hope of changing them. Roundabouts appeared to be a possible opportunity area since NYSDOT is working hard to safely and effectively light them.

Following this discussion, J. Bullough/LRC thanked attendees for their participation and adjourned the meeting.

SUMMARY AND RECOMMENDATIONS

Table 5 provides values of X and values of unified luminance (Rea et al., 2004) for different prescribed photopic light levels (columns) and different light source S/P ratios (rows). Table 5 enables a lighting engineer to deliver a new light level equivalent to the prescribed photopic light level using a different light source that would require lower electrical power to operate. For example, a light source with an S/P ratio of 2.45 could be operated at one-third the (photopic) light level as another source with an S/P ratio of 0.75, while achieving the same unified luminance in the mesopic range (see shaded cells in Table 5).

	Photopic ($V(\lambda)$) luminance (cd/m^2)													
S/P	0.001		0.003		0.01		0.03		0.1		0.3		0.55	
	X	L	X	L	X	L	X	L	X	L	X	L	X	L
0.25	0	0.0002	0	0.0007	0.0026	0.0025	0.0119	0.0082	0.0562	0.0347	0.3306	0.1990	0.8811	0.5288
0.35	0	0.0003	0.0001	0.0010	0.0043	0.0036	0.0172	0.0113	0.0749	0.0459	0.3652	0.2198	0.8876	0.5327
0.45	0	0.0004	0.0006	0.0014	0.0060	0.0046	0.0223	0.0144	0.0919	0.0560	0.3938	0.2369	0.8934	0.5362
0.55	0	0.0005	0.0011	0.0017	0.0076	0.0056	0.0273	0.0174	0.1074	0.0653	0.4183	0.2516	0.8986	0.5393
0.65	0	0.0006	0.0016	0.0020	0.0093	0.0066	0.0322	0.0203	0.1218	0.0739	0.4397	0.2644	0.9032	0.5420
0.75	0	0.0007	0.0021	0.0023	0.0110	0.0076	0.0370	0.0231	0.1352	0.0820	0.4588	0.2758	0.9075	0.5446
0.85	0	0.0008	0.0026	0.0026	0.0126	0.0085	0.0416	0.0259	0.1477	0.0895	0.4761	0.2862	0.9113	0.5469
0.95	0	0.0009	0.0031	0.0028	0.0142	0.0095	0.0462	0.0286	0.1595	0.0966	0.4917	0.2956	0.9149	0.5490
1.05	0.0001	0.0010	0.0036	0.0031	0.0158	0.0105	0.0506	0.0313	0.1707	0.1033	0.5061	0.3042	0.9181	0.5509
1.15	0.0002	0.0011	0.0041	0.0034	0.0174	0.0114	0.0549	0.0339	0.1814	0.1096	0.5194	0.3121	0.9211	0.5527
1.25	0.0004	0.0012	0.0046	0.0037	0.0190	0.0124	0.0592	0.0365	0.1915	0.1157	0.5318	0.3196	0.9239	0.5544
1.35	0.0006	0.0013	0.0051	0.0040	0.0206	0.0133	0.0634	0.0390	0.2011	0.1215	0.5433	0.3265	0.9264	0.5559
1.45	0.0007	0.0014	0.0056	0.0043	0.0221	0.0143	0.0675	0.0414	0.2104	0.1270	0.5541	0.3329	0.9288	0.5574
1.55	0.0009	0.0015	0.0060	0.0046	0.0237	0.0152	0.0715	0.0438	0.2192	0.1323	0.5643	0.3390	0.9311	0.5587
1.65	0.0011	0.0016	0.0065	0.0049	0.0252	0.0161	0.0754	0.0462	0.2278	0.1374	0.5739	0.3448	0.9332	0.5600
1.75	0.0012	0.0017	0.0070	0.0052	0.0267	0.0170	0.0793	0.0485	0.2360	0.1424	0.5830	0.3502	0.9352	0.5612
1.85	0.0014	0.0018	0.0075	0.0055	0.0282	0.0179	0.0831	0.0508	0.2439	0.1471	0.5915	0.3553	0.9370	0.5623
1.95	0.0016	0.0019	0.0080	0.0058	0.0297	0.0188	0.0868	0.0530	0.2516	0.1517	0.5997	0.3602	0.9388	0.5633
2.05	0.0017	0.0020	0.0085	0.0061	0.0312	0.0197	0.0905	0.0552	0.2590	0.1561	0.6075	0.3649	0.9404	0.5643
2.15	0.0019	0.0021	0.0090	0.0064	0.0327	0.0206	0.0941	0.0574	0.2661	0.1604	0.6149	0.3693	0.9420	0.5653
2.25	0.0021	0.0022	0.0094	0.0067	0.0342	0.0215	0.0977	0.0595	0.2730	0.1646	0.6220	0.3736	0.9435	0.5662
2.35	0.0022	0.0023	0.0099	0.0069	0.0356	0.0224	0.1012	0.0616	0.2798	0.1686	0.6287	0.3776	0.9449	0.5670
2.45	0.0024	0.0024	0.0104	0.0072	0.0371	0.0232	0.1046	0.0637	0.2863	0.1725	0.6352	0.3815	0.9462	0.5678
2.55	0.0026	0.0025	0.0109	0.0075	0.0385	0.0241	0.1080	0.0657	0.2927	0.1763	0.6415	0.3852	0.9475	0.5686
2.65	0.0027	0.0026	0.0114	0.0078	0.0400	0.0249	0.1114	0.0677	0.2989	0.1800	0.6474	0.3888	0.9487	0.5693
2.75	0.0029	0.0027	0.0118	0.0081	0.0414	0.0258	0.1147	0.0697	0.3049	0.1836	0.6532	0.3923	0.9499	0.5700

Table 5. *Values of X and unified luminance (L) for various combinations of S/P ratio and photopic luminance.*

It must be emphasized that the process for determining equivalence in Table 5 is dependent upon the prescribed light level. At high light levels, above 0.6 cd/m², the photopic luminous efficiency function is applicable in the unified system of photometry so all light sources, no matter their S/P ratio, would be compared in terms of their conventional, published luminous efficacy (photopic lumens per watt) values. As the prescribed light levels become lower, however, the unified system of photometry can be used to select equivalent light sources of higher S/P ratios which may require significantly less electrical power to operate (see, for example, Figures 15 and 17). In effect then, the unified system of photometry is only practically important for reducing electric power requirements at low prescribed light levels.

Of course, electrical energy is only one of many issues important in light source selection. For roadway applications, maintenance is particularly important to consider. Current practice is dominated by high pressure sodium (HPS) lighting systems. In fact, very few light sources require less maintenance than HPS, so it is often difficult to justify selecting any other light source even though a different light source providing equivalent light levels in the unified system of photometry might reduce electrical energy consumption by a considerable amount.

