Sustainable Roadway Lighting Seminar

Final Report

July 2014

NYSERDA Report 14-28
NYS DOT Task C-13-05

The New NY WORKS for Energy

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New York State
Department of Transportation

Sustainable Roadway Lighting Seminar

Final Report

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NYSERDA Report 14-28 NYSERDA Contract 30904 NYSDOT C-13-05 July 2014

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Technical Report Documentation Page

<table>
<tr><td>1. Report No.
C-13-05</td><td>2. Government Accession No.</td><td colspan="3">3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
Sustainable Roadway Lighting Seminars</td><td colspan="3">5. Report Date
July 2014</td></tr>
<tr><td colspan="3">6. Performing Organization Code</td></tr>
<tr><td colspan="2">7. Author(s)
John D. Bullough, Leora C. Radetsky</td><td colspan="3">8. Performing Organization Report No.
14-28</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
Lighting Research Center, Rensselaer Polytechnic Institute, 21 Union Street, Troy, NY 12180</td><td colspan="3">10. Work Unit No. (TRAIS)</td></tr>
<tr><td colspan="3">11. Contract or Grant No.
Contract No. 30904</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address
New York State Energy Research and Development Authority (NYSERDA), 17 Columbia Circle, Albany, NY 12203; New York State Department of Transportation (NYSDOT), 50 Wolf Road, Albany, NY 12232</td><td colspan="3">13. Type of Report and Period Covered
Final Report (2013-2014)</td></tr>
<tr><td colspan="3">14. Sponsoring Agency Code</td></tr>
<tr><td colspan="5">15. Supplementary Notes
Project funded in part with funds from the Federal Highway Administration. Joseph D. Tario from NYSERDA and Humayun Kabir from NYSDOT served as project managers.</td></tr>
<tr><td colspan="5">16. Abstract
The objective of this project was to develop and conduct a half-day educational seminar on sustainable roadway lighting at three locations within New York State: Rochester, New York City, and Albany. Primary attendees were engineers from the New York State Department of Transportation (NYSDOT), and individuals from local municipalities, electric utilities and engineering firms also attended. Topics covered in the seminar included: roadway lighting basics, roadway lighting technologies, visibility and safety, economics and benefit/cost analyses, and new approaches to roadway lighting including ecoluminance, pedestrian crosswalk lighting, mesopic vision and brightness appearance. The seminar was received favorably by participants at each location. The present report summarizes the educational material presented in the seminar for use by engineers at NYSDOT and other organizations interested in energy-efficient roadway lighting.</td></tr>
<tr><td colspan="2">17. Key Words
Roadway lighting, energy efficiency, light-emitting diodes, visibility, safety, economics, ecoluminance, mesopic vision</td><td colspan="3">18. Distribution Statement
No restrictions.</td></tr>
<tr><td>19. Security Classif. (of this report)
Unclassified</td><td>20. Security Classif. (of this page)Unclassified</td><td>21. No. of Pages
58</td><td>22. Price</td></tr>
</table>

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Abstract

The objective of this project was to develop and conduct a half-day educational seminar on sustainable roadway lighting at three locations within New York State: Rochester, New York City, and Albany. Primary attendees were engineers from the New York State Department of Transportation (NYSDOT), and individuals from local municipalities, electric utilities, and engineering firms also attended. Topics covered in the seminar included: roadway lighting basics, roadway lighting technologies, visibility and safety, economics and benefit/cost analyses, and new approaches to roadway lighting including ecoluminance, pedestrian crosswalk lighting, mesopic vision, and brightness appearance. The seminar was received favorably by participants at each location. The present report summarizes the educational material presented in the seminar for use by engineers at NYSDOT and other organizations interested in energy-efficient roadway lighting.

Acknowledgments

This project was sponsored by the New York State Energy Research and Development Authority (NYSERDA) and the New York State Department of Transportation (NYSDOT), under the direction of Joseph D. Tario of NYSERDA and Humayun Kabir of NYSDOT. Helpful input was provided by Jonathan Golon, Charles Riedel, Norm Schips, and Guy Tedesco from NYSDOT; Jeffrey Morris and Joseph Stahl from the New York State Thruway Authority; Sandra Misiewicz from the Capital District Transportation Committee; Emmett McDevitt and John Nickelson from the Federal Highway Administration; and Jean Paul Freyssinier and Bonnie Westlake from the Lighting Research Center at Rensselaer Polytechnic Institute.

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1 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 (NYS), an estimated 3.2 billion kilowatt-hours (kWh) of electricity per year is currently used for roadway lighting (Navigant 2012), which corresponds to the production of about 2.1 million tons of carbon dioxide (CO_2), 17,900 tons of sulfur dioxide (SO_2), and 7,800 tons of nitrogen oxides (NO_X). Recent developments in energy efficient light sources (particularly, light-emitting diodes [LEDs]) and in knowledge of the human visual system's response to light at night provide opportunities to optimize roadway lighting systems and potentially, realize substantial energy savings and associated environmental benefits.

This project was conducted to share recent information on roadway lighting technologies and new approaches to roadway lighting with individuals responsible for making decisions about roadway lighting in NYS. Hence, a half-day workshop, entitled Sustainable Roadway Lighting Seminar, was developed and presented by the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute at different locations across NYS. This report describes the seminar content and is intended to serve as a reference for roadway lighting decision makers throughout NYS.

2 Seminar Development

The Lighting Research Center developed the Sustainable Roadway Lighting Seminar in response to a Program Opportunity Notice jointly issued by NYSERDA and NYSDOT related to sustainable transportation in NYS. The project's primary objective was to help disseminate recent research findings and new developments in lighting technologies and techniques.

2.1 Development Process

To begin the process of developing the seminar, a project kick-off meeting was held with project sponsors at NYSDOT headquarters. Individuals from NYSDOT, NYSERDA, the NYS Thruway Authority, the Federal Highway Administration (FHWA) and the Capital District Transportation Committee participated, providing feedback about the type of content that seemed most needed. The curriculum for the seminar was finalized as follows:

- Roadway Lighting Basics: The purpose of roadway lighting; recommendations and standards; criteria for specifying and characterizing roadway lighting performance; simple tools for specification.
- Roadway Lighting Technologies: Lamps, luminaires including conventional (e.g., high pressure sodium and metal halide), and alternative (e.g., light-emitting diode, induction, and plasma) light source technologies; control systems; methods for comparing lighting system performance.
- Roadway Lighting, Visibility and Safety: An overview of when, where, and how roadway lighting can make the largest impact on traffic and pedestrian safety; tools and approaches to assist in identifying if/when roadway lighting might be warranted.
- Economics and Benefit-Cost Analyses: Approaches to evaluating the performance and expected benefits of roadway lighting in terms of installation costs, energy use, maintenance costs, and expected safety benefits including impacts of adaptive lighting strategies.
- New Approaches to Roadway Lighting: Includes ecoluminance, pedestrian crosswalk bollard lighting, and mesopic vision.

2.2 Seminar Locations

To provide the opportunity for as many people as possible to participate in the seminar, three locations were identified: Rochester (held on April 11, 2014), New York City (held on April 18, 2014), and Albany (held on June 23, 2014). Seminars were held at NYSDOT regional facilities in Rochester and New York City and at headquarters in Albany. Participants from surrounding regions were invited to attend each seminar.

2.3 Seminar Participants

Participants in the Rochester seminar (13 in all) were from:

- NYSDOT (Region 4 and Region 5).
- Monroe County.
- Rochester Gas and Electric.
- Wendel Energy.

Participants in the New York City seminar (31 in all) were from:

- NYSDOT (Main Office, Region 10, and Region 11).
- Town of Huntington.

Participants in the Albany seminar (14 in all) were from:

- NYSDOT (Main Office, Region 1, Region 2, and Region 7).
- NYSERDA.
- City of Cohoes.
- National Grid.
- HNTB Corporation.
- Creighton Manning.

2.4 Evaluation

Participants were asked to complete an evaluation questionnaire immediately after each seminar to gauge their opinions about the content, delivery, and clarity of information. A series of general questions about the seminar overall was included, followed by questions specific to each section. Responses were very similar across all three seminar locations and are summarized by number and percentage for all three locations in the next section. Participants could also write additional comments, which are also included. Not all respondents answered every question, so totals for each question are not always the same, and percentages may not add to 100% because of rounding.

2.5 Questionnaire Results

In general, the comments were largely positive and indicated substantial interest in the topics and materials presented in the seminar.

2.5.1 Instructional Content

- Generally, the information provided was: too basic (0: 0%), about right (42: 75%), advanced (14: 25%).
- The level of technical information was: too general (0: 0%), about right (45: 82%), too detailed (10: 18%).
- The information will be useful to me in my job: not useful (2: 4%), useful (44: 79%), very useful (10: 18%).
- I found the topics selected for the program to be: not useful (1: 2%), useful (36: 63%), very useful (20: 35%).
- I found the course material to be: not useful, (0: 0%) useful (34: 62%), very useful (21: 38%).

2.5.2 Program

- The program moved at a comfortable pace: too slow (0: 0%), about right (50: 91%), too fast (5: 9%).
- The presenters were clear and easy to understand: not clear (0: 0%), clear (15: 28%), very clear (39: 72%).
- Answers to audience questions were responsive and easy to understand: not helpful (0: 0%), helpful (28: 52%), very helpful (26: 48%).
- I would attend another Lighting Research Center program: no (0: 0%), maybe (18: 33%), definitely (36: 67%).
- This program met my expectations: no (0: 0%), in part (14: 25%), definitely (41: 75%).

2.5.3 Individual Seminar Sections

- Roadway Lighting Basics was: not helpful (1: 2%), helpful (15: 29%), clear and helpful (36: 69%).
- Roadway Lighting Technologies was: not helpful (2: 4%), helpful (16: 31%), clear and helpful (33: 65%).
- Roadway Lighting, Visibility and Safety was: not helpful (0: 0%), helpful (16: 32%), clear and helpful (34: 68%).
- Economics and Benefit/Cost Analysis was: not helpful (2: 4%), helpful (25: 48%), clear and helpful (25: 48%).
- New Approaches to Roadway Lighting was: not helpful (1: 2%), helpful (20: 38%), clear and helpful (31: 60%).

2.5.4 Additional Comments

- Interested in standards/warrants on expressways and research behind recommendations.
- Put the basics up front: should you light or not?
- Need to learn as much as possible about LEDs – information out there is confusing.
- Research projects were too detailed for my course expectations – more interested in where we are now commercially versus where we may go in the future.
- 4 hour timeframe is good, maybe start earlier to avoid lunch hour. Do sections 1-4 only in that amount of time, take a few more questions, allow time for things to sink in.
- I wish to know more about the basics of highway/street lighting: minimum requirement, current (state or city and other states) common practice, etc.
- Class could be longer to have more time to learn about the subjects.
- Discuss New York City Department of Transportation (NYCDOT) standards in addition to NYSDOT standards.

- Would like to see double the amount of example projects and scenarios. I would like to see more examples of the ecoluminance.
- Practical research shown on videos in addition to slide. Presentation could be more presentable/understandable to audience.
- Put more pictures (photos) in the slides – it will help visualize real situations better.
- More freeway benefit/cost analyses.
- Solar lighting information.
- More studies and research on LED street lighting.
- I would like to know about LED more.
- Perhaps have less information per slide (and therefore more slides).
- I'm interested in lighting for overhead signs. We're generally moving away from lighting the panels in favor of highly retro-reflective panel sheeting. We'd like to know whether this is really effective. Also, we think there are applications where this may be unadvisable, but we could use some guidance (sight distance, sign panels not directly in line of headlights, etc.).
- Add photos of each type of light (high pressure sodium, metal halide, etc.), sort of a "field identification" guide.
- Possible alternatives to lighting such as reflective sheeting, etc.
- Benefits of renewable energies (i.e., solar) to roadway lighting in addition to efficiency of lighting types.

2.6 Statement on Implementation

The subsequent chapters of this report describe the technical and educational content of the seminar information. Thus, this report can serve as a useful guidebook for engineers and other roadway lighting decision-makers regarding the selection of new technologies and techniques to maximize the sustainability of roadway lighting.

3 Roadway Lighting Basics

When considering roadway lighting, it is first necessary to understand the area in question; many locations are currently unlighted and lighting is not necessarily warranted in all locations. Among the factors used by many warrants and policies for lighting (NYSDOT 1979; AASHTO 2005) include traffic volume, roadway type and complexity, pedestrian activity level, and the types of buildings around the particular location (e.g., schools, offices, restaurants and taverns, sports facilities, and entertainment venues). Although the link between roadway lighting and crime is not firmly established (Tien et al. 1977), lighting is often part of a strategy to combat crime and certainly plays a role in influencing people's perceptions of safety and security in outdoor locations (Leslie and Rodgers 1996; Rea et al. 2009).

The primary source of recommendations for continuous roadway lighting in NYS is the American National Standard Practice for Roadway Lighting published by the Illuminating Engineering Society (IES 2000). The recommended criteria for roadway lighting offered by the American Association of State Highway and Transportation Officials (AASHTO 2005) are based on IES (2000) recommendations, as are the criteria stipulated in Chapter 12 (Highway Lighting) of the NYSDOT Highway Design Manual (NYSDOT 1995). A number of municipalities may also have requirements for roadway lighting based on IES recommendations; some municipalities might also have stipulations for pole heights or spacing, and luminaire types for specific areas.

3.1 Roadway Lighting Metrics

3.1.1 Illuminance, Luminance, and Uniformity

Illuminance is a measure of the number of lumens (lm) of light falling on a unit area of a surface such as the roadway, and it is measured in units of footcandles (fc) if the surface area is specified in square feet (ft^2), or lux (lx) if the surface is specified in square meters (m^2). As an approximation, 1 fc equals about 10 lx. As the distance between a light source and the surface that it is illuminating doubles, the illuminance will decrease by a factor of four (the inverse square law). The concept behind specifications of illuminance is that roadway lighting should provide coverage over an area for people to be able to see action at a distance within that area. IES (2000) recommends different illuminance levels for different types of roads; generally, higher illuminances (i.e., 0.4 to 1.7 fc [4 to 17 lx]) are specified for more complex, higher speed roads, with lower illuminances (i.e., 0.4 to 0.9 fc [4 to 9 lx]) specified for lower-speed roads. Illuminances can also be modified based on the expected pedestrian conflict level; higher levels are provided when pedestrian traffic is expected to be high. Minor adjustments to recommended illuminances can also be made for different road surface materials (i.e., lower illuminances are needed for concrete roads than for roads using darker asphalt material).

