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Cost- and Energy-Efficient (LED, Induction and Plasma) Roadway Lighting

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JOINT TRANSPORTATION RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION
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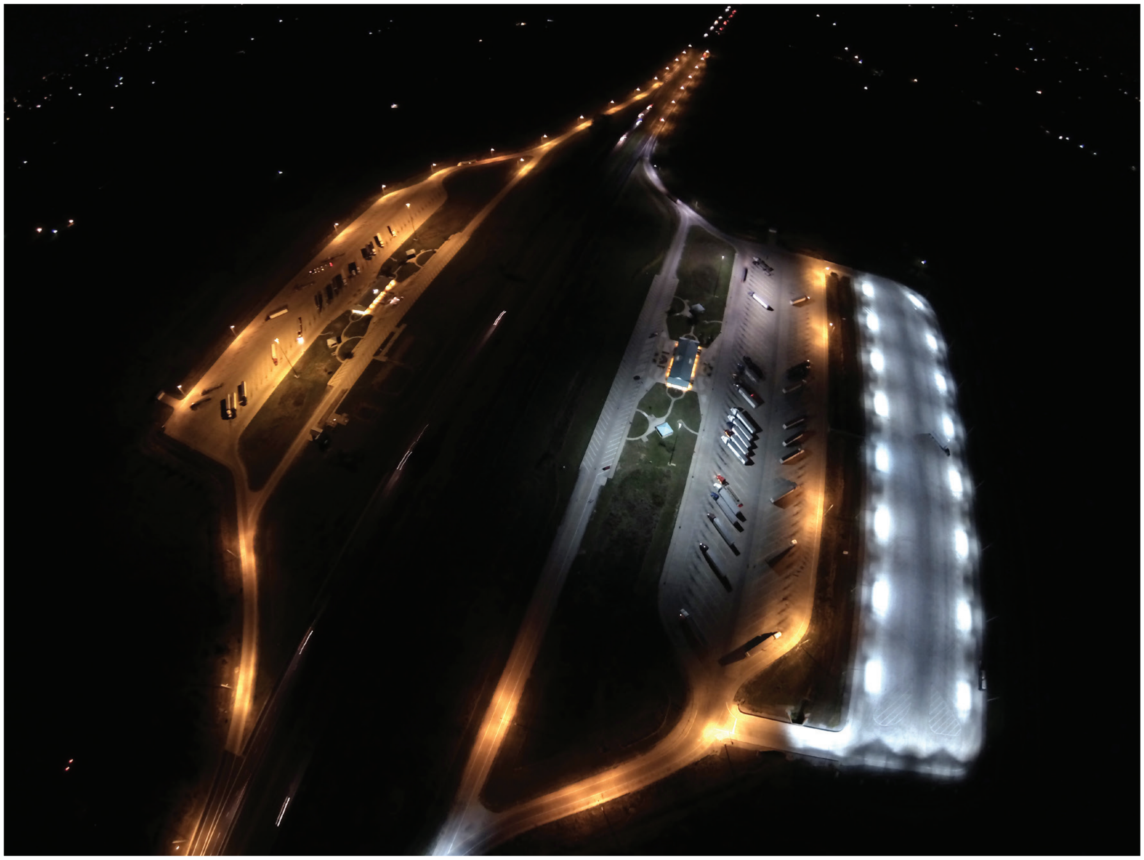
Cost- and Energy-Efficient (LED, Induction and Plasma) Roadway Lighting



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16. Abstract

There is an increasing interest in using new lighting technologies such as light emitting diode (LED), Induction, and Plasma light sources in roadway lighting. The most commonly claimed benefits of the new lighting systems include increased reliability, improved efficiency, and reduced maintenance costs. While Indiana Department of Transportation (INDOT) is also getting a lot of interest from vendors pushing the new light sources for roadway lighting applications, none of these new lighting technologies has been used in the state highway systems by INDOT. Before adopting the new lighting technologies, INDOT would like to determine if the new lighting technologies meet required light output and if they are cost effective. Moreover, it is necessary for INDOT to establish standardized guidelines for evaluating the new lighting systems prior to the formal adoption.

This study first conducted literature reviews on the new lighting technologies. Surveys were also conducted to identify the perceptions of state highway agencies and local cities towards the new lighting technologies including LED, Induction, and Plasma, and their experiences in use of these new lighting technologies. Various luminaires, including HPS, LED, Plasma, and Induction luminaires from different manufacturers were installed and evaluated for both conventional and high mast lightings at a test site over a period of 12 months. Illuminance measurements were made to determine the light levels and illuminance uniformities produced by those LED, Plasma and Induction luminaires with the existing lighting infrastructures. Comparisons were also made between the light performances produced by different luminaires. Electric currents were measured to determine the energy consumptions by different luminaires. Life cycle cost analysis was also conducted to determine if the new lighting sources are cost-effective compared to the corresponding HPS lighting sources and assess the possible return or payback periods for the LED, Plasma, and Induction luminaires evaluated in this study. Illuminance measurements were also made for two urban street lightings to map the light performances of LED and Plasma luminaires with different lighting layouts.

Main findings and recommendations were made to assist INDOT Traffic Engineering in upgrading the lighting policies and developing technical specifications for adopting the new lighting technologies.