The unified system of photometry is based upon equivalent levels of visual performance (speed and accuracy). Visual performance may not be the most important criterion in every lighting design. For example, equivalent levels of *perceived brightness* might be more important in an outdoor retail application. In fact, several published case study demonstrations comparing “white” light sources with HPS have shown that perceived brightness is an important criterion for helping ensuring people’s sense of security (e.g., Akashi et al., 2005). Moreover, the appearance of scenes lighted by white light sources is consistently preferred over HPS, even at much lower photopic light levels. Further, much greater energy savings appear to be possible if light sources selected on an equivalent *brightness* criterion rather than the equivalent visual performance criterion which underlies the unified system of photometry.

Two barriers exist for the utilization of equivalent brightness as a design criterion. First, a system of photometry based upon brightness does not exist. Therefore, there is no analog to Table 5 based upon brightness perception that might be used for this purpose. Second, whereas brightness may be closely related to a perceived sense of security, it is not closely related to traffic safety. Traffic safety, a primary concern for NYSDOT, is more directly related to the speed and accuracy of processing visual information than it is to perceived brightness.

In summary then, whereas the unified system of photometry has been thoroughly researched, completed and validated (e.g., Rea et al., 2004; Rea and Bullough, 2007), it may have limited utility for the lighting installations implemented by NYSDOT for the following reasons. First, and foremost, NYSDOT does not undertake many lighting projects. Rather, they more likely design and install lighting systems for municipalities to then own and maintain.

Second, when lighting is undertaken by NYSDOT for their purposes (e.g., along highways interchanges), the prescribed light levels are generally rather high (IESNA, 2000). Thus, the energy benefits inherent in the unified system of photometry will not be realized unless low light levels are prescribed. Although these are not generally used in NYSDOT projects, low light levels are commonly experienced in suburban and rural areas, as illustrated in Figures 2 through 11. These locations, while perhaps outside the direct purview of NYSDOT, could perhaps be promising locations for the implementation of lighting practices based on unified photometry. Although design criteria based upon equivalent brightness could probably support energy reductions, there is no system comparable to the unified system of photometry based upon brightness. And since traffic safety is probably not related to brightness, it seems unlikely that such a system would be important to NYSDOT even if it were developed.

Third, reduction of energy use is only one of the criteria important to NYSDOT when engineering lighting. Certainly, MH lighting system technologies do not offer substantial advantages over conventional HPS lamps in terms of their annualized life-cycle costs.

The analyses in this report do show, however, that a relatively new lighting technology, electrodeless fluorescent systems, could change this picture quite considerably in the next two or three years. In addition, innovations in MH lamp technology (e.g., ceramic MH lamps) are resulting in increased efficiency and life relative to conventional MH lamps, and have been shown to provide improved visibility relative to HPS at equal photopic light levels (Akashi et al., 2007).

LED sources for roadway lighting are also being developed by manufacturers with some aggressiveness. However, the cost and relative efficiency of the LED luminaires evaluated in the present report did not demonstrate that they are viable choices at present, even for rural applications where the spectral effects are largest. If LED equipment costs are reduced in the future, an economic benefit of this technology relative to HPS will probably emerge.

NYSDOT is encouraged to monitor developments in light source cost, life and lumen maintenance so that it can reassess the value of the unified system of photometry for lighting applications where prescribed light levels are at 0.6 cd/m² or less.

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APPENDIX 1: EXTRACTS FROM NYS MUNICIPAL CODES ADDRESSING PUBLIC/OUTDOOR LIGHTING

Auburn
Lighting. Fixed lighting shall be so arranged to prevent direct glare of beams onto any public or private property or streets.

Batavia
Where lighting facilities for a parking station are provided, they shall be so constructed as to deflect the light away from any adjacent residential or park area.

Beacon
Exterior lighting. All exterior lighting accessory to a multifamily or nonresidential use, including the lighting of signs, shall be of such type and location and shall have such shading as will prevent the source of light from being seen from any adjacent residential property or from the street. Hours of lighting may be limited by the Planning Board in acting on any site development plan.

Binghamton
Criteria. (a) Illumination levels. Lighting, where required by this chapter, or otherwise required or allowed by the Supervisor of the Office of Building and Construction, shall have intensities, uniformities and glare control in accordance with the recommended practices of the Illuminating Engineering Society of North America (IESNA). (b) Lighting fixture design. [1] Fixtures shall be of a type and design appropriate to the lighting application. [2] For the lighting of predominantly horizontal surfaces such as, but not limited to, parking areas, roadways, vehicular and pedestrian passage areas, merchandising and storage areas, automotive-fuel dispensing facilities, automotive sales areas, loading docks, culs-de-sac, active and passive recreational areas, building entrances, sidewalks, bicycle and pedestrian paths, and site entrances, fixtures shall be aimed straight down and shall meet IESNA full-cutoff criteria. Fixtures with an aggregate rated lamp lumen output per fixture that does not exceed the rated output of a standard sixty-watt incandescent lamp, i.e., 1,000 lumens, are exempt from the requirements of this subsection. [3] For lighting of predominantly non-horizontal surfaces such as, but not limited to, facades, landscaping, signs, billboards, fountains, displays, and statuary, fixtures shall be fully shielded and shall be installed and aimed so as to not project their output into the windows of neighboring residences, adjacent uses, past the object being illuminated, skyward or onto a public roadway. Fixtures with an aggregate rated lamp lumen output per fixture that does not exceed the rated output of a standard sixty-watt incandescent lamp, i.e., 1,000 lumens, are exempt from the requirement of this subsection. [4] "Barn lights," also known as "dusk-to-dawn lights," where visible from other properties, shall not be permitted unless fully shielded. (c) Control of nuisance and disabling glare. [1] All lighting shall be aimed, located, designed, fitted, and maintained so as not to present a hazard to drivers or pedestrians by impairing their ability to safely traverse and so as not to create a nuisance by projecting or reflecting objectionable light onto a neighboring use or property. [2] Floodlights and spotlights shall be so shielded, installed and aimed that they do not project their output into the windows of neighboring