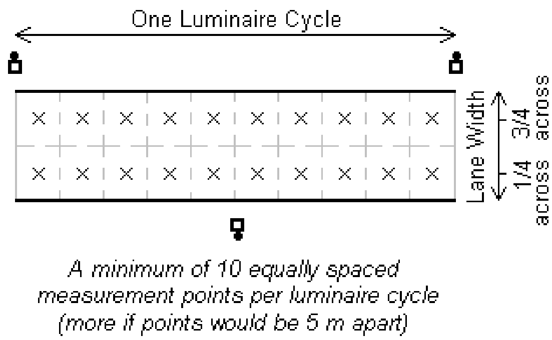
Luminance is a measure of the amount of light reflected from or emitted by a surface (such as the roadway) in a particular direction. It is conceptually similar to brightness. Luminance is often considered a more meaningful quantity related to what people see. For instance, the same illuminance of 1 fc (or about 10 lx) may fall on both a new blacktop asphalt surface or a white-painted line on the same nearby surface. Although the illuminance on both surfaces is the same, the luminance of the painted line will be much higher because more light reflects from the white paint than from the black asphalt. The most common unit of luminance is candelas per square meter, and it represents the intensity of a particular section of surface area. Importantly, the luminance of a surface in one direction may differ for someone viewing the surface from a different direction, so it is very important to specify the viewing geometry for a specification of luminance. For roadway lighting (IES 2000), the luminance in question is that of a portion of roadway surface 83 m ahead of a vehicle driver.

IES (2000) and consequently AASHTO (2005) recommendations for lighting are given in terms of illuminance or in terms of luminance. The recommended luminance values for different roadway types are generally proportional to the recommended illuminances for the same types of roads.

Recommendations for roadway lighting from IES (2000) and AASHTO (2005) are given in terms of average illuminance or luminance values, but in practice, illumination is never delivered perfectly uniformly across the roadway surface, so the actual light level corresponding to a specific point on the roadway can be higher or lower than the average. To ensure that no part of the road has a light level that would make it hard to see hazards, various uniformity levels are stipulated (IES 2000; AASHTO 2005). Usually these are given in terms of the maximum ratio between the average and minimum light levels. For complex, high-speed roadways, the maximum permissible average-to-minimum illuminance ratio is 3:1, and the maximum permissible average-to-minimum luminance ratios range from 3:1 to 3.5:1. For lower speed roadways, the maximum permissible average-to-minimum illuminance ratios range from 4:1 to 6:1, and the maximum permissible average-to-minimum luminance ratios range from 3:1 to 6:1.

To verify whether the lighting system for a particular roadway location meets a specific set of design criteria, IES (2000) has developed procedures for conducting field measurements of the illuminance produced by a roadway lighting system. (In practice, making field measurements of the luminance produced by a roadway lighting system is so difficult that they are not made for luminance criteria.) Because continuous roadway lighting systems will consist of a regular array of poles and luminaires, usually only a portion of the roadway within a luminaire spacing cycle is measured. Figure 1 shows the required spacing of measurement points within a luminaire cycle that should be measured within a traffic lane. Points should be located one-quarter and three-quarters of the way across each lane, and there should be a minimum of 10 measurement points along the lane. If the length of a luminaire cycle would result in a distance between measurement points of greater than 5 m (16 ft) then the number of equally spaced points should be increased until the distance between them is less than 5 m.

Figure 1. Locations of Illuminance Measurement Points for Roadway Lighting Field Measurements



3.1.2 Glare

The potential for glare is an inherent consequence of roadway lighting using high-lumen light sources spaced as far apart as possible (to minimize economic costs). Two types of glare can be produced by roadway lighting: disability glare and discomfort glare. Disability glare is the reduction in visibility that is caused by light scattered in the eye from a light source. Discomfort glare is the annoying or even painful sensation that can accompany a light source that is very bright relative to its surroundings. Disability and discomfort glare often occur simultaneously, but that is not always the case. For example, bright dashboard displays are unlikely to create visual discomfort, but can reduce visibility of the road ahead while driving at night. When a light source in a roadway luminaire is unshielded, the potential for glare exists. IES (2000) and AASHTO (2005) recommendations for roadway lighting include a calculation procedure for estimating disability glare, and limits on the amount of scattered light that should be produced by a roadway lighting installation. Discomfort glare is generally more difficult to quantify precisely because it can be influenced by psychological factors. As an example, a particular amount of light from a roadway luminaire into a driver's eyes might be very uncomfortable on a winding, unfamiliar road, but might not even be noticeable as glare by the same driver on a straight, familiar road. A method for estimating discomfort glare from outdoor lighting installations has been developed by the Alliance for Solid State Illumination Systems and Technologies (ASSIST 2011a) and can be downloaded online by searching for its title A Method for Estimating Discomfort Glare from Exterior Lighting Systems.

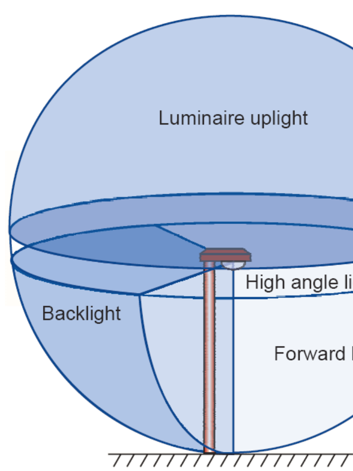
3.2 Nondesigned Roadway Lighting

Many roadway lighting installations, particularly at the municipal level, are not continuous installations using poles designed and spaced to optimize the distribution of lighting. Rather, many installations are mounted on existing utility poles, the spacing and height of which are not based on lighting but rather on the utility cable they carry. Poles are also often located along property boundaries, and are likely to be located along a single side of the road, unlike many continuous roadway lighting systems where poles can be mounted in staggered manner on both sides of the road. A typical spacing between luminaires on so-called nondesigned lighting installations using utility poles is 46 m (150 ft), but wide variations are found. As a consequence of using existing utility poles for roadway lighting, such installations might meet average light level recommendations but are unlikely to conform with uniformity or glare recommendations of the IES (2000). In actuality, the light level, uniformity and glare recommendations (IES 2000) are really only applicable to systems designed for continuous roadway lighting using dedicated light poles.

3.3 Lighting System Classification

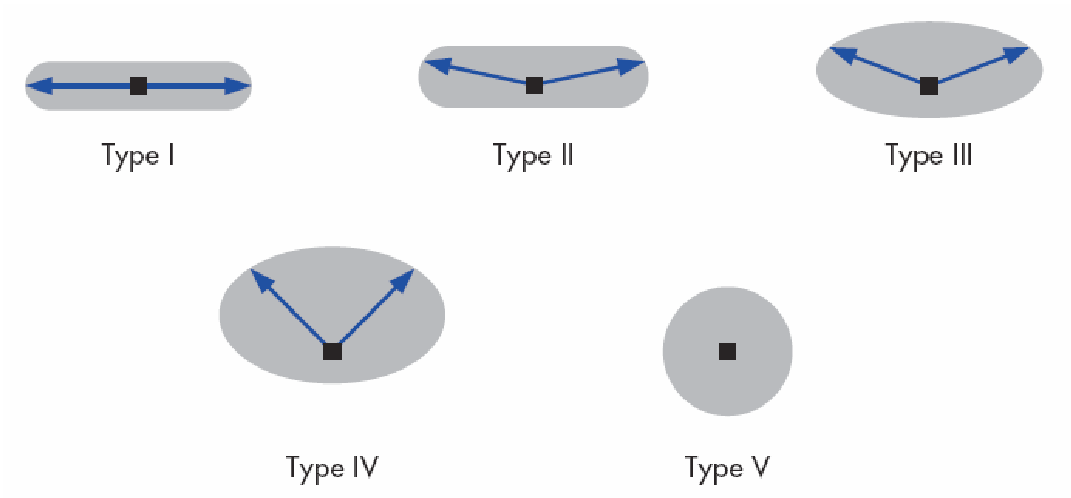
Roadway luminaires can be classified in several different ways based on their distribution of light. A recent classification system that was developed by the IES (2011) uses several angular regions (Figure 2) to characterize the amount of light (in lumens) emitted upward (uplight) where it can contribute to sky glow, at high angles (high angle light) where it can contribute to glare, or behind the luminaire (backlight) where it can contribute to light trespass on neighboring properties.

Figure 2. Angular Regions For The Distribution of Light in the IES Luminaire Classification System (IES 2011)



Other classification systems include the lateral classification, which indicates the relative ability of the luminaire to distribute light across the roadway. Roman numeral types I through V are used to indicate increasing lateral distributions as illustrated in Figure 3. For example, a Type I luminaire might be used to illuminate a narrow, two-lane roadway with no sidewalks, whereas a Type III luminaire might be used on a road with more lanes and pedestrian sidewalks adjacent to the road.

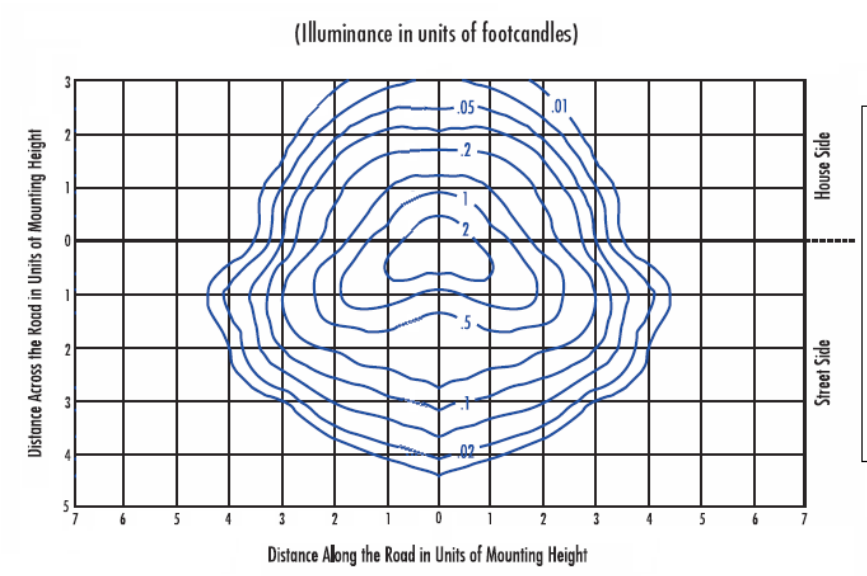
Figure 3. Representative Distributions of Light for Each Lateral Type



3.4 Preliminary Illuminance Design Tools

Commonly, lighting software packages are used to develop layouts and roadway lighting designs. At the initial planning stages, several simple tools can be useful in understanding the layout and number of luminaires required. One is the iso-illuminance diagram (Figure 4) found on many luminaire data sheets. The diagram helps the engineer estimate the shape and distribution of the light level "footprint" on the roadway. The diagram on a data sheet will correspond to one particular mounting height. Because the grid scale is given in terms of mounting height, the illuminance values will change but the shape of the distribution for different mounting heights will not. The illuminance values can be adjusted using the inverse-square law. As shown in Figure 4, a table of correction factors is often provided for different mounting heights.

Figure 4. Iso-Illuminance Diagram for a Sample Roadway Luminaire

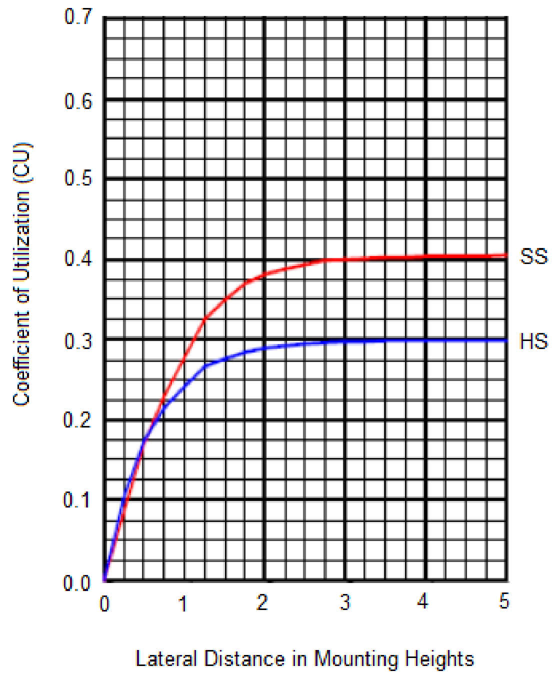


Illuminances correspond to a mounting height of 32 feet. For different mounting heights apply the following multipliers:

Mounting Height	Multiplier
10	10.24
15	4.551
20	2.560
25	1.638
30	1.138
35	0.836
40	0.640
45	0.506
50	0.410

Another useful preliminary design tool is the utilization curve (Figure 5), which can be used to provide a coefficient of utilization (CU) for a luminaire based on its mounting height and the width of the roadway. A luminaire data sheet typically shows two utilization curves for a luminaire, one curve indicated as the street side (SS) CU, and one labeled as the house side (HS) CU. The CU values on the vertical axis of the utilization curve diagram shows the proportion of light produced by the lamp inside the luminaire (or for LED luminaires, the proportion of light produced by the entire luminaire) that is distributed onto the ground level in front of (for the SS curve) and behind (for the HS curve) the luminaire.

Figure 5. Utilization Curves for a Representative Roadway Luminaire



As an example, for a mounting height of 27 ft and a roadway width of 40 ft, and assuming the luminaires are mounted above the edge of the roadway, the lateral distance across the road (in mounting heights) is approximately 1.5. (The mounting height and roadway width must be in the same units.) The CU value of the street side (SS) curve in Figure 5 is about 0.35. Knowing the CU for a particular roadway geometry, it is possible to estimate the spacing of luminaires that would produce a particular average illuminance, using Equation 1:

$$\text{Spacing} = (LL \times CU \times LLF) / (E \times W) \quad (1)$$

where:

- LL is the amount of light (in lumens) produced by the lamp inside the luminaire (or for LED luminaires, the number of lumens produced by the entire luminaire).
- CU is the coefficient of utilization determined using the procedure described above.
- LLF is a light loss factor that accounts for reductions in light level caused by dirt and aging of the lamp and luminaire (a value of 0.75 is commonly used for roadway lighting).
- E is the desired target illuminance, and W is the width of the roadway.

Returning to the previous example, suppose the desired target illuminance was 0.9 fc, and the luminaire being considered used a 150 watt (W) high pressure sodium (HPS) lamp producing 16,000 lumens. Applying Equation 1 produces:

$$\text{Spacing} = (16{,}000 \times 0.35 \times 0.75) / (0.9 \times 40) = 117 \text{ ft}$$

Therefore, an estimated spacing between two luminaires to achieve an average illuminance of 0.9 fc is about 117 ft. If the design illuminance (E) in the equation were given in lx rather than fc, then the roadway width (W) must be given in meters rather than feet.

4 Roadway Lighting Technologies

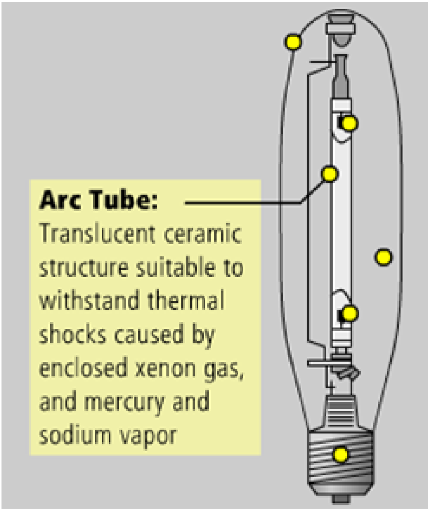
4.1 Discharge Sources

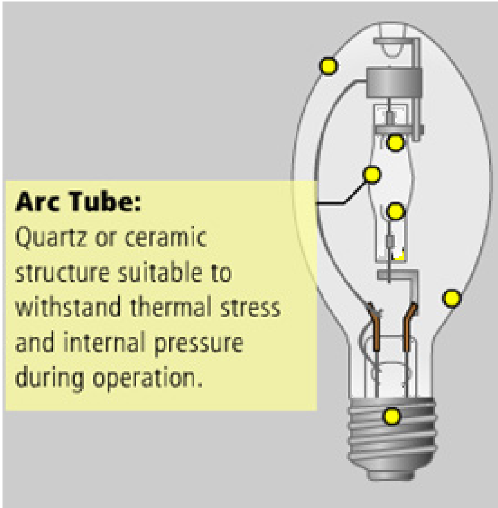
Most light sources presently used for roadway lighting are one of various types of discharge sources. These lamps use an electric discharge between two electrodes through a vapor-filled arc tube. The chemical composition of the vapor fill determines the color, efficacy, and life of the lamp. These lamps also require ballasts to provide high initial voltages needed to start the lamps and to regulate the lamp voltage. The ballast uses some power that must be considered when calculating the energy used. For example, a typical ballast for a 150 W HPS lamp uses 35 W, so the total system energy use is 185 W (not 150 W). Even including the power used by the ballast, discharge sources used for roadway lighting generally produce high lumen output and have relatively high efficacies (lumens per watt, lm/W).

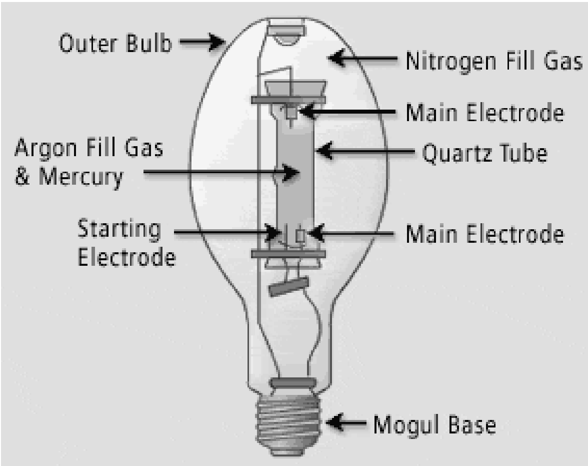
Several high-intensity discharge (HID) lamps using high pressure discharges are among the most common light sources used for roadway lighting: HPS, metal halide (MH) and mercury vapor (MV) lamps (Figure 6). HPS lamps use a sodium vapor and are highly efficacious, producing illumination with a yellowish color. MH lamps use mercury vapor in conjunction with halide salts and produce illumination that is white in color, and are used where color rendering is important. Some MH lamps (denoted CMH for ceramic metal halide) use ceramic arc tubes that have long life and high efficacy compared to conventional MH lamps. MV lamps were very common in the past for roadway lighting, but they have substantially lower efficacy relative to MH and HPS lamps and are being phased out for all lighting applications. HID lamps have small, point-source-like luminous areas.

Figure 6. High-Intensity Discharge Lamps

a) High pressure sodium, b) metal halide, c) mercury vapor.



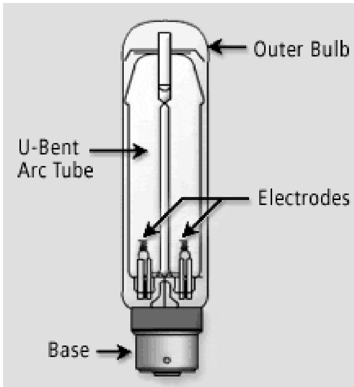


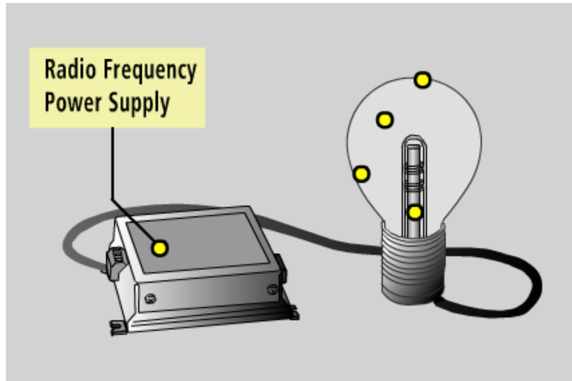


Some discharge sources utilized for roadway lighting have a low pressure discharge (Figure 7); these include low pressure sodium (LPS) lamps that use sodium vapor and produce nearly monochromatic yellow illumination with no color rendering capability, and electrodeless fluorescent induction lamps that use an induction coil to stimulate a mercury vapor that in turn stimulates fluorescent phosphors like those used in conventional fluorescent lamps. Unlike HID lamps, these sources have extended light emitting areas.

Figure 7. Low Pressure Discharge Lamps

a) Low pressure sodium, b) fluorescent induction.

a. 

b. 

More recently, electrodeless HID lamps known as plasma discharge sources (Figure 8) have been developed for outdoor lighting applications (Radetsky 2013). These produce high lumen packages with small luminous areas, and consist of a lamp or emitter containing the high-pressure vapor, an applicator, or resonator to couple electrical power to the lamp, and a high-frequency ballast such as an RF generator or magnetron. Currently available plasma discharge sources can be directional light sources designed to operate under a limited range of orientations.

Figure 8. A Plasma Discharge Lighting System

The component on the left contains the lamp/emitter and applicator; the ballast is on the right.

4.2 Discharge Source Comparisons

Rated life is defined for discharge sources as the median operating life on an 11-hours-on, 1-hour-off cycle of a large sample of lamps. Figure 9 shows ranges of rated life for different sources. There is substantial overlap in the range between 10,000 and 40,000 hours with the main exception of induction lamp systems, which have rated lives between 60,000 and 100,000 hours. In terms of luminous efficacy, most of the discharge sources included in Figure 10 have efficacies exceeding 50 lm/W with the exception of MV lamps. Lower efficacies are among the reasons MV lamps are being phased out for roadway lighting applications.

Figure 9. Ranges of Rated Life for Different Discharge Light Sources

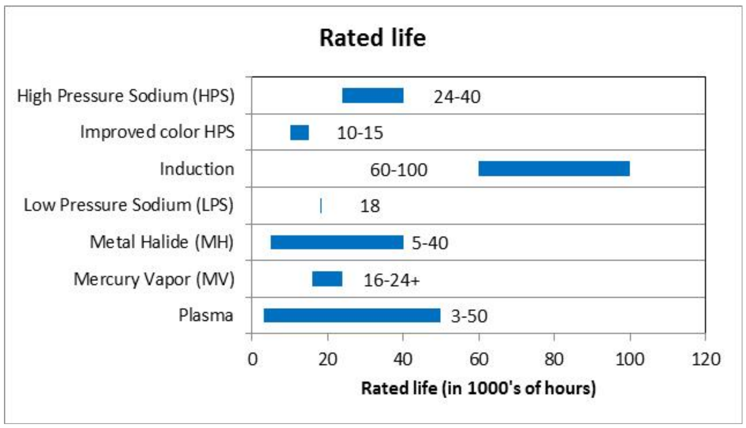
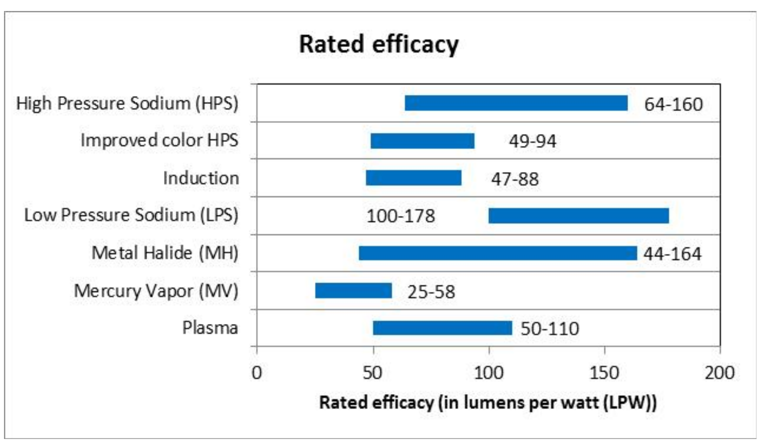


Figure 10. Ranges of Luminous Efficacy for Different Discharge Light Sources



In terms of color rendering, the color rendering index (CRI) is a measure of how a light source renders colors relative to an incandescent or daylight source with a similar color appearance. Figure 11 shows the range of CRI values typical for each discharge source. Improved-color HPS, induction, MH, and plasma discharge sources can all produce relatively high CRI values (>60). HPS lamps, MV lamps, and LPS lamps all have relatively low CRI values, particularly LPS where color rendering is nonexistent. Figure 12 shows the range of correlated color temperature (CCT) for each type of discharge lamp. Sodium lamps (HPS and LPS) have the lowest CCT values consistent with the yellow-appearing illumination produce by a sodium vapor arc. The discharge light sources producing white-appearing illumination (MH, induction, MV, and plasma) have CCT values ranging from 3000-4000 kelvins (K) (warm white) to 5000+ K (cool white).

Figure 11. Ranges of CRI Values for Various Discharge Light Sources

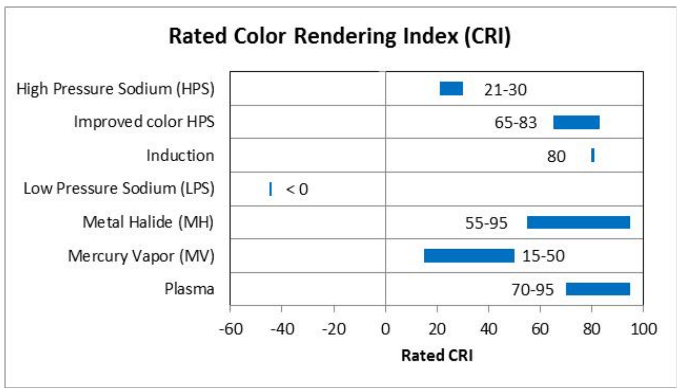
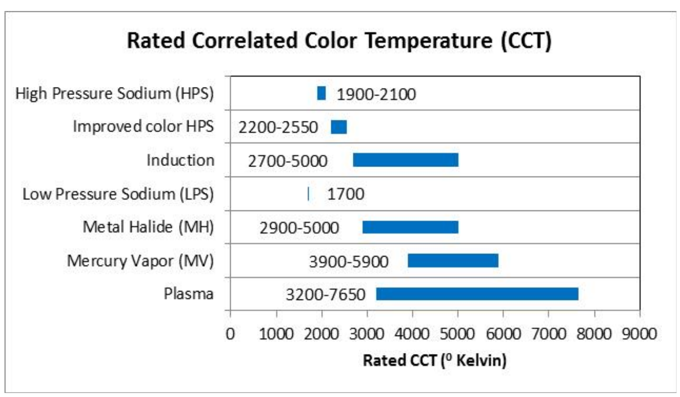


Figure 12. Ranges of CCT Values for Various Discharge Light Sources



Not all discharge sources emit useful light immediately when they are switched on, and some require a cool-down time to switch back on if they are switched off for any reason such as a temporary power failure. Figure 13 shows ranges of warm-up time, defined as the time a lamp takes to produce its full light output after it is switched on, and Figure 14 shows ranges of re-strike time, defined as the time needed for the lamp to cool down before it can be switched on, after it is turned off. Except for fluorescent induction lamps, discharge lamps require at least a minute for warm-up, and 2-3 minutes to cool down in order to re-strike. Some MH lamps have very long re-strike times, which can be up to 20 minutes.

As previously mentioned, as light sources age they tend to produce lower amounts of light, and this reduction or depreciation is different for different types of lamps. Figure 15 shows ranges of this reduction, called lumen depreciation, for different types of discharge lamps. Reductions of 10% to 40% are typical, depending upon the type of lamp.