residences, adjacent uses, past the object being illuminated, skyward or onto a public roadway or pedestrian way. [3] Parking facility and vehicular and pedestrian way lighting (except for safety and security applications and all-night business operations) for commercial, industrial and institutional uses shall be automatically extinguished no later than one hour after the close of business or facility operation. When safety or security lighting is proposed for after-hours illumination, it shall not be in excess of 33% of the number of fixtures required or permitted for illumination during regular business hours. [4] Illumination for signs, billboards, building facades and/or surrounding landscapes for decorative, advertising or aesthetic purposes is prohibited between 11:00 p.m. and dawn, except that such lighting situated on the premises for a commercial establishment may remain illuminated while the establishment is actually open for business, and until one hour after closing. [5] Vegetation screens shall not be employed to serve as the primary means for controlling glare. Rather, glare control shall be achieved primarily through the use of such means as cutoff fixtures, shields and baffles, and appropriate application of fixture mounting height, wattage, aiming angle and fixture placement. [6] The illumination projected from any use onto a residential property shall at no time exceed 0.5 footcandle, measured line-of-sight from any point on the receiving residential zoning district. [7] The illumination projected from any property to a nonresidential property district shall at no time exceed 1.0 footcandle, measured line-of-sight from any point on the receiving property. [8] Externally illuminated billboards and signs shall be lighted by fixtures mounted at the top of the billboard or sign and aimed downward. The fixtures shall be designed, fitted and aimed to place the light output onto and not beyond the sign or billboard. [9] Except for certain recreational lighting, fixtures meeting IESNA full-cutoff criteria shall not be mounted in excess of 20 feet above finished grade. Fixtures not meeting IESNA full-cutoff criteria shall not be mounted in excess of 16 feet above finished grade. [10] The United States and the state flag shall be permitted to be illuminated from dusk until dawn. All other flags shall not be illuminated past 11:00 p.m. Flag lighting sources shall not exceed 10,000 lumens per flagpole. The light source shall have a beam spread no greater than necessary to illuminate the flag. [11] Under-canopy lighting, for such applications as gas/service stations, hotel/theater marquees, or fast-food/bank/drugstore drive-ups, shall be accomplished using flat-lens full-cutoff fixtures aimed straight down and shielded in such a manner that the lowest opaque edge of the fixture shall be below the light source at all lateral angles. The average illumination intensity in the area directly below the canopy shall not exceed 20 maintained footcandles, and the maximum intensity shall not exceed 40 maintained footcandles.

Buffalo
Such parking lots shall be lighted after sundown during its period of operation with sufficient light to give protection to persons using said lot.

Exterior lighting of the vehicle storage area shall be required and shall be directed towards the vehicle storage area in a manner that is sufficient to light the entire area to allow all of the vehicles to be clearly seen during the hours of darkness. The lighting must not reflect or glare into adjoining residences or businesses. Lighting must be operational during the hours of darkness and must be kept in good working condition.

No exterior artificial lighting shall be permitted to cast direct rays of light on any residential property located in a residential district.

No artificial lighting shall be installed, modified, or operated in connection with commercial, industrial, or residential property in such a manner as will increase the amount of light, measured in lumens, entering any facing windows of contiguous property used for residential purposes or such property separated by a street. Corrective measures to mitigate the increased levels of light shall be commenced within 10 days after the owner or operator of the premises is notified by the Department of Permit and Inspection Services, and such corrective work shall be continuously and expeditiously pursued to completion.

Canandaigua
Any lighting used to illuminate any off-street loading areas shall be so arranged as to reflect the light away from the adjoining premises in any residential district.

All exterior and interior lighting shall be so designed and directed as to 1) cause no hazard to the operation of vehicles on the public streets, and 2) create no annoyance or hindrance to the occupants or users of nearby properties. The lighting should enhance the appearance of the service station site as much as possible.

Geneva
Fixed lighting shall be so arranged to prevent direct glare of beams onto any public or private property or streets.

Glen Cove
That all outdoor lighting is of such nature and so arranged as to preclude the diffusion of glare onto adjoining properties and streets. All electrical wiring providing electricity from an outside utility source in new construction shall be placed underground.

Glare. No glare from lighting from any principal or accessory use shall be visible beyond the property line.

Hudson
The following uses are prohibited in all districts: A. Any trade, industry, process or use which is noxious, offensive or objectionable by reason of the emission of smoke, dust, gas, odor or other form of air pollution or by reason of the deposit, discharge or dispersal of liquid or solid wastes in any form in a manner or amount as to cause permanent damage to the soil and streams or to adversely affect the surrounding area, or by reason of the creation of noise, vibration, electromagnetic or other disturbance, or by reason of illumination by artificial light or light reflection beyond the limits of the lot on or from which such light or light reflection emanates, or which involves any dangerous fire, explosive, radioactive or other hazard, or which causes injury, annoyance or disturbance to any of the surrounding properties or to their owners and occupants, and any other process or use which is unwholesome and noisome and may be dangerous or

prejudicial to health, safety or general welfare. B. Artificial lighting facilities of any kind with light sources visible beyond the lot lines or which create glare beyond such lines.

Ithaca
Illumination. Driveways must be adequately lighted so as to provide safe access and egress. Lighting shall be placed so as to produce no glare to passing motorists or adjacent property.

Jamestown
Lighting. Any fixture used to illuminate any automotive use area shall be so arranged as to direct the light away from the street and any adjoining premises.

Kingston
All outdoor lighting is to be of such a nature and so arranged as to preclude the diffusion of glare onto adjoining properties, streets and the waterfront.

Lackawanna
A. The following minimum lighting levels shall be provided for uses requiring site plan review: (1) Parking lots: 0.5 footcandles. (2) Driveways: 0.25 footcandles. (3) Pedestrian walkways: 0.18 footcandles. (4) Building entrances: 0.5 footcandles. (5) Accent illumination: 0.5 footcandles. B. Exterior lighting shall be planned, erected and maintained so the light is confined to the property and will not cast direct light or glare upon adjacent properties or public roads. C. Except pedestrian-oriented accent lights, all light fixtures shall be concealed source fixtures. D. Light sources shall not be higher than 20 feet; pedestrian light fixtures shall not exceed 15 feet in height. E. Security lighting fixtures and exterior wall-mounted floodlights are restricted to enclosed service courtyards. F. High intensity lighting is prohibited.

Lockport
Roadway or area lighting shall be reflected away from adjoining properties and major thoroughfares.

Middletown
No spotlights, floodlights, ground lights, roof lights, pole lights, wall lights or any other lights for exterior illumination for commercial and industrial areas or uses shall be used unless reflectors shall be provided with proper glass lenses concentrating the illumination upon the business area so as to prevent direct glare upon the street or adjacent property. All commercial and industrial uses shall have lighting installed on pedestals or poles such that the lighting is directed upon the lot on which such use is located and upon any buildings located on such lot, and away from other lots and public streets.

Mount Vernon
Exterior lighting. All exterior lighting accessories on private property, including the lighting of signs, shall be of such type and location and have such shading as will prevent the source of light from being seen from any adjoining streets and residential

properties and which shall prevent objectionable glare observable from such streets or properties.

Newburgh
All lighting is to be installed in accordance with a plan to be submitted to and approved by the City Engineer and the Building Inspector and so designed as to prevent light from being thrown onto neighboring properties.