Figure 13. Ranges of Warm-Up Time for Various Discharge Light Sources

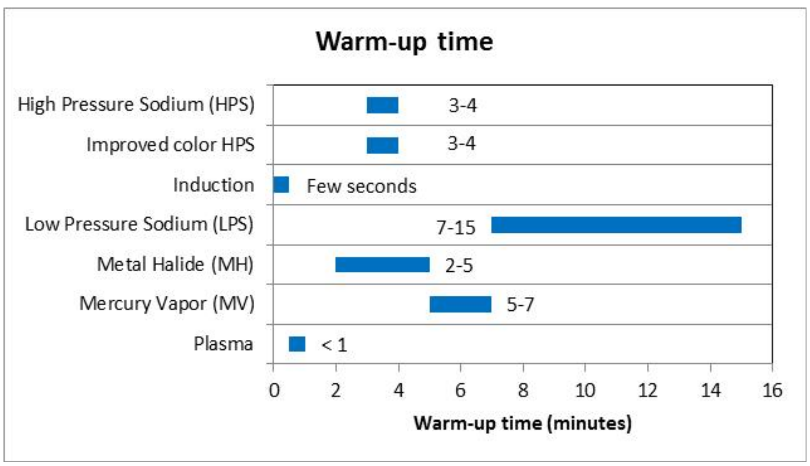


Figure 14. Ranges of Re-Strike Time for Various Discharge Light Sources

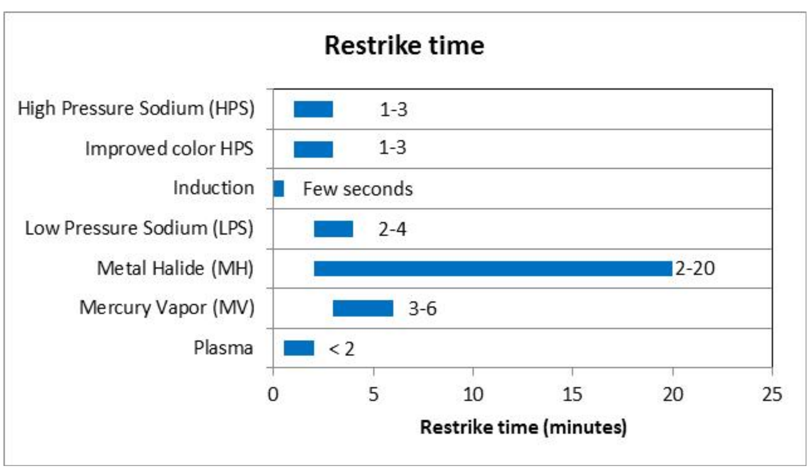
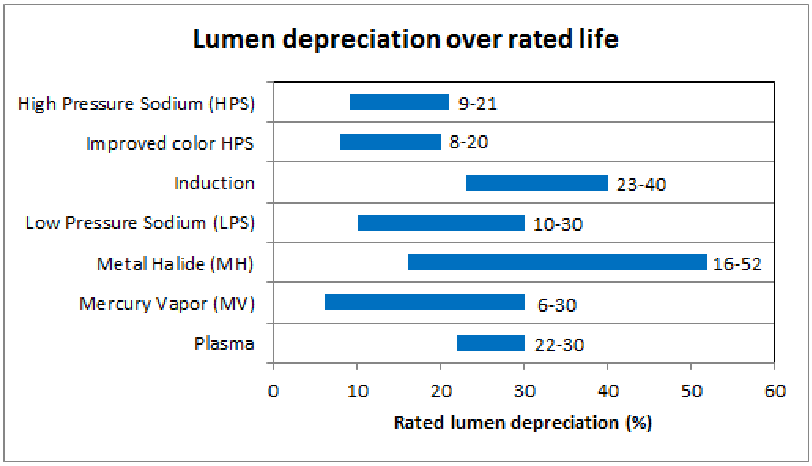


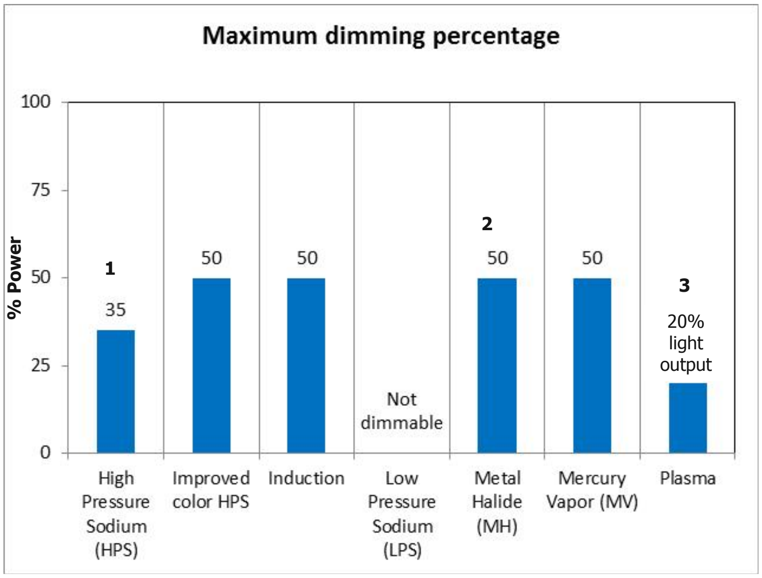
Figure 15. Ranges of Lumen Depreciation for Various Discharge Light Sources



As adaptive or dynamic roadway lighting becomes more common (Bullough 2010), the ability to dim lamps will be increasingly important. Most discharge sources can be dimmed with the appropriate control gear. Figure 16 shows the maximum dimming possible with each type of discharge lamp (as a function of maximum input power, except for plasma discharge lamps, which are reported as a function of maximum light output. Dimming can also affect lamp color as indicated in the notes in Figure 16.

Figure 16. Maximum Dimming Percentages as a Function of Total Lamp Power

The exception for this figure is plasma discharge lamps, where maximum dimming is given as a function of total light output. Notes: 1) Dimming decreases CCT with little impact on CRI; 2) Dimming changes both CCT and CRI; 3) Dimming increases CCT with little impact on CRI.



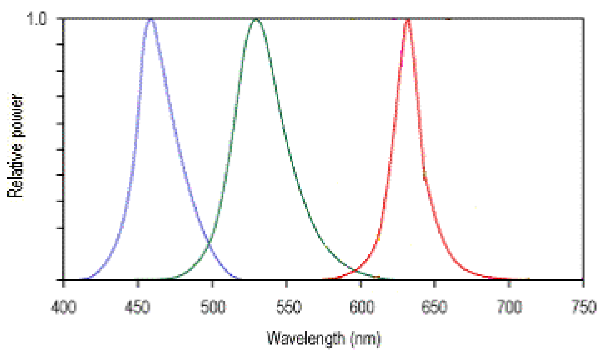
Most discharge lamps are unaffected by ambient temperature. Induction lamps may exhibit decreased output at low (<15o C) temperatures, and higher temperatures result in decreased output for plasma discharge sources. Similarly, most discharge lamps are unaffected by their operating position. The primary exceptions are MH and plasma discharge lamps, which are designed to be used in a particular orientation.

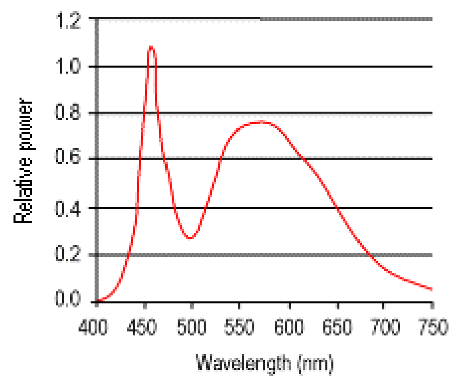
4.3 LED Light Sources

LED sources can produce white light in one of two ways. By mixing light from red, green, and blue (RGB) LEDs in the proper proportion, it is possible to create white light. Figure 17a shows spectral distributions of blue, green, and red LEDs. More commonly at present, white light can also be created by using a blue LED and a phosphor coating that converts some of the blue light to yellow light and a resulting spectral distribution similar to Figure 17b.

Figure 17. Spectral Distribution of Various LEDs

a) Blue, green, and red LEDs, b) Spectral distribution of a phosphor-converted white LED

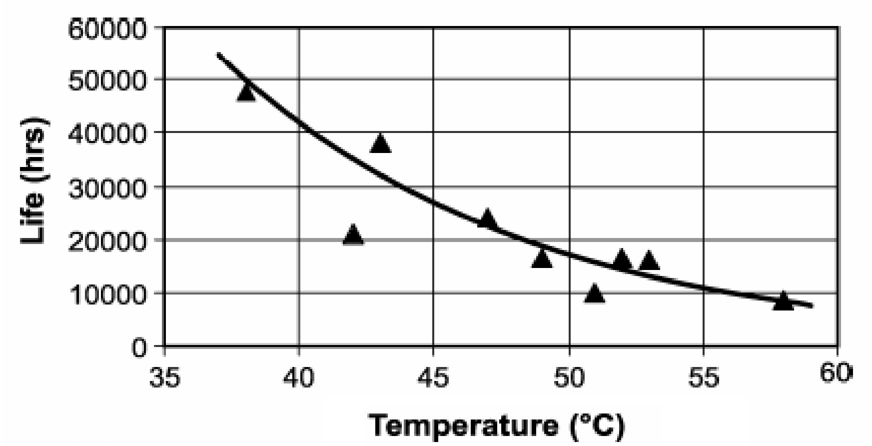




Luminous efficacies of LED products have improved substantially in the past decade and are projected to continue to do so in the coming decade. Efficacies for commercially available LEDs of 40 lm/W (for warm white) to 50 lm/W (for cool white) were obtained around 2006-2007, but these values have more than tripled to 130 lm/W (for warm white) to 160 lm/W (for cool white) in 2013. It is projected that by the year 2025, RGB LEDs will achieve efficacies of 250 lm/W and phosphor-converted LEDs will approach 200 lm/W.

LED operating life is defined differently than for discharge lamps, because LEDs rarely fail by burning out like other light source types. They exhibit lumen depreciation over time, with the time to reach 70% light output (30% lumen depreciation) commonly accepted as a definition for useful life (IES 2008). Primarily, the useful life is influenced by the temperature of the LED junction. As a rule of thumb (Narendran and Gu 2005), it is estimated that for every 10°C increase in junction temperature, the useful life of the LED is halved (Figure 18). For this reason, a key component of LED luminaires is the heat sink, which often consists of metal fins and grooves, which conduct heat from the LED sources to the surrounding air. Although LED sources are unlikely to undergo catastrophic failure, the driving circuitry may be more susceptible to failure, particularly if it contains electrolytic capacitors, as is common in many LED lighting system drivers.

Figure 18. Useful life (to 70% light output) for several LED light sources as a function of temperature (Narendran and Gu 2005)



Earlier LED roadway luminaires (available up to 2011) were able to meet IES (2000) criteria for light levels, uniformity and glare, but often required shorter pole spacing than HPS lamps, which are the most commonly used light sources for roadway lighting (Radetsky 2010, 2011). Nonetheless, even with shorter pole spacing the LED systems resulted in an average energy use reduction of 10% compared to HPS. In addition, luminaire costs for those early LED luminaires were high (between 5 and 15 times the cost of an HPS luminaire), so that the overall life cycle costs of the early LED roadway lighting systems were substantially higher than those of HPS lighting systems.

More recent LED roadway lighting systems since 2011 can now meet IES (2000) lighting criteria with similar or longer pole spacing than HPS systems (Bullough and Radetsky 2013). Some LED products could be used with a pole spacing of 280 ft, compared to an average of 220 ft for HPS luminaires. Energy savings between 10% and 35% are achievable, and depending upon initial costs of the LED systems, life cycle costs can be comparable as well even though initial costs are still generally higher than for HPS.

4.4 Lighting Controls

Because roadway lighting systems operate, for the most part, from dusk to dawn, the performance and reliability of controls that switch lighting on and off are critical. Most commonly, roadway luminaires use photosensor controls that turn lights on when the ambient light level decreases below a specific criterion level experienced at dusk, and turns them off when the ambient level exceeds the criterion at dawn. The photosensor location is usually on the top of the luminaire where it is not influenced by light sources below the luminaire. Some photosensor controls may have a partial-night control where the luminaire only operates for a fixed number of hours each night after switching on. Roadway lighting can also be controlled using an astronomical time clock that accounts for sunset and sunrise times throughout the calendar year but these clocks are commonly used for parking area lighting and less common for roadway lighting. Time clocks tend to be more expensive than photosensor controls.

Motion or occupancy sensor controls are also available for light sources with short warm-up times. More common in parking applications, it is important that the sensor's coverage area for motion detection corresponds to the light distribution for the luminaire on which it is mounted. Increasingly, a number of remote monitoring systems using wired and wireless communications protocols can assist in monitoring roadway lighting system performance. These monitoring systems may become more common with the future growth in adaptive or dynamic lighting systems (Bullough 2010).

4.5 Comparing Light Source Technologies For Roadway Lighting

As part of an analysis for the National Cooperative Highway Research Program, Bullough and Radetsky (2013) compared various discharge and LED roadway luminaires in terms of their performance for illuminating collector roads and freeways.

4.5.1 Collector Roads

The base case lighting system for collector roads was a 150 W HPS, lateral Type III luminaire mounted 27 ft high. Three HPS systems were identified, as well as two MH systems (a conventional and a CMH lamp) and six LED systems. A challenge in comparing different technologies is that different products are documented in data sheets with different formats and data elements, so the performance of each luminaire was collated into a consistent apples-to-apples format that can serve as a way to assess technologies as available in 2013. The maximum pole spacings that allowed the luminaires of each type to meet IES (2000) recommended criteria for lighting collector roads are shown in Figure 19. For the LED luminaires, the maximum pole spacing ranged from 200 ft to 255 ft.

Figure 19. Range of maximum pole spacings achievable for each type of luminaire for collector roads

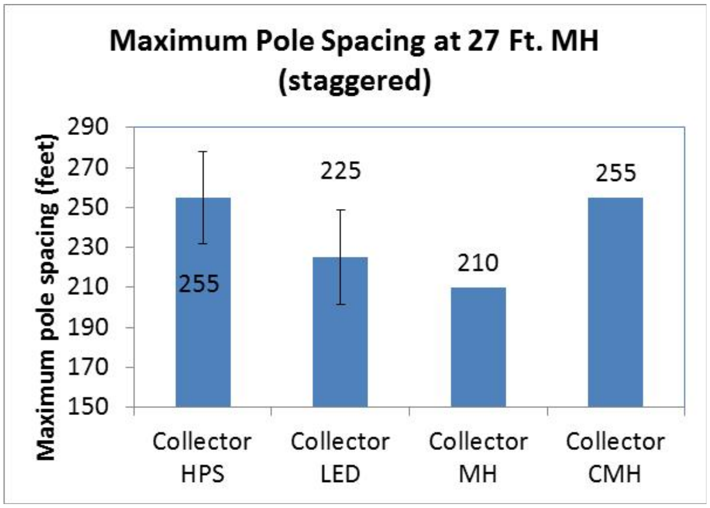
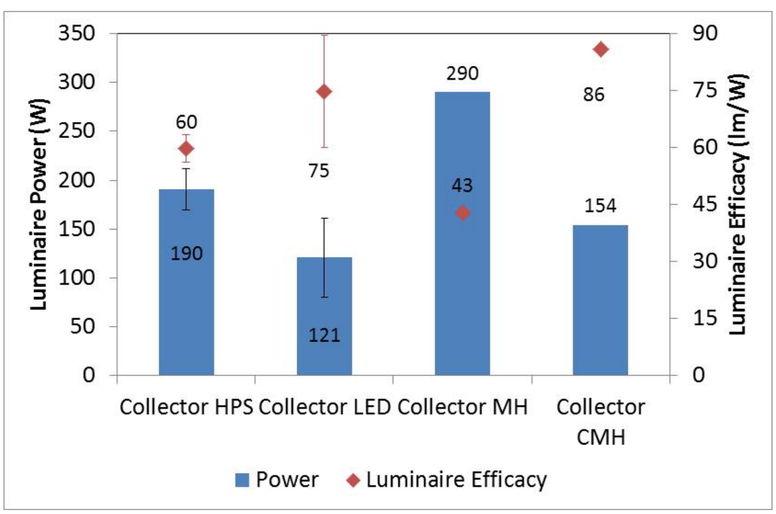


Figure 20 shows the ranges of luminaire power (bars) and luminous efficacy (diamonds) for the different lighting systems types. The LED luminaires (on average) and the CMH luminaire had higher efficacy than the average HPS luminaire. On average the LED luminaires used 37% less power demand than HPS, while the CMH luminaire used 19% less power, and the conventional MH luminaire used 52% more power. For the collector road scenario that was investigated, there was little relationship between the power used by a luminaire and the maximum spacing that could be achieved.

Figure 20. Ranges of luminaire power (bars, left vertical axis) and efficacy (diamonds, right vertical axis) for each type of luminaire for collector roads



4.5.2 Freeways

For comparisons when used to illuminate freeways, the base case type of lighting system was a 250-W HPS, lateral Type II luminaire mounted 40 ft above ground level. Three HPS luminaires, two MH luminaires (one conventional, one CMH), six LED luminaires, and one plasma discharge lighting system were identified for the comparison. On average, the maximum achievable spacing was similar among all of the lighting system types (Figure 21), although for the LED luminaires evaluated, there was a large variation in the maximum spacing (from 205 to 300 ft), underscoring the importance of evaluating specific luminaires individually before selecting one.

Figure 21. Range of maximum pole spacings achievable for each type of luminaire for freeways

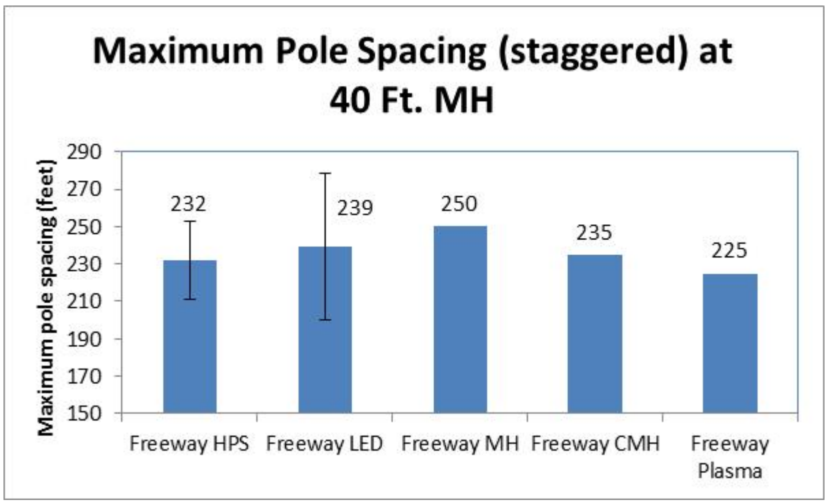


Figure 22 shows the ranges of luminaire power (bars) and luminous efficacy (diamonds) for the different lighting systems types for freeways. The LED luminaires (on average), the CMH luminaire and the plasma discharge luminaire had higher efficacy than the average HPS luminaire. On average the LED luminaires had 31% lower power demand than HPS, while the CMH luminaire used 24% less power, the plasma luminaire used 3% more power, and the conventional MH luminaire used 52% more power. Unlike for collector roads, for the freeway scenario that was investigated, luminaires of a particular type (e.g., HPS or LED) using less power tended to have lower maximum spacing values.

Figure 22. Ranges of luminaire power (bars, left vertical axis) and efficacy (diamonds, right vertical axis) for each type of luminaire for freeways

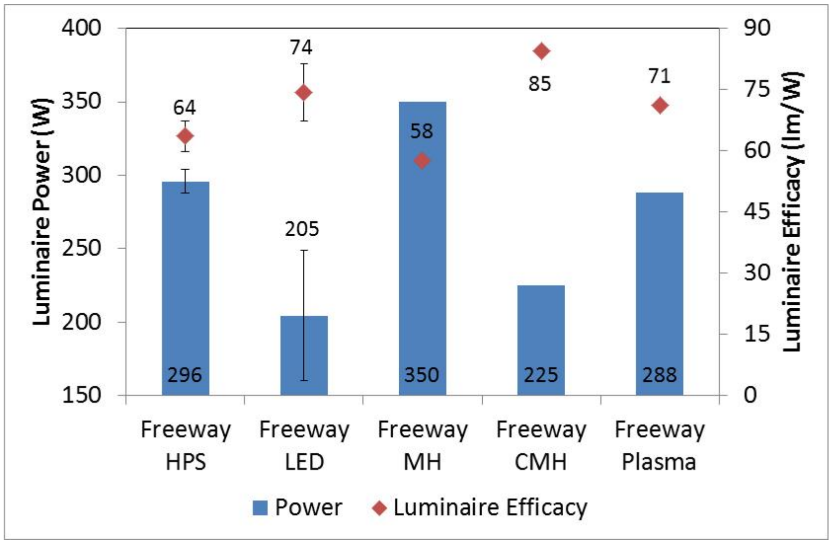


Table 1 shows, for several LED roadway luminaires, how a reduction in energy use compared to HPS can help to justify higher initial cost of many LED systems. Assuming a base case illuminating a collector road with a 150-W HPS, lateral Type III luminaire that has an initial cost of $1,000, Table 1 shows the maximum initial cost that would result in a simple payback within five years compared to the HPS system. Of the eight LED luminaires represented in Table 1, all but one could have a higher initial cost than the HPS system and would result in a simple payback because of energy cost reductions. One system would use slightly more energy than the HPS base case and therefore would need to have a lower initial cost than $100 to break even with the HPS system within five years.

Table 1. Comparison of several LED luminaires to an HPS base case in terms of power, maximum spacing, and energy cost

Also shown is the maximum initial cost of the LED luminaire that would, because of energy cost savings, result in a simple payback (within five years) over the HPS base case, assuming the HPS luminaire initial cost was $100.

Brand/Model	Type	Watts	Poles per mi	Spacing (ft)	kW/mi	Energy savings	Energy cost per year/mi	Cost to break even
Base case	HPS	183	47	220	8.5	0%	$6410	$100
Product 1	LED	208	36	279	7.5	11%	$5688	$198
Product 2	LED	216	41	256	8.8	-2%	$6516	$87
Product 3	LED	130	41	249	5.4	38%	$3996	$392
Product 4	LED	157	41	249	6.5	24%	$4867	$286
Product 5	LED	144	44	240	6.2	28%	$4636	$305
Product 6	LED	130	44	236	5.7	34%	$4237	$348
Product 10	LED	140	47	220	6.5	23%	$4908	$260
Product 11	LED	129	49	213	6.2	27%	$4685	$277

- Spacing and electric load (kW/km) calculated when luminaires are installed at 25 ft above ground and meet the average light level (0.9 fc), uniformity ratio (avg/min = 4), and veiling luminance ratio (0.3) criteria in IES RP-08 for collector roads.
- Base case is a Type III medium, full cutoff 150W HPS cobra head. The mounting height is set by the base case (HPS) and is not optimized for each LED luminaire.
- Life of HPS lamp is rated at 24,000 hours and all of the LED luminaires are rated at 50,000 to 130,000 hours.
- Energy cost per year per mile if the system is used 4380 h per year and energy cost is $0.17 per kWh.
- Cost to break even is the cost per luminaire so that a simple payback of 5 years is achieved through energy savings alone.

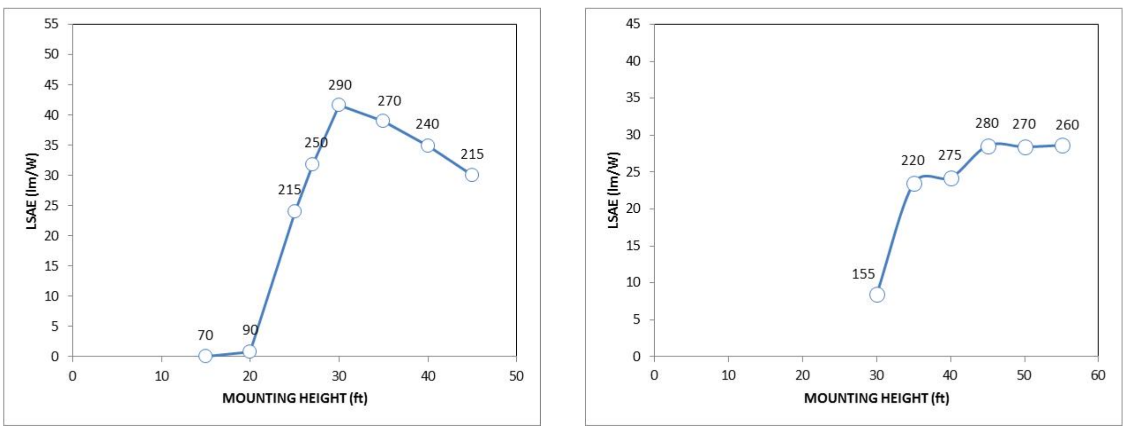
4.6 Luminaire System Application Efficacy

Individual luminaire distributions, even within the same light source type, vary greatly from luminaire to luminaire. Therefore, it stands to reason that an optimized configuration for one luminaire could have a different optimal pole mounting height than another luminaire also optimized for a particular lighting application. Because lighting recommendations from the IES (2000) and AASHTO (2005) only account for illumination on the roadway, light outside this area is not efficacious toward achieving these recommendations. A concept developed by the Alliance for Solid State Illumination Systems and Technologies (ASSIST 2011b) called luminaire system application efficacy (LSAE) is described in a report available online entitled “Recommendations for Evaluating Street and Roadway Luminaires.”

If the luminaire height can be modified from a predetermined value for a particular roadway lighting installation (e.g., because poles will be replaced or because the design is for a brand new installation), Bullough and Radetsky (2013) found that changing the pole height can result in dramatic differences in LSAE values and in the maximum pole spacing that could be used to meet IES (2000) and AASHTO (2005) recommended lighting criteria (Figure 23). When energy use is an important design criterion, calculation of LSAE as described by ASSIST (2011b) may provide useful comparisons among different luminaires.

Figure 23. LSAE values and optimal pole spacings

Data for pole spacing are shown above each data point for different mounting heights for: a) an example luminaire used to illuminate a collector road; b) an example luminaire used to illuminate a freeway.



5 Roadway Lighting, Visibility, and Safety

A major purpose of roadway lighting, according to the IES (2000), is "to reduce night accidents, attendant human misery, and economic loss." It is almost universally accepted, and most published evidence suggests, that roadway lighting reduces nighttime crashes, and a commonly repeated value is that roadway lighting is associated with a 30% reduction in nighttime crashes (IES 1989, CIE 1992; Elvik 1995). It is reasonable to believe that lighting improves driver visibility, which in turn leads to improved safety by providing longer distances and greater time within which to response to hazards along the roadway, but direct links relating roadway lighting to visual performance and in turn to nighttime safety are few and far between. This chapter summarizes a two-pronged study (Bullough et al. 2013) to investigate the statistical relationship between roadway lighting and improved nighttime safety, and the analytical relationship between roadway lighting and improved nighttime visual performance. To the extent that these two approaches yield similar conclusions, the notion that lighting improves visibility, which in turn underlies improved safety, can be reinforced.

The scenarios upon which this two-pronged study is based are state roadway intersections in the state of Minnesota. The focus on intersection lighting is primarily a matter of what data were available for investigating both nighttime crash frequency and roadway lighting presence.

5.1 Statistical Approach

Using data from the Highway Safety Information System (HSIS), Bullough et al. (2013) gathered data for more than 6,400 roadway intersections for a four-year period spanning 1999-2002 including daytime and nighttime crash frequencies per year, presence of roadway intersection lighting (or not), and other data such as traffic volume, type of traffic control devices, access control, local area type (e.g., urban versus rural), posted speed limits, percentage of heavy truck traffic, and other features such as median and shoulder types. Comparing signalized and unsignalized intersections in urban, suburban, and rural areas, it was found in all cases that urban and suburban intersections behaved very similarly and therefore were combined into a single category. The change (if any) in the night-to-day crash ratio when lighting was present for each of the four types of intersections was estimated using nonlinear multiple regression models (while controlling for all of the available traffic and geometric data) as an estimate of the nighttime safety impact of roadway intersection lighting, and the following statistical results were found:

- Urban/suburban unsignalized intersections: 13% reduction in the night-to-day crash ratio.
- Urban/suburban signalized intersections: 7% reduction in the night-to-day crash ratio.
- Rural unsignalized intersections: 2% reduction in the night-to-day crash ratio.
- Rural signalized intersections: 0% reduction in the night-to-day crash ratio.

Using the reduction in the night-to-day crash ratio as a surrogate for the nighttime crash reduction, the findings from Bullough et al. (2013) showing at most an approximately 10% reduction in nighttime crashes is consistent with data from the Highway Safety Manual, but smaller than the 30% reductions reported by other studies summarized by IES (1989), CIE (1992) and Elvik (1995).