New Rochelle
All exterior lighting accessory on private property, including the lighting of signs, shall be of such type and location and have such shading as will minimize the source of light from being seen from any adjoining streets and residential properties and which shall prevent objectionable glare observable from such streets or properties.

Ogdensburg
Lighting. Any lighting used to illuminate off-street parking areas should be located, shielded and directed upon the parking area in such a manner that it does not reflect or cause glare onto adjacent properties or interfere with street traffic. In no instance shall bare, unshaded bulbs be used for such illumination.

Olean
Street lighting. Lighting fixtures which are installed within a subdivision shall be the responsibility of the subdivider. The light system which is established shall result primarily in the illumination of the streets and sidewalks within the subdivision. The design of the system shall be coordinated with and approved by the Niagara Mohawk Power Corporation.

Oneida
Lighting. (1) Lighting shall be provided in accordance with a plan designed by the utility company, or using as a guideline the standards set forth by the IES Lighting Handbook. (2) Lighting for safety shall be provided at intersections, along walkways, at entryways, between buildings, and in parking areas. (3) Spacing of standards shall be equal to approximately four times the height standard. (4) The maximum height of standards shall not exceed the maximum building height permitted, or 25 feet, whichever is less. (5) The height and shielding of lighting standards shall provide proper lighting without hazard to drivers or nuisance to residents, and the design of lighting standards shall be of a type appropriate to the development and the City of Oneida. (6) Spotlights, if used, shall be placed on standards pointing toward the building and positioned so as not to blind the residents, rather than on the buildings and directed outwards which creates dark shadows adjacent to the buildings.

Oneonta
Exterior lighting shall be of such nature, arranged, and utilized in a manner so as to minimize interference with adjoining landowners. No outdoor light source shall be directly focused on adjacent properties nor shall be more than 10 feet above the ground level underneath it.

Peekskill
Maximum site-generated light shall not exceed 0.5 footcandle at the property line, and the source of all exterior lighting shall not be visible beyond the property line.

Port Jervis
Glare and heat. No offensive glare from lighting shall be transmitted so as to endanger the public health and safety nor shall it be transmitted into or within any residence district so as to impair the value and enjoyment of any lot therein. No radiant heat shall be perceptible outside the lot where it originates.

Poughkeepsie
Off-street parking areas shall be adequately illuminated for convenience and safety, but no lighting for parking areas shall cause glare on adjoining property.

Rensselaer
Exterior lighting. Artificial lighting shall be provided to illuminate walks, driveways and parking spaces for the safe movement of pedestrians and vehicles at night.

Rochester
No licensee shall have his or her parking lot open for the parking or storing of vehicles at any time from 1/2 hour after sunset until 1:00 a.m., unless he or she shall have in place and in operation a lighting system capable of producing a minimum light level anywhere on the parking surface of 0.5 horizontal footcandle. Said lighting system shall cast no glare upon adjoining properties or streets.

Rye
All licensed parking lots which are operated during any portion of the period between one hour after sunset to one hour before sunrise shall be adequately lighted so as to meet the approval of the Building Inspector.

Saratoga Springs
Street lighting system. Maintain, repair and replace, as necessary, the street lighting system within the district consisting of 13 cedar light poles, fixtures, sodium vapor lamps, photo-electric controls and relays and approximately 1,500 feet of underground 240-volt cable and conduit.

Troy
Lighting: (a) All storefronts, entryways, walking paths, and parking areas shall be adequately lit to at least 0.5 footcandles. (b) All parking and security lighting shall be on a pedestrian scale with a sixteen-foot maximum light height for site illumination. The mounting height of a lighting fixture shall be defined as the vertical distance from the grade elevation of the surface being illuminated to the bottom of the lighting fixture (i.e., luminaire). (c) All parking area and security lighting will be fall cut-off type fixtures. Full cut-off fixtures must be installed in a horizontal position, as designed. (d) All exterior lights and illuminated signs shall be designed, located, installed and directed in such a

manner as to prevent objectionable light trespass and glare across the property lines and/or disability glare at any location on or off the property. (e) Uplighting is allowed only for highlighting important architectural features of a facade. Such uplighting shall be limited to 5:00 p.m. to 12:00 midnight. Externally lit signs, display, building and aesthetic lighting must be shielded to prevent direct glare and/or light trespass in excess of 0.2 footcandle. The lighting must also be, as much as physically possible, contained to the target area. (f) Internally lit signs are acceptable, provided that they meet the requirements of the Sign Ordinance. (g) Adjacent to residential property, no direct light source shall be visible at the property line at ground level or above. (h) When an outdoor lighting installation is being modified, extended, expanded or added to, the entire outdoor lighting installation shall be subject to the requirements of this section. (i) Expansion, additions, or replacements to outdoor lighting installations shall be designed to avoid harsh contrast in color and/or lighting levels. (j) Where practicable, electrical service to outdoor lighting fixtures shall be underground. (k) Proposed lighting installations that are not covered in this section may be approved if the Planning Board finds that they are designed to minimize glare, do not direct light beyond the boundaries in excess of 0.2 footcandle of the area being illuminated or onto adjacent properties or streets, and do not result in excessive lighting levels. (l) Holiday lighting during the months of November, December and January, and street tree lighting all year round, shall be exempt from the provisions of this section, provided that such lighting does not create dangerous glare on adjacent streets or properties.

Watertown
Illumination. In no event shall an illuminated sign or lighting device be so placed or so directed as to permit the beams or illumination therefrom to be directed so as to cause glare or reflection upon a public street, sidewalk or adjacent privately owned premises.

Yonkers
Lighting. A. All owners, operators or maintainers of parking lots with a capacity of more than twenty-five (25) motor vehicles shall place shielded floodlights or other type of approved lighting at such locations and in such manner as will permit owners of cars to have reasonable access to all portions of such space during the hours of darkness. A certificate approving the lighting installation and service shall be obtained from the Bureau of Housing and Buildings. B. Parking lots which are operated after daylight hours shall be adequately illuminated. The minimum illumination shall be one-tenth (1/10) of one (1) watt per square foot of parking area, distributed over the entire area. The maximum illumination shall be five-tenths (5/10) of one (1) watt per square foot of parking area, distributed over the entire area. Lights shall be provided with reflectors arranged so that the illumination is directed downward and away from all adjacent property, so as not to interfere with the comfort of adjacent residents.