5.2 Analytical Approach

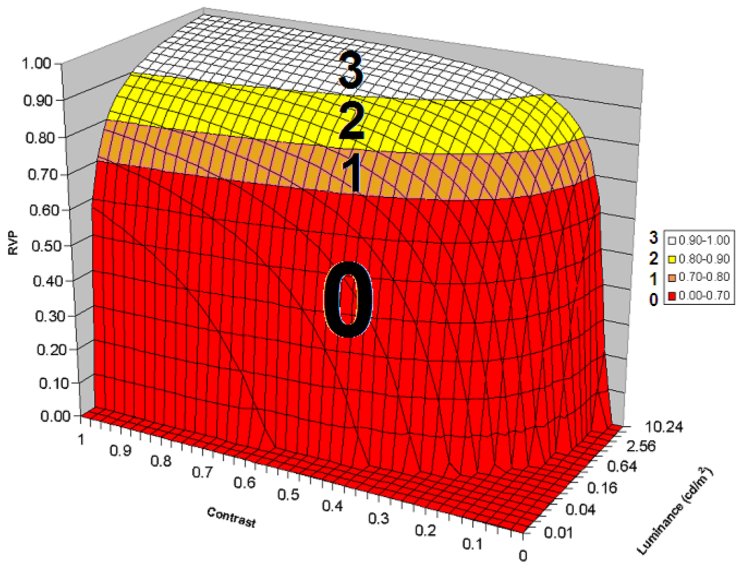
Using the Minnesota Department of Transportation (MNDOT) Roadway Lighting Design Manual as a basis for understanding how roadway intersections in Minnesota are illuminated (if and when they are illuminated), it was found that MNDOT adheres closely to IES (2000) and AASHTO (2005) recommendations, which was confirmed with checks using photologs. Using a published model (Rea and Ouellette 1991) of relative visual performance (RVP) (i.e., the speed and accuracy of visual processing) using light level, the contrast between an object and its background, and the size of an object as an objective measure of visibility, Bullough et al. (2013) estimated the visual performance improvement at roadway intersections of the same types described in the previous section when lighting was present, compared to when no roadway lighting was present. The primary type of crashes considered by Bullough et al. (2013) for this analysis were misjudgments of the location and velocity of vehicles made by drivers planning to enter an intersection, based on published findings from Chovan et al. (1994).

Taking into account the presence of higher levels of ambient light in urban/suburban locations relative to rural locations, and including the effects of vehicle headlights as sources of both useful illumination and glare from oncoming vehicles, Bullough et al. (2013) used a calculation method developed by Rea et al. (2010) and estimated that roadway intersection lighting was associated with the following improvements in a score (Figure 24) derived from RVP values:

- Urban/suburban unsignalized intersections: +1.86 RVP score units.
- Urban/suburban signalized intersections: +0.73 RVP score units.
- Rural unsignalized intersections: +0.21 RVP score units.
- Rural signalized intersections: +0.27 RVP score units.

Figure 24. RVP values for a roadway target having different luminances (right horizontal axis) and contrast values (left horizontal axis)

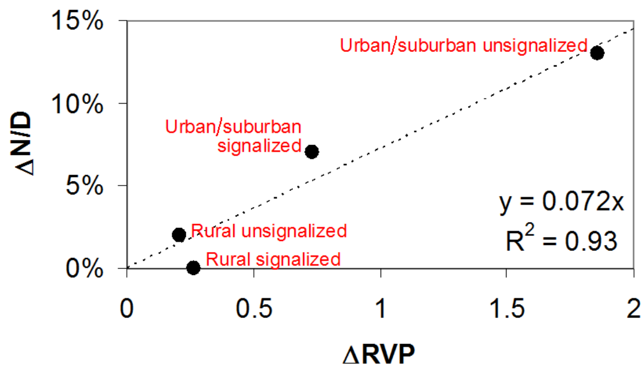
Shading of the surface shows corresponding RVP score values.



5.2.1 Provisional Transfer Function

Interestingly, the statistical crash reductions associated with roadway intersection lighting for each intersection type were strongly correlated with the visual performance improvements associated with roadway lighting for the same intersection types (Figure 25). The strong correlation between the results of the two approaches suggests that visual performance modeling can be the basis of a provisional transfer function allowing predictions of safety impacts from lighting. This finding is important because using models like the RVP model (Rea and Ouellette 1991), visual performance can be predicted, whereas crash frequencies require years of data and large data samples before statistically reliable associations can be demonstrated.

Figure 25. Correlation between visual performance improvements associated with roadway intersection lighting (horizontal axis) and modeled statistical reductions in nighttime crashes (vertical axis) associated with roadway intersection lighting (Bullough et al. 2013)



As an example of how the transfer function in Figure 25 could be utilized, consider that according to both approaches used by Bullough et al. (2013), rural intersection lighting as practiced by MNDOT (and by most transportation agencies) has little benefit to nighttime safety. Part of the reason is that speed limits on many rural roads are high (>40 mph), but typical intersection lighting usually consists of only one or two luminaires located at the junction of the intersection, with a modest light level on the roadway. If a vehicle is at the intersection waiting to enter traffic on the intersecting road, it is important for the driver of that vehicle to be able to judge the relative speed and location of approaching traffic not when it is near the junction, but rather when it is approaching from perhaps hundreds of feet away. If the intersection lighting were extended by installing multiple luminaires to provide coverage along the intersecting road up to 300 ft away from the junction, and if the light levels were increased by a factor of three, the RVP model would predict a sevenfold improvement in a driver's ability to judge the motion of the approaching vehicle compared to a single luminaire at the junction. Rather than a 1-2% reduction in nighttime crashes predicted by the provisional transfer function in Figure 25, the improvement in visibility from an extended configuration of roadway luminaires would be predicted to yield an 11% reduction in nighttime crashes.

6 Economics and Benefit-Cost Analyses

Using an economic analysis conducted by Bullough and Rea (2011), this chapter describes an approach to understanding benefit-cost characteristics of roadway lighting.

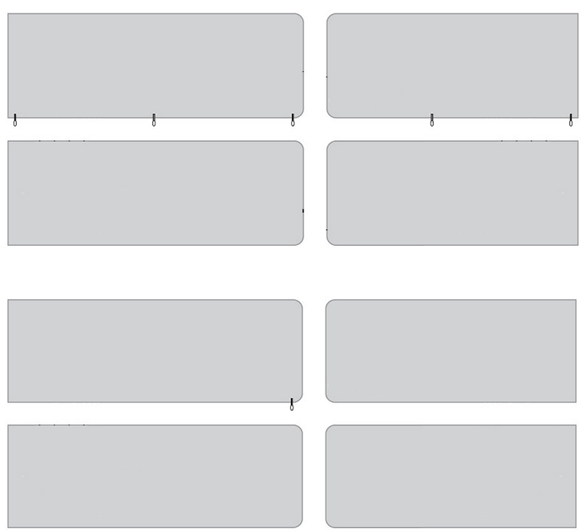
6.1 Roadway Lighting Costs

Taking into account the initial installation costs for roadway lighting (R.S. Means 2008) annualized over a period of 20 years, and the operation and maintenance costs (electricity, lamp replacement), the annualized costs for roadway lighting at two different types of intersections are as follows:

- Urban/suburban signalized: $1,790.
- Rural unsignalized: $600.

The cost is higher for urban/suburban signalized intersections because roadway intersection lighting in urban/suburban locations is likely to be part of a continuous lighting system (with more poles and luminaires) whereas in rural locations, roadway lighting at an intersection is typically isolated to the intersection junction. Figure 26 illustrates the installations for both types of intersections. Importantly, the costs of lighting are unrelated to the amount of traffic volume that an intersection experiences.

Figure 26. Representative lighting layout for a) urban/suburban signalized intersection lighting; b) rural unsignalized intersection lighting

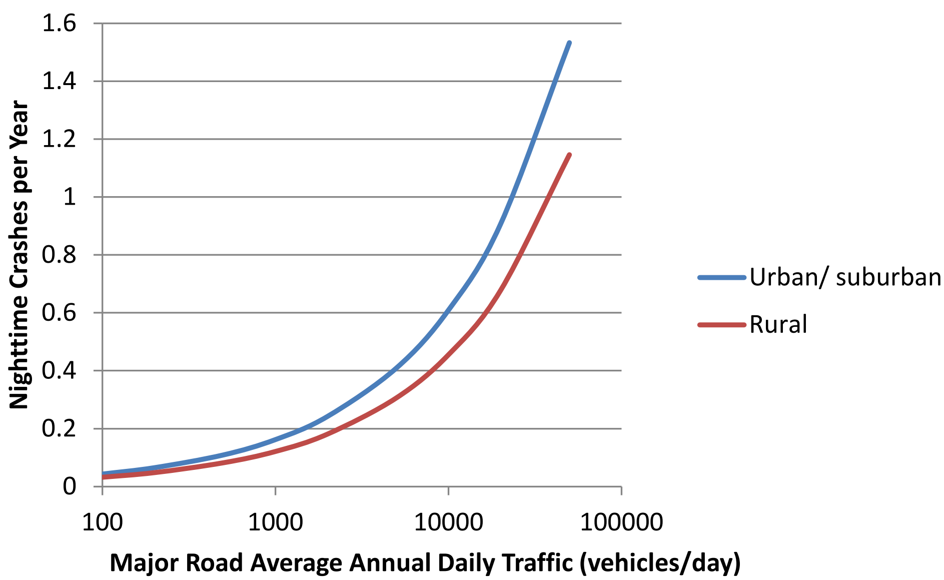


6.2 Economic Value of Avoided Crashes

The U.S. Department of Transportation (DOT 2008) developed cost estimates for crashes varying in severity. It is estimated that a crash involving a fatality represents an economic loss of $5.8 million, whereas a property-damage-only crash represents an economic loss of $4,462. Considering that driving speeds at urban/suburban signalized intersections are likely to be lower than at rural unsignalized intersections, the severity of crashes at the former type of intersection is also lower. Based on crash severity data from Minnesota intersections, it is estimated that the weighted-average cost of a crash at an urban/suburban signalized intersection is $122,056, and the weighted-average cost of a crash at an rural unsignalized intersection is $232,142.

Based on the provisional transfer function between visibility and safety shown in Figure 25, and on the visual improvements associated with roadway intersection lighting summarized in the previous chapter, the estimated nighttime crash reduction associated with roadway intersection lighting at urban/suburban signalized intersections is 5.3%, and at rural unsignalized intersections is 1.5%. Figure 27 shows how many nighttime crashes occur at each type of intersection when they are unlighted; it is seen that the number of crashes depends upon the traffic volume.

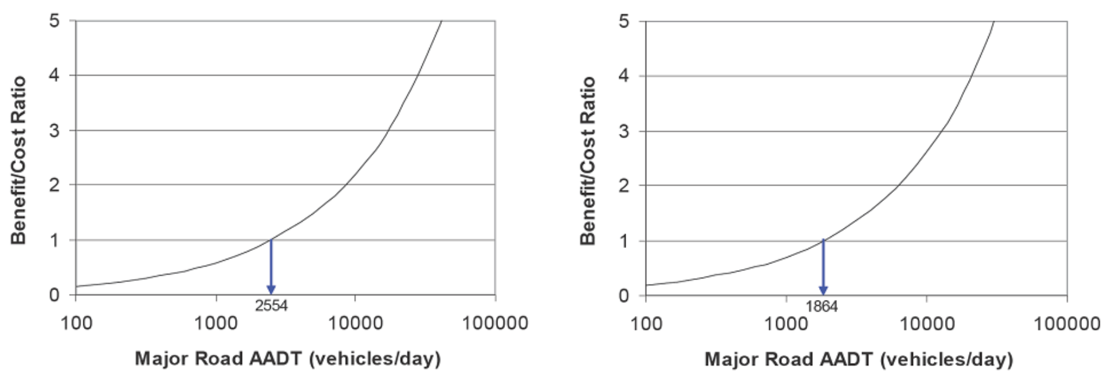
Figure 27. Number of nighttime crashes per year at unlighted urban/suburban intersections and at unlighted rural intersections as a function of traffic volume along the major road through the intersection



Based on the provisional transfer function, roadway intersection lighting should be expected to reduce the quantities shown in Figure 27 by 5.3% for urban/suburban signalized intersections, and by 1.5% for rural unsignalized intersections. It is therefore possible to estimate the number of nighttime crashes that could be avoided. Further, it is possible to estimate the economic value of these avoided crashes per year by multiplying the results by $122,056 for urban/suburban signalized intersections and by $232,142 for rural unsignalized intersections. These quantities can then be compared to the annual costs for lighting each intersection type ($1,790 for urban/suburban signalized intersections and $600 for rural unsignalized intersections) to determine a benefit-cost ratio associated with lighting. Figure 28 shows the benefit-cost ratios associated with roadway lighting at both types of intersections (Bullough and Rea 2011). As the traffic volume increases, the benefit-cost ratio also increases. It can be seen that the benefit-cost ratio for urban/suburban signalized intersections exceeds a value of 1.0 when the major road traffic volume exceeds 2,554 vehicles/day. For rural unsignalized intersections, a benefit/cost ratio of 1.0 is obtained when the traffic volume on the major road exceeds 1,864 vehicles/day.

Figure 28. Benefit-cost ratios for roadway intersection lighting as a function of major road traffic volume

a) Urban/suburban signalized intersections; b) rural unsignalized intersections.