APPENDIX 2: PRESENTATIONS FROM ROUNDTABLE MEETING HELD DECEMBER 2007

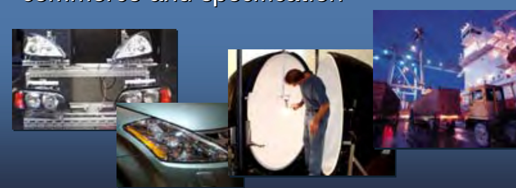
The unified system of photometry: A model of mesopic vision

Mark S. Rea
Lighting Research Center, Rensselaer Polytechnic Institute

December 7, 2007

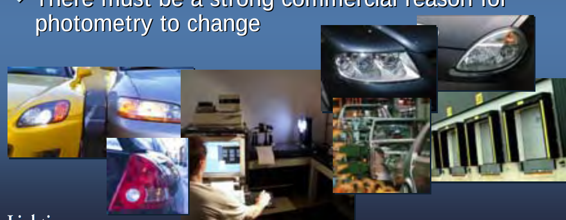
What is photometry?

- A simple, mathematically precise system of measuring and specifying light agreed to by an international community involved with its commerce and specification



Why is photometry important?

- Promotes international trade
- Provides a quantitative language for communicating between stakeholders
- There must be a strong commercial reason for photometry to change



What are the strengths and limitations of the current system of photometry?

- Strengths
  - Based on visual response: Vλ and V'λ
  - CIE Standard Observer: Vλ and V'λ are additive
  - Several visual responses have spectral sensitivity close to Vλ and V'λ and are additive, or nearly so (Lennie et al., 1993)

What are the strengths and limitations of the current system of photometry?

- Limitations
  - Judd correction needed for fovea (V_m)
  - $V_{10\lambda}$ needed for off-axis
  - Can't accurately characterize brightness
  - Can't accurately characterize visual performance
    - "More light, better light" – but only for small or low contrast targets
    - Interaction between stimulus variables
  - Mesopic: Which to use, V_λ or V'_λ?

Dynamic range of human vision compared to range of electric lighting

Luminance (cd/m^2)	Physical Description	Human Response	
10^{10}	Sun's surface at noon	Damaging	
10^9			
10^8			
10^7		Photopic	
10^6	100 W lamp filament		
10^5			
10^4	Paper under sun		
10^3			
10^2	Paper in office		Interior lighting recommend-ations
10			
1		Mesopic	Exterior lighting recommend-ations
10^{-10}			
10^{-2}	Paper under moon		
10^{-3}		Scotopic	
10^{-4}	Paper under stars		
10^{-5}			
10^{-6}			

Adapted from Sekuler and Blake, 1990

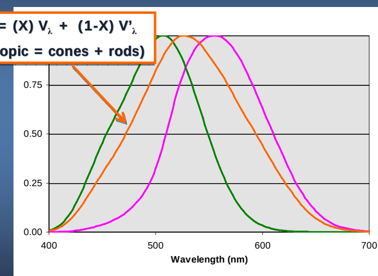
Unified system of photometry—
Spans photopic and scotopic through mesopic

- A unified system of photometry should:
  I. Be based upon studies of human vision
  II. Preserve Abney's law of additivity
  III. Preserve both the photopic (V_λ) and scotopic (V'_λ) luminous efficiency functions
  IV. Be practical to use

Scotopic – Mesopic – Photopic

$V_{mes} = (X)\, V_\lambda + (1-X)\, V'_\lambda$

(mesopic = cones + rods)



A practical system

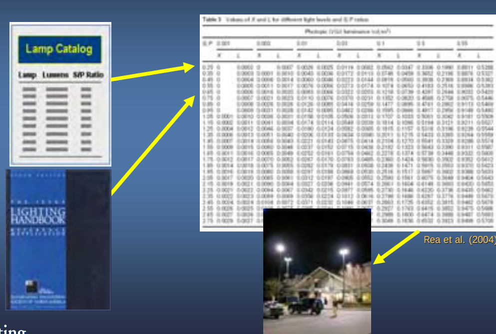


Table 3 Values of X and L for different light levels and S/P ratios

S/P	Photopic (V(λ)) luminance (cd/m²) 0.001		0.003		0.01		0.03		0.1		0.3		0.55	
	X	L	X	L	X	L	X	L	X	L	X	L	X	L
0.25	0	0.0002	0	0.0007	0.0026	0.0025	0.0119	0.0082	0.0562	0.0347	0.3306	0.1990	0.8811	0.5288
0.35	0	0.0003	0.0001	0.0010	0.0043	0.0036	0.0172	0.0113	0.0749	0.0459	0.3652	0.2198	0.8876	0.5327
0.45	0	0.0004	0.0006	0.0014	0.0060	0.0046	0.0223	0.0144	0.0919	0.0560	0.3938	0.2369	0.8934	0.5362
0.55	0	0.0005	0.0011	0.0017	0.0076	0.0056	0.0273	0.0174	0.1074	0.0653	0.4183	0.2516	0.8986	0.5393
0.65	0	0.0006	0.0016	0.0020	0.0093	0.0066	0.0322	0.0203	0.1218	0.0739	0.4397	0.2644	0.9032	0.5420
0.75	0	0.0007	0.0021	0.0023	0.0110	0.0076	0.0370	0.0231	0.1352	0.0820	0.4588	0.2758	0.9075	0.5446
0.85	0	0.0008	0.0026	0.0026	0.0126	0.0085	0.0416	0.0259	0.1477	0.0895	0.4761	0.2862	0.9113	0.5469
0.95	0	0.0009	0.0031	0.0028	0.0142	0.0095	0.0462	0.0286	0.1595	0.0966	0.4917	0.2956	0.9149	0.5490
1.05	0.0001	0.0010	0.0036	0.0031	0.0158	0.0105	0.0506	0.0313	0.1707	0.1033	0.5061	0.3042	0.9181	0.5509
1.15	0.0002	0.0011	0.0041	0.0034	0.0174	0.0114	0.0549	0.0339	0.1814	0.1096	0.5194	0.3121	0.9211	0.5527
1.25	0.0004	0.0012	0.0046	0.0037	0.0190	0.0124	0.0592	0.0365	0.1915	0.1157	0.5318	0.3196	0.9239	0.5544
1.35	0.0006	0.0013	0.0051	0.0040	0.0206	0.0133	0.0634	0.0390	0.2011	0.1215	0.5433	0.3265	0.9264	0.5559
1.45	0.0007	0.0014	0.0056	0.0043	0.0221	0.0143	0.0675	0.0414	0.2104	0.1270	0.5541	0.3329	0.9288	0.5574
1.55	0.0009	0.0015	0.0060	0.0046	0.0237	0.0152	0.0715	0.0438	0.2192	0.1323	0.5643	0.3390	0.9311	0.5587
1.65	0.0011	0.0016	0.0065	0.0049	0.0252	0.0161	0.0754	0.0462	0.2278	0.1374	0.5739	0.3448	0.9332	0.5600
1.75	0.0012	0.0017	0.0070	0.0052	0.0267	0.0170	0.0793	0.0485	0.2360	0.1424	0.5830	0.3502	0.9352	0.5612
1.85	0.0014	0.0018	0.0075	0.0055	0.0282	0.0179	0.0831	0.0508	0.2439	0.1471	0.5915	0.3553	0.9370	0.5623
1.95	0.0016	0.0019	0.0080	0.0058	0.0297	0.0188	0.0868	0.0530	0.2516	0.1517	0.5997	0.3602	0.9388	0.5633
2.05	0.0017	0.0020	0.0085	0.0061	0.0312	0.0197	0.0905	0.0552	0.2590	0.1561	0.6075	0.3649	0.9404	0.5643
2.15	0.0019	0.0021	0.0090	0.0064	0.0327	0.0206	0.0941	0.0574	0.2661	0.1604	0.6149	0.3693	0.9420	0.5653
2.25	0.0021	0.0022	0.0094	0.0067	0.0342	0.0215	0.0977	0.0595	0.2730	0.1646	0.6220	0.3736	0.9435	0.5662
2.35	0.0022	0.0023	0.0099	0.0069	0.0356	0.0224	0.1012	0.0616	0.2798	0.1686	0.6287	0.3776	0.9449	0.5670
2.45	0.0024	0.0024	0.0104	0.0072	0.0371	0.0232	0.1046	0.0637	0.2863	0.1725	0.6352	0.3815	0.9462	0.5678
2.55	0.0026	0.0025	0.0109	0.0075	0.0385	0.0241	0.1080	0.0657	0.2927	0.1763	0.6415	0.3852	0.9475	0.5686
2.65	0.0027	0.0026	0.0114	0.0078	0.0400	0.0249	0.1114	0.0677	0.2989	0.1800	0.6474	0.3888	0.9487	0.5693
2.75	0.0029	0.0027	0.0118	0.0081	0.0414	0.0258	0.1147	0.0697	0.3049	0.1836	0.6532	0.3923	0.9499	0.5700

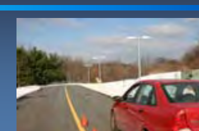
Calculation examples

- Illuminance (V_λ) and normalized power requirements for different light sources needed to provide equivalent values of X (ref: 400 W HPS @ 0.6, 0.3 and 0.1 cd/m²; 0.07 reflectance)

Light source (S/P ratio)	X = 1.00 @ 0.6 cd/m²		X = 0.44 @ 0.3 cd/m²		X = 0.12 @ 0.1 cd/m²	
	Illuminance (lux)	Power (%)	Illuminance (lux)	Power (%)	Illuminance (lux)	Power (%)
180W LPS (0.25)	26.9	69%	16.0	82%	7.6	118%
400 W HPS (0.66)	26.9	100%	13.5	100%	4.5	100%
400 W MH (1.57)	26.9	119%	10.0	88%	2.4	63%
Fl. 6500 K (2.19)	26.9	130%	8.5	82%	1.8	52%

Practical example

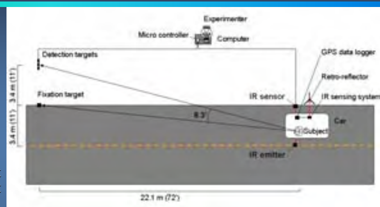
- Compared MH with HPS in drivers' responses at mesopic light levels
- Used a task that required more difficult target identifications and higher-order decision-making than simply responding to the targets



Akashi, Y., M. Rea and J. Bullough. 2007. Driver decision making in response to peripheral moving targets under mesopic light levels. *Lighting Res. Technol.* 39, 1; pp. 53-67. London, UK.

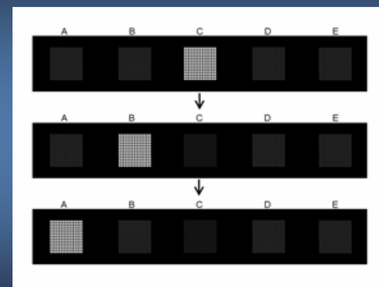
Study setup

Experiment layout



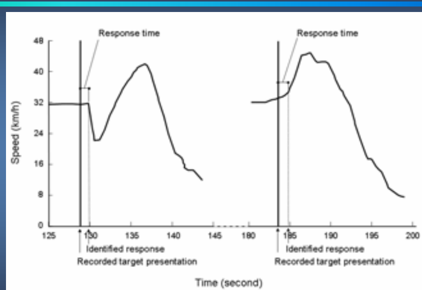
Fixation target

Study setup



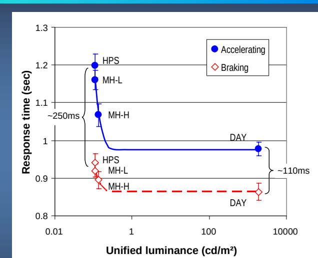
Detection targets

Driving study



Two examples of raw speed data collected from one subject by the GPS data logger (left: braking; right: accelerating)

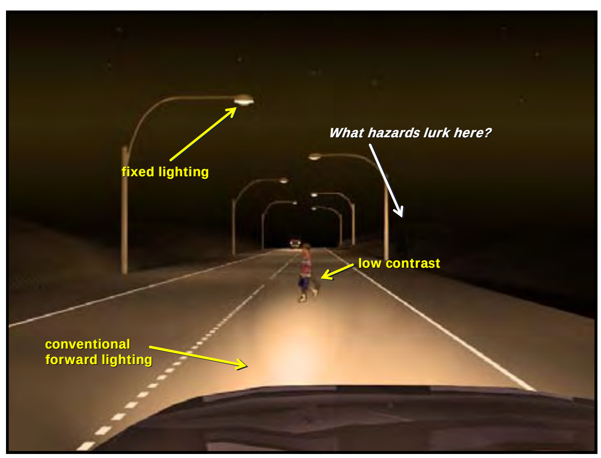
Driving study results

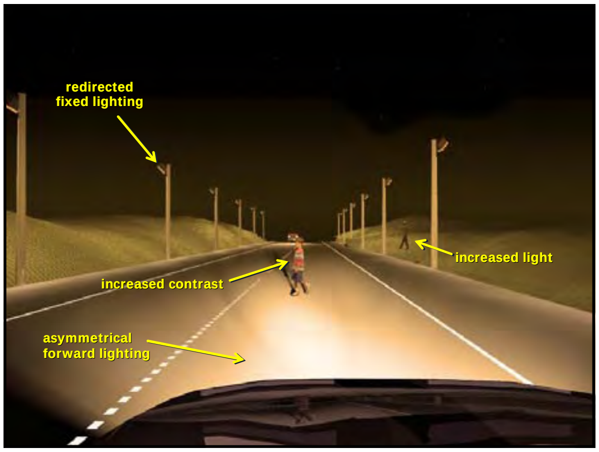


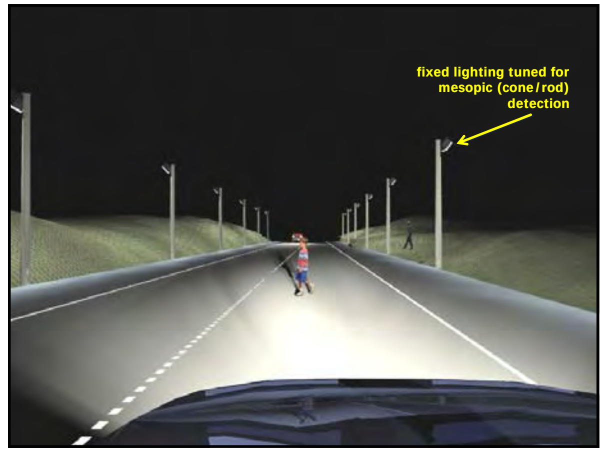
Response times as a function of unified luminance of the targets, including headlamp contributions