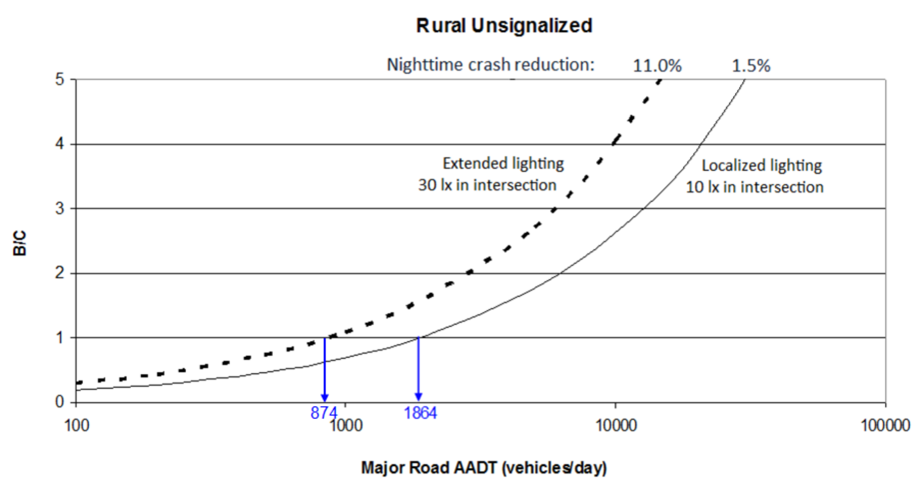


These analyses can be used as a model for developing policies and warrants for roadway lighting. Figure 28, which is based on data for Minnesota roadway intersections, suggests that the economic benefits of roadway intersection lighting occur when the major road traffic volume exceeds a certain value (2,554 vehicles/day for urban/suburban signalized intersections, and 1864 vehicles/day for rural unsignalized intersections).

6.3 Examples

This benefit-cost approach can be used to explore the economic implications of alternatives to typical roadway lighting practices. For example, it has been stated in the previous chapter that conventional rural intersection lighting practices do not appear to provide a substantial safety benefit, but that extending the lighting several hundred feet from the intersection and increasing the light level would provide a larger benefit, based on the provisional transfer function in Figure 25. Of course, doing so would also result in a higher cost since additional poles and luminaires would be needed, and the energy and maintenance costs would increase too. Figure 29 shows the benefit/cost ratio for rural unsignalized intersection lighting as typically practiced, and for the extended and increased lighting previously discussed. Despite its higher cost, the safety benefit would also be higher (11% reduction in nighttime crashes, compared to 1.5% for conventional lighting), so that a benefit-cost ratio of 1.0 would be reached when the major road traffic volume were only 874 vehicles/day rather than1,864 vehicles/day.

Figure 29. Benefit-cost ratios for two types of roadway intersection lighting at rural unsignalized intersections, as a function of major road traffic volume.



The benefit-cost approach can also be used to assess the value of adaptive roadway lighting. Traffic volume (and hence traffic crashes) at night rarely occurs uniformly throughout the night. It is estimated that 61% of nighttime traffic (Ivan et al. 2002) and 50% of nighttime crashes (Bullough and Rea 2011) occur during the busiest four hours of the 12-hour nighttime period. Clearly, lighting will not have the same benefit at all hours of the night. Using the same rural unsignalized intersection as an example, it is possible to use the transfer function and benefit/cost analyses to compare an adaptive lighting schedule to a conventional, dusk-to-dawn lighting regimen. The adaptive lighting schedule in this example is to triple the light level used for rural unsignalized intersection lighting, but to use this higher level only during the busiest four hours of the night. During the remaining eight hours, the roadway lighting would be switched off. Such a schedule would result in approximately the same costs for the lighting system, because the energy use would be tripled but the duration of use would be reduced by a factor of three.

It needs to be emphasized that this example is not a recommendation. There are many reasons not to switch roadway lighting off completely for part of the night. Providing some illumination for pedestrians crossing the intersection late at night is just one reason not to switch lighting off. Nonetheless, it is possible to estimate the impact on nighttime crash frequency of the example adaptive lighting schedule previously described.

Using the provisional transfer function in Figure 25, it is estimated that the visual performance improvement from an increased light level would correspond to a 5.6% reduction in nighttime crashes (compared to a reduction of 1.5% from conventional lighting). However, because the lighting would only be switched on for the busiest four hours, it would only reduce half of the crashes by a percentage of 5.6%, with an overall net reduction of 2.8%. Therefore, the example adaptive lighting schedule would result in an estimated nighttime crash reduction of 2.8%, nearly double the estimated reduction from conventional lighting, but with approximately the same annual cost of installation and operation.

These examples show how the approach outlined in this chapter can be used to evaluate the impacts of new lighting schedules and configurations.

7 New Approaches to Roadway Lighting

Up to this point the discussion of roadway lighting has been largely based on conventional, pole-mounted overhead lighting that often uses HPS lamps, although the use of LED sources and other lamp types is increasing. In this chapter, several alternative approaches to designing and specifying roadway lighting are discussed.

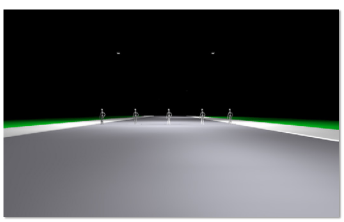
7.1 Bollard-Based Pedestrian Lighting

In many areas, pedestrian crosswalk lighting uses conventional overhead lighting systems, but these systems are not necessarily optimized to produce high levels of visibility of pedestrians by drivers approaching the crosswalks. Figure 30a shows a rendering of overhead crosswalk lighting and several pedestrians. Sometimes the pedestrians are brighter than their backgrounds, and sometimes they are darker. This transition between positive and negative contrast can result in poor visibility.

Figure 30. Crosswalk Lighting

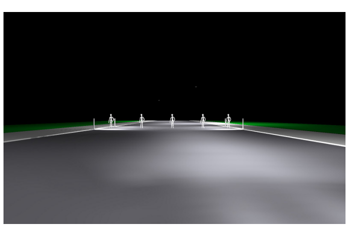
a) Conventional overhead crosswalk lighting; b) Bollard-based crosswalk lighting.

a.



Pedestrian location no.	Object luminance (cd/m²)	Background luminance (cd/m²)	Contrast	RVP	Vertical illuminance (fc)
1	0.1	0.344	-0.709	0.946	0.2
2	0.15	0.135	0.114	0.635	0.3
3	0.25	0.198	0.261	0.878	0.6
4	0.25	0.374	-0.332	0.921	0.6
5	0.15	0.322	-0.535	0.937	0.3

b.



Pedestrian location no.	Object luminance (cd/m²)	Background luminance (cd/m²)	Contrast	RVP	Vertical illuminance (fc)
1	0.6	0.210	1.855	0.953	2.3
2	0.9	0.190	3.734	0.956	3.3
3	0.6	0.172	2.495	0.952	2.2
4	0.9	0.245	2.680	0.958	2.7
5	0.6	0.354	0.697	0.947	2.2

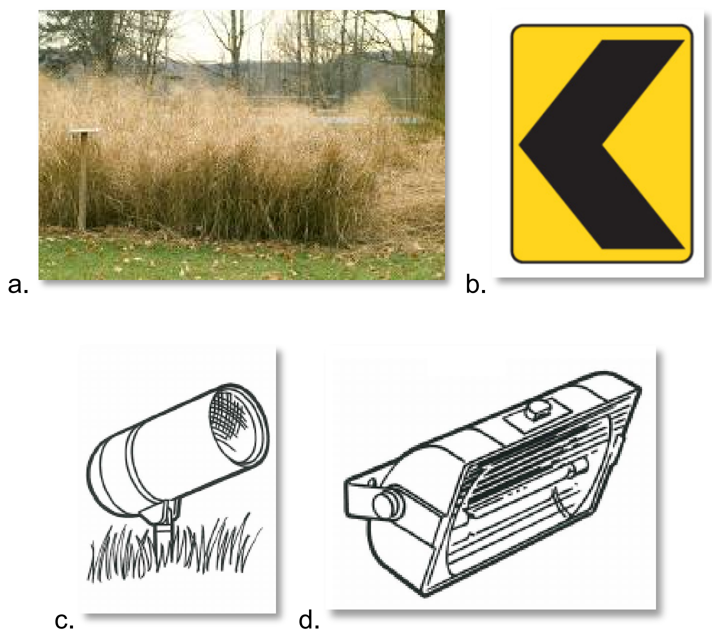
An alternative approach (Figure 30b) used in a study for the New Jersey DOT (Bullough et al. 2009a), and subsequently evaluated in Aspen, Colorado (Bullough and Rea 2013), uses bollard luminaires to provide vertical illumination along the crosswalk. This increases the luminance of pedestrians, while keeping the luminance of the background lower, and enhancing contrast. This increases visibility of pedestrians by drivers, according to the relative visual performance (RVP) model. As an aside, this approach to lighting can use substantially less energy than overhead lighting as well. The bollard approach was judged favorably by transportation agencies, transit authorities, police departments, and the general public in field demonstrations.

7.2 Ecoluminance

Building on the idea of increasing contrast and providing visual information rather than simply providing a blanket of illumination from overhead roadway lighting, a concept called ecoluminance (Bullough et al. 2009b) was developed to use both illuminance from controlled, localized lighting systems such as the previously described crosswalk bollards, and luminance from reflected surfaces, retroreflective devices, and in some cases from vegetation, to enhance delineation of roadways. The elements of the ecoluminance toolbox are shown in Figure 31.

Figure 31. Ecoluminance Concept Elements

a) Vegetation; b) retroreflective devices; c) low level landscape lighting; d) controlled optical systems for providing illuminances as needed.



A promising application for the ecoluminance approach is roundabouts. Roundabouts are usually illuminated by a large number of overhead pole-mounted luminaires and can be energy-intensive. Following a series of computer simulations (Figure 32) and visual performance analyses (Table 2), a full-scale field installation was conducted in Albany County, NY (Bullough et al. 2012). The demonstration used vegetation in the central roundabout island, LED landscape lighting to illuminate vegetation (Figure 33), glass retroreflective markers located around the perimeter of the island, bollard-based crosswalk lighting, and low-level LED lighting along sidewalks between entrances to the roundabout.

Figure 32. Lighting Roundabouts

Rendering of a) conventional overhead lighting at a roundabout; b) ecoluminance approach to roundabout lighting. Note the increased contrast of the pedestrian at the right of the image.

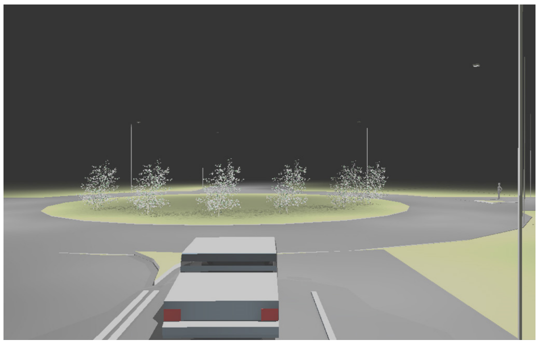
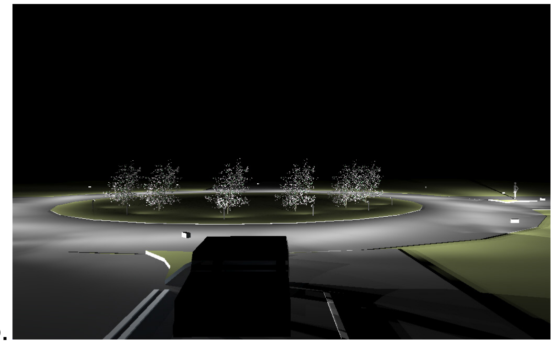
a.  b. 

Table 2. Luminances, contrast, and RVP values for roadway elements for lighting roundabouts under a) conventional, and b) ecoluminance approach

Object	Average Luminance (cd/m²)	Contrast	RVP Value
Roadway	1.2	n/a	n/a
Grass	2.2	0.45	0.945
Vegetation	n/a	n/a	n/a
Pedestrian	0.95	0.21	0.902

Object	Average Luminance (cd/m²)	Contrast	RVP Value
Roadway	0.3	n/a	n/a
Grass	0.1	0.67	0.929
Vegetation	0.5	0.8	0.935
Pedestrian	4	0.93	0.939

Figure 33. Vegetation and landscape lighting installed at a roundabout

7.3 Mesopic Vision

Photometric units like fc, lx and cd/m² are used to define and specify lighting quantities, but there is a growing awareness that they do not predict all aspects of human vision, particularly at night. The dynamic range of human vision covers levels from damaging sunlight to objects viewed under starlight-only levels, a range of more than a billion to one. Part of the way that the human visual system copes with this large range is by having two types of visual photoreceptor systems in the eye, one (photopic) that deals primarily with high, daytime light levels (cones) and another (scotopic) that deals mainly with very low, nighttime levels. Conventional photometric quantities are based only on the photopic response. However, most roadway lighting conditions occur at levels, known as mesopic light levels, where both cones and rods participate in seeing. Cones and rods respond differently to different parts of the visible spectrum (Figure 34); the cone (photopic) system is maximally responsive to green-yellow light, and the rod (scotopic) system is maximally sensitive to blue-green light.