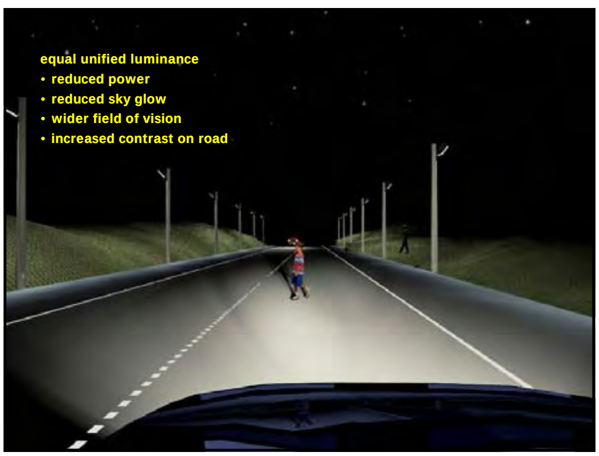
Driving study results

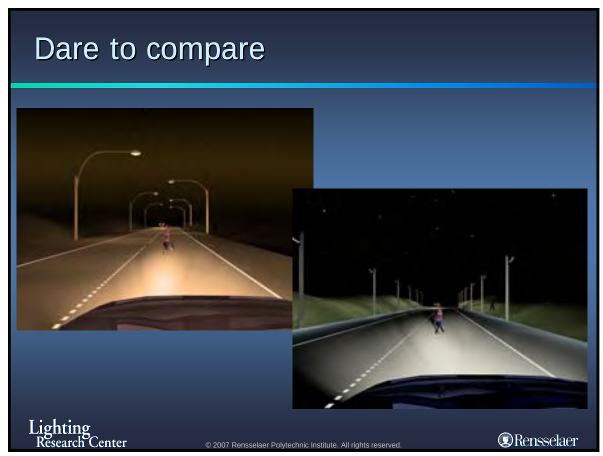
- For both acceleration and braking:
  - MH-Low = HPS-High
  - Energy savings ≈ 40%




redirected
fixed lighting
increased light
increased contrast
asymmetrical
forward lighting


fixed lighting tuned for
mesopic (cone/rod)
detection


equal unified luminance
• reduced power
• reduced sky glow
• wider field of vision
• increased contrast on road


Dare to compare
Lighting
Research Center
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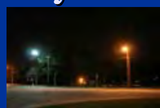
Does Tuning a Light Source to Mesopic Vision Really Work?



Taking Lab Results into the Real World

Peter Morante

Demonstrations of Mesopic Technologies

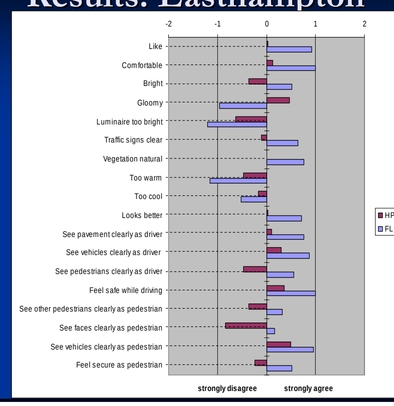
- Easthampton, MA – 70 W HPS to 50 W, 6500K FL
- Other examples of HPS (CCT 2100 K) to FL (linear and induction) and MH having CCTs of 4100K to 6500 K
- Street lighting and parking lot lighting

The Results: Easthampton

70 W HPS @ 2100K CCT

50 W Fluorescent T5 Twin Tube @ 6500 K CCT

Results: Easthampton



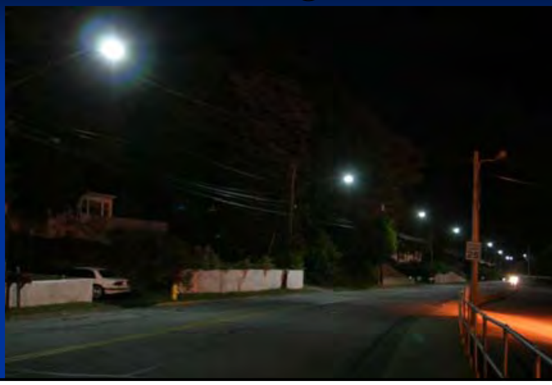
High Pressure Sodium and Metal Halide

100 W HPS @ 2100K CCT

70 W Metal Halide @ 4000K CCT

100 W HPS @ 2100K CCT

55 W Induction @ 6500K CCT



HPS and Fluorescent

250 W HPS @ 2100K CCT

2, 50 W Fluorescent @ 4100K CCT

Conclusions

- Results from all testing are similar: Observers perceptions of visibility, safety, brightness and color rendering more positive with mesopically tuned (e.g., “whiter”) lighting
- A 30% reduction in power possible while maintaining visual performance if light source tuned toward mesopic vision
- Based on observers perceptions visibility, safety, brightness are maintained even under greater wattage reductions with mesopically tuned lighting

Policies, Practices and Economics

John D. Bullough
Lighting Research Center
Rensselaer Polytechnic Institute

December 7, 2007

Outline

- Policies
  - New York State
  - Other states
  - International standards bodies
- Practices
  - Survey of roadway lighting in Capital District
  - Implications for mesopic vision/unified photometry
- Economics
  - Based on light level, energy use, maintenance

2

Policies in NYS

- NYSDOT Policy on Highway Lighting (1979)
  - Warrants for lighting based on traffic, safety
  - $: NYSDOT installs, municipality operates
- NYSDOT Highway Design Manual (1995)
  - Illuminance criteria for lighting (not luminance)
  - High pressure sodium (HPS) lamps preferred
- NYSDOT Standard Specifications (2006)
  - HPS and mercury vapor (MV) lamps mentioned

3

Municipal Policies in NYS

- 32 municipal codes reviewed w/r/t lighting
  - Some specifically call out use of HPS lamps
  - Some specify a maximum allowed wattage
  - Some require fully-shielded/full-cutoff lamps
  - Generally they are inconsistent from city to city

4

Outside NYS

- About half (so far) are aware of research regarding mesopic vision/unified photometry
- No agency has changed policy
  - Possible exception: CO DOT Lighting Design Guide
- HPS lamps are primary lamp used
  - Some use MV lamps for signs, LPS for tunnels
  - Lamp life, lumen maintenance is a major factor
  - For "amenity lighting" metal halide is sometimes permitted
- UK: reduced illuminance (25%-40%) permitted in residential areas if "white" light is used

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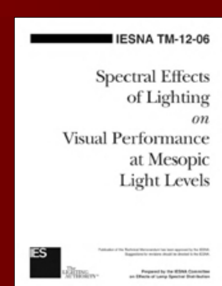
International Standards Bodies

- Illuminating Engineering Society of North America (IESNA) TM-12-06
  - Summarizes laboratory and field research on visual performance at mesopic light levels
  - Sets stage for incorporating unified photometry into lighting practice
- Commission Internationale de l'Eclairage (CIE) TC1-58
  - Developing a document for a form of unified photometry


IESNA TM-12-06

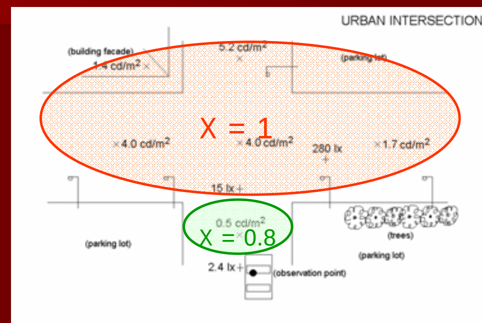
Spectral Effects of Lighting *on* Visual Performance at Mesopic Light Levels

6

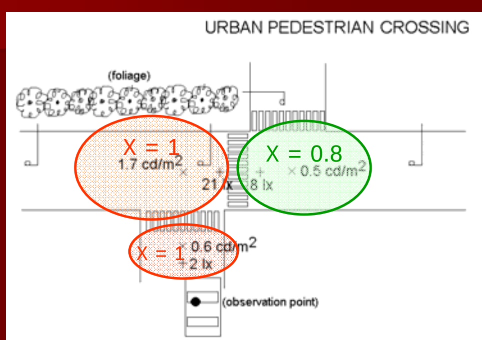
Roadway Lighting Practices

- Field measurements of illuminance and luminance
- Examples
  - Urban intersection
  - Rural intersection
  - Urban pedestrian crossing (near school)
  - Suburban mid-block crossing
- Identification of mesopic/photopic adaptation regions
  - Red = photopic (X=1), Green = high mesopic (X>0.5), Blue = low mesopic (X<0.5)

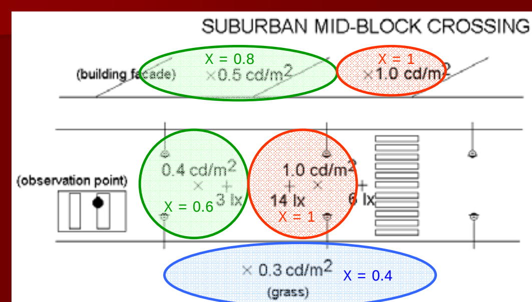
Urban Intersection



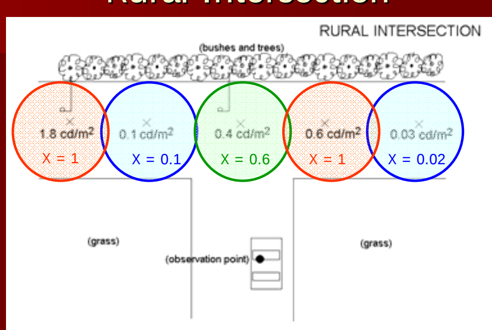
Urban Pedestrian Crossing



Suburban Mid-Block Crossing



Rural Intersection



Summary of Field Measurements

- Many roadway lighting installations including those with pedestrian roadway users have light levels in the mesopic range
  - Trees and foliage often reduce intended light levels
- Spectral 'tuning' could result in improved visibility
  - Particularly for suburban and rural locations

www.tribuneindia.com/2002/20021126/ldh5.jpg

Economic Implications

- Using representative values of X for:
  - Suburban mid-block crossing (X=0.6)
  - Rural intersection (X=0.4)
- What are the implications of using lamps other than HPS (S/P=0.6) to provide equal light level based on unified photometry?
  - 4000 K MH (S/P=1.7)
  - 6500 K electrodeless fluorescent [FL] (S/P=2.8)

Lamp Operating Characteristics

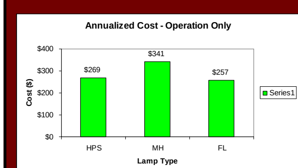
- HPS
  - 30,000 hour life
  - 90% lumen maintenance
  - 100 lm/W
- MH
  - 20,000 hour life
  - 70% lumen maintenance
  - 85 lm/W
- Electrodeless FL
  - 60,000 hour life
  - 90% lumen maintenance
  - 65 lm/W

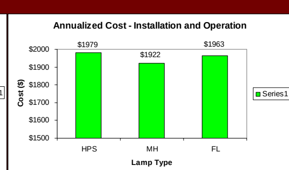
Electrodeless FL at Union Square Park, NYC

www.lrc.rpi.edu/programs/DELTA/pdf/union.pdf

Mid-Block Crossing Example

- Relative number of poles for equal unified luminance (X=0.6):
  - 6 poles (HPS), 5.3 poles (MH), 5 (FL)

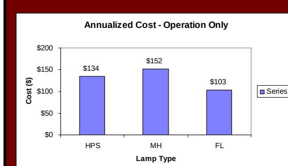


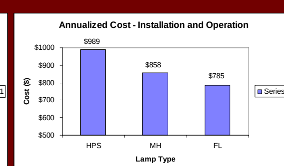


Assumes a 20-year annualization period

Rural Intersection Example

- Relative number of poles for equal unified luminance (X=0.4):
  - 3 poles (HPS), 2.4 poles (MH), 2 poles (FL)





Summary

- Using unified photometry as a criterion for roadway lighting could result in
  - Reduced energy use
  - Reduced light pollution
- While maintaining equal visibility of potential hazards such as pedestrians, animals
- Important to take other criteria (life, cost, etc.) into account

Discussion Questions

- Importance of standards and best practice documents?
- Importance of demonstration projects?
- Issues driving the selection of light sources?
- Special considerations (roundabouts, mid-block crossings, etc.)?
- What could justify changing practices?