Figure 34. Spectral (color) sensitivity of rods (blue curve, left) and cones (green curve, right) in the human eye

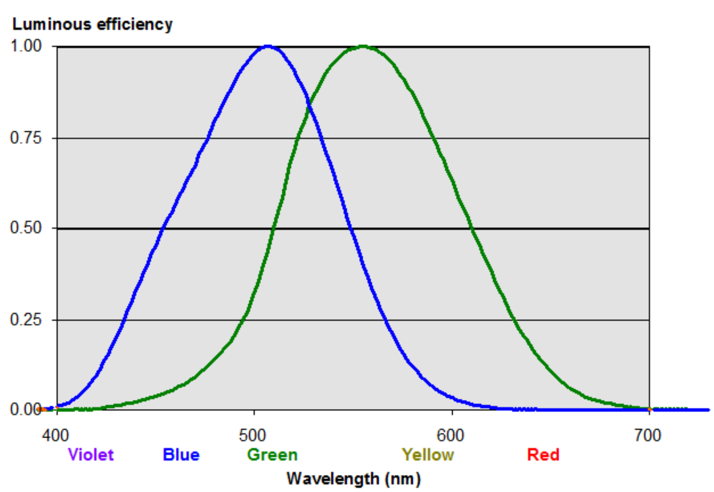


Figure 35. Typical spectral power distributions and S/P ratios for a) HPS, b) MH and c) LED light sources

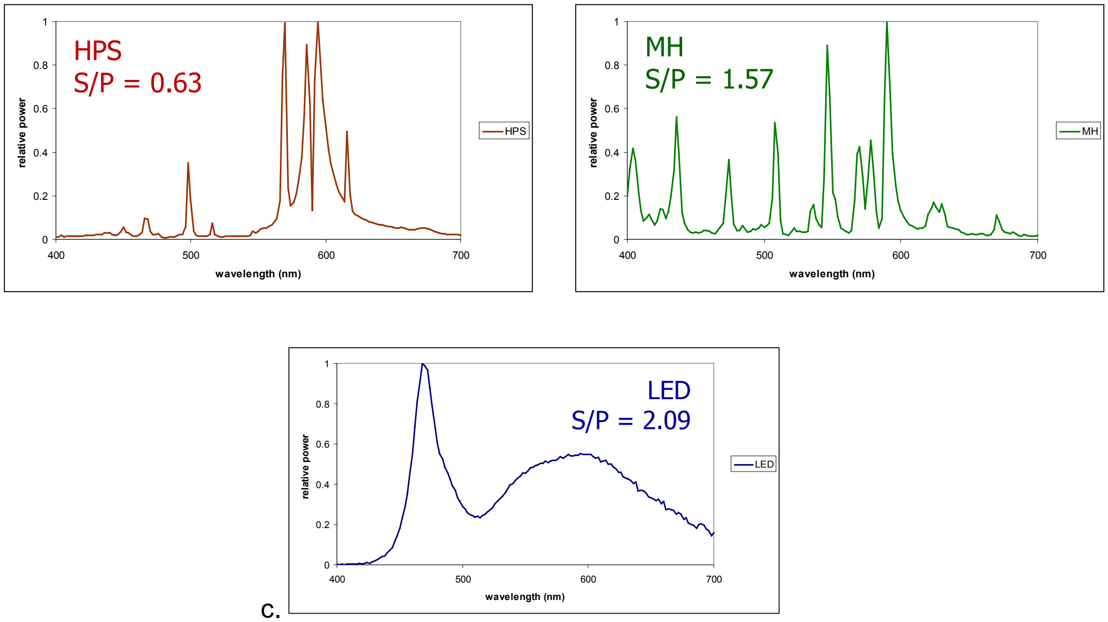


Figure 35 shows typical spectral distributions for three light sources: HPS, MH, and an LED source. HPS produces mainly light in the yellow portion of the spectrum (and hence, HPS appears yellowish), while MH and LED sources distribute light throughout the visible spectrum, resulting in a white color appearance. Figure 35 also shows the scotopic/photopic (S/P) ratios of each light source, an indication of the relative amount of rod stimulation from each source when equated for cone stimulation. The HPS lamp produces little rod-stimulating energy and has a low S/P ratio compared to MH and LED.

Figure 36. Response times to peripheral targets viewed under HPS and MH illumination, as a function of the light level

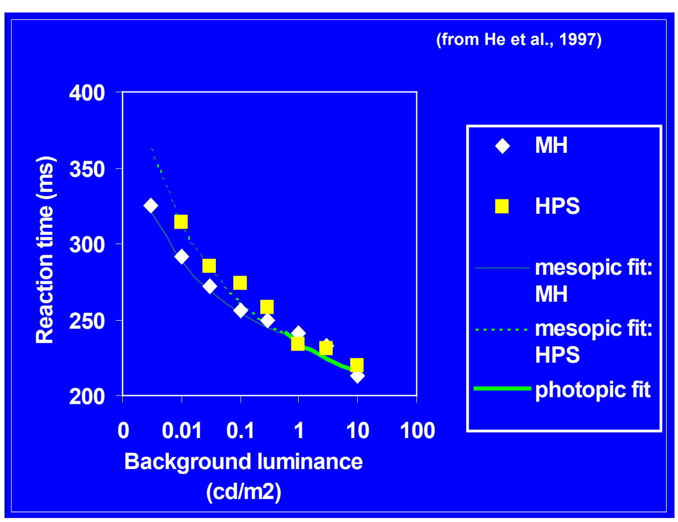
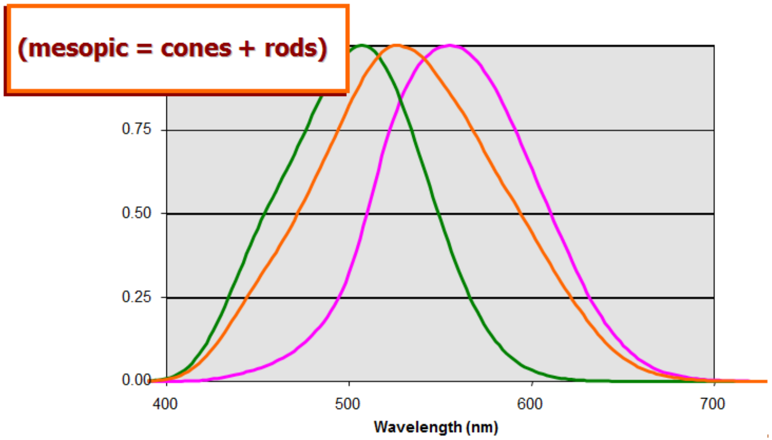


Figure 37. Spectral sensitivity of the cone (fuchsia curve) and rod (green curve) systems, and the combined sensitivity for one mesopic light level (orange curve)

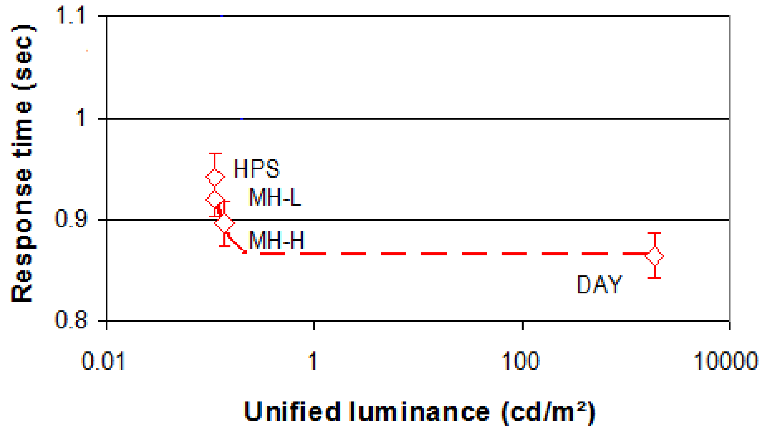


The consequence of different S/P ratios can be seen in Figure 36 (He et al. 1997). Response times to off-axis targets are similar under HPS and MH illumination at relatively high light levels (>1 cd/m²) but as the light level drops below this value and cone + rod or mesopic vision occurs, MH illumination produces shorter response times compared to HPS. Such data were used to develop a new way to quantify light for mesopic vision by combining the responses of cones and rods (Figure 37).

Importantly, laboratory findings like those in Figure 36 have been extended to actual driving conditions. Akashi et al. (2007) found, as illustrated in Figure 38, that braking times to off-road hazards were shorter when the road was illuminated to 0.9 fc from MH (denoted MH-H) than when it was illuminated to 0.9 fc from HPS. In fact, the light level from MH could be reduced to 0.5 fc (denoted MH-L) and the braking times to off-axis hazards were statistically equivalent. Figure 38 shows that the unified, mesopic vision model illustrated in Figure 37 properly rank ordered the measured response times in the study by Akashi et al. (2007).

Figure 38. Braking times in response to off-road hazards as a function of unified luminances of the targets

Illuminances on the roadway were: HPS (0.9 fc), MH-H (0.9 fc), MH-L (0.5 fc), DAY (approximately 2000 fc).



Assuming HPS is the baseline light source for most roadway lighting, and using mesopic vision as a criterion for selecting light levels, it is possible to trade off the light level from light sources with relatively higher S/P ratios than HPS as illustrated in Table 3. In this table, rows designate light source with varying S/P ratios, and the columns designate various photopic luminance values. As an example, the IES (2000) recommends illuminating local residential roads to a luminance of 0.3 cd/m². Because the S/P ratio of HPS lamps is near 0.65 (see Figure 35), Table 3 indicates that the resulting mesopic (or unified) luminance is 0.2639 cd/m² as shaded in the table.

If an LED with a spectral distribution similar to that in Figure 35 were used, having an S/P ratio near 2.05, an equivalent mesopic luminance would be produced under this light source when the measured photopic luminance were not 0.3 cd/m² but rather 0.2 cd/m², which has a mesopic luminance of 0.2705 cd/m², also shaded in Table 3. In this example, the measured light level under the LED source (and the resulting energy use) could be reduced by 33% while maintaining equivalent vision as under the HPS light source. An online publication from the Alliance for Solid State Illumination Systems and Technologies (ASSIST 2009) entitled "Outdoor Visual Efficacy" describes how to compare light sources varying in S/P ratio at any light level in the mesopic range.

Table 3. Mesopic (unified) luminances under light sources varying in S/P ratio (rows) at different measured photopic luminances (columns); shaded cells refer to the example in the text

	Base light level (photopic luminance (cd/m^2))											
S/P	**0.14**	**0.16**	**0.18**	**0.20**	**0.22**	**0.24**	**0.26**	**0.28**	**0.30**	**0.32**	**0.34**	**0.36**
0.25	0.0573	0.0704	0.0849	0.1009	0.1184	0.1373	0.1574	0.1788	0.2012	0.2246	0.2487	0.2736
0.45	0.0864	0.1026	0.1197	0.1377	0.1565	0.1760	0.1963	0.2172	0.2387	0.2607	0.2831	0.3060
0.65	0.1092	0.1273	0.1459	0.1649	0.1844	0.2043	0.2245	0.2451	0.2659	0.2871	0.3085	0.3301
0.85	0.1283	0.1477	0.1672	0.1869	0.2068	0.2268	0.2470	0.2672	0.2876	0.3081	0.3286	0.3492
1.05	0.1448	0.1651	0.1853	0.2054	0.2255	0.2456	0.2656	0.2856	0.3055	0.3254	0.3452	0.3651
1.25	0.1593	0.1803	0.2010	0.2215	0.2417	0.2617	0.2816	0.3013	0.3208	0.3402	0.3594	0.3786
1.45	0.1724	0.1940	0.2150	0.2357	0.2560	0.2759	0.2956	0.3150	0.3341	0.3531	0.3718	0.3903
1.65	0.1843	0.2063	0.2276	0.2484	0.2687	0.2886	0.3081	0.3272	0.3460	0.3645	0.3827	0.4007
1.85	0.1952	0.2175	0.2391	0.2599	0.2802	0.3000	0.3193	0.3381	0.3566	0.3747	0.3924	0.4099
2.05	0.2053	0.2279	0.2496	0.2705	0.2907	0.3103	0.3294	0.3480	0.3661	0.3838	0.4012	0.4182
2.25	0.2146	0.2374	0.2592	0.2801	0.3003	0.3198	0.3387	0.3570	0.3748	0.3922	0.4091	0.4257

An informational brochure posted on the NYSDOT website entitled "New Lighting Technologies and Roadway Lighting" (LRC 2012) describes how light sources such as LEDs and induction lamps could be used to replace HPS lighting systems, while maintaining visual effectiveness and reducing energy use. The brochure focuses on several roadway types including parkways, residential streets, and rural intersections.

Figure 39. Pedestrian Perception of Outdoor Lighting Situations

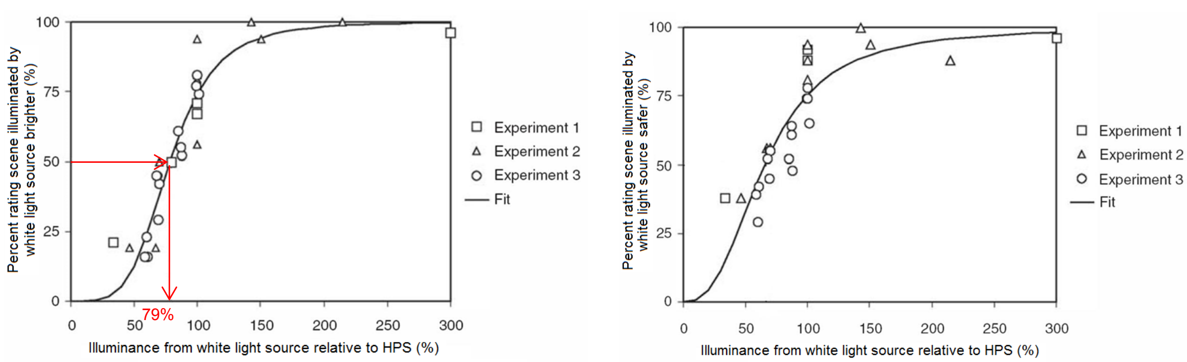
Pedestrians tend to judge outdoor scenes as brighter under MH lamps (left) than under HPS lamps (right), even if the light levels are the same.

7.4 Brightness and Safety Perceptions

Most of the information in this report has focused on roadway lighting and its impacts on traffic safety, but pedestrians are also important roadway users in many locations. When roadways and their adjacent sidewalks are illuminated by HPS lamps, or to the same measured light levels by lamps such as MH or LED sources with white color appearance, people tend to judge the brightness of the roadway scene as greater under the white light source (Figure 39). In fact, Rea et al. (2009) found that a street scene illuminated by a warm white MH lamp (2800 K CCT) was judged as equally bright when the illuminance was only 79% of the illuminance from a yellowish HPS lamp (Figure 40a). Interestingly, very similar trends were also found when pedestrians were asked to judge the appearance of personal safety and security (Figure 40b) under HPS and MH lighting installations varying in light level, suggesting that brightness perception can be a surrogate measure for a sense of personal security by pedestrians.

Figure 40. Perception of Scene Brightness

a) Scene brightness under HPS lamps was judged as equal to that under MH when the MH illuminance was only 79% of the HPS illuminance. b) Similar trends were found for judgments of personal safety and security under the two light sources.



In a later series of experiments, Rea et al. (2011) demonstrated that scene brightness under outdoor illumination had a different underlying mechanism than mesopic vision, and that a cone mechanism sensitive to "blue" light can be used to develop a metric for scene brightness. This metric (Rea 2013) can be used to design roadway lighting from different light sources, such as HPS and LED, that will result in equivalent perceptions of brightness and of personal safety and security by pedestrians. For example, the illuminance from an LED source similar in spectral content to that in Figure 35 will be judged as equally bright, and equally safe and secure as the illumination from an HPS lamp, but when the measured illuminance from the LED source is only 54% of the illuminance from HPS.

These findings can have important energy-savings (and light-pollution-reducing [Brons et al. 2008]) implications for roadway lighting when pedestrians’ perceptions of personal security are important, as in many urban locations.

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Final Report
July 2014

NYSERDA Report 14-28
NYSDOT Task C-13-05