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EXECUTIVE SUMMARY

COST- AND ENERGY-EFFICIENT (LED, INDUCTION AND PLASMA) ROADWAY LIGHTING

Introduction

There is an increasing interest in using new lighting technologies such as light emitting diode (LED), induction, and plasma light sources in roadway lighting. The most commonly claimed benefits of the new lighting systems include increased reliability, improved efficiency, and reduced maintenance costs. While the Indiana Department of Transportation (INDOT) is also getting a lot of interest from vendors pushing the new light sources for roadway lighting applications, none of these new lighting technologies have been used in the state highway systems by INDOT. Before adopting the new lighting technologies, INDOT would like to determine if the new lighting technologies meet required light output and if they are cost effective. Moreover, it is necessary for INDOT to establish standardized guidelines for evaluating the new lighting systems prior to the formal adoption.

This study first conducted literature reviews on the new lighting technologies. Surveys were also conducted to identify the perceptions of state departments of transportation (DOTs) and local cities towards the new lighting technologies including LED, induction, and plasma, and their experiences in use of these new lighting technologies. Various luminaires, including HPS, LED, plasma, and induction luminaires from different manufacturers, were installed and evaluated for both conventional and high mast lightings at a test site over a period of 12 months. Illuminance measurements were made to determine the light levels and illuminance uniformities produced by those LED, plasma and induction luminaires with the existing lighting infrastructures. Comparisons were also made between the light performances produced by different luminaires. Electric currents were measured to determine the energy consumptions by different luminaires. Life cycle cost analysis was also conducted to determine if the new lighting sources are cost-effective compared to the corresponding HPS lighting sources and assess the possible return or payback periods for the LED, plasma, and induction luminaires evaluated in this study. Illuminance measurements were also made for two urban street lightings to map the light performances of LED and plasma luminaires with different lighting layouts.

Main findings and recommendations were made to assist INDOT Traffic Engineering in upgrading the lighting policies and developing technical specifications for adopting the new lighting technologies.

Findings

Roadway Lighting Surveys

LED lighting technology is probably the most attractive new lighting technology for DOTs, followed by the induction lighting technology. Local cities seem very receptive to new lighting technologies and are also more attractive to LED lighting than to induction and plasma lighting technologies.

Both DOTs and local cities have adopted new lighting technologies for these very same reasons, including maintenance saving, energy saving, and better light performance. In the Midwest, Michigan adopted new lighting technologies mainly for energy savings, and Ohio adopted LED lighting for both maintenance savings and longer lamp life. No DOT intends to pursue savings by sacrificing lighting performance. Federal grants have also played a role in adopting new lighting technologies by local cities.

The main barriers for DOTs to adopt the new lighting technologies are the concerns about light level and luminous efficacy and savings unconvincing. In the Midwest, some DOTs indicated the need for specifications to adopt new lighting technologies and also raised concerns about the performance of induction lighting.

Induction lighting has been used by some DOTs much earlier than LED and plasma lightings. The adoption of LED lighting by DOTs commenced approximately 3 years ago (baseline year: 2012). Plasma lighting is relatively new and its use by DOTs started approximately in 2011. Local cities started to use LED lighting at approximately the same time as DOTs. Induction and plasma lightings have recently started to find a way into street lighting.

For DOTs, LED lighting has been used for conventional, high mast and decorative lightings on roadways with different functional classifications in both rural and urban areas. LED lighting has also been used at interchange, intersection and parking lot. Induction lighting has been used for interstate lighting and tunnel and underpass lighting by several DOTs. Florida has uses induction lighting as the primary light source for sign lighting. Plasma lighting has been used for parking lot lighting so far. In the Midwest, LED lighting has been used for interstate, US highway and off-highway lighting, and induction lighting for interstate lighting. LED lighting has recently received increasing use in roadway lighting. For local cities, LED lighting has been used on urban roadways of different classifications at different locations. Use of the induction or plasma lighting is still limited in urban street lighting.

The average service life expected by DOTs is approximately 13, 15, and 10 years for LED, induction, and plasma lighting, respectively. The average LCC is approximately $80, $70, and $122 for LED, induction, and plasma lighting, respectively. Induction lighting was perceived to have the longest service life and the plasma lighting to have the greatest LCC. The expected average service life expected by local cities is about 16 years for LED lighting, longer than induction or plasma lighting. The service life of induction lighting has not lived up to the expectation so far.

In use of the new lighting technologies by DOTs, the top issue is the light performance. Issues also arose with electronic driver and surge protection. Early failures were observed for induction luminaires. For local cities, the major issues in use of new lighting technologies are surge protection and electronic driver failure. Issues also arose with the installation, particularly with use of the existing pole infrastructure.

Both DOTs and local cities are commonly using specifications from the manufacturers or vendors currently. Several DOTs are in the process of developing LED lighting specifications.

New lighting technologies, particularly LED lighting, have made great progress in roadway lighting for highway and urban street lightings. However, many DOTs are looking forward to some kind of national guidance from AASHTO or FHWA.

Field Installation

For Phillips RVM LED, basically, every aspect was user friendly. The fixtures are lighter and easier to hold and level. For GE ERS4 LED, the fixtures are a little heavier and a little difficult to level. However, they were a solid unit and the internal access was user friendly. For Stray Light Tesla II plasma, the fixtures were easy to install and level. The electrical connections are also very user friendly and easy to access. For EcoLuminator induction, the fixtures were the most time consuming and difficult to install. They were heavier than the other three types of fixtures. The terminal block is more difficult to access and has a small screw termination. No issues were identified in installation with other fixtures.

Light Distribution

In conventional lighting, HPS, GE LED and Philips LED luminaires produced oval-shaped lighted areas and the Horner LED and EcoLuminator induction luminaires produced circular lighted areas. The illuminance measurements demonstrated a double-hump distribution for the GE LED luminaires and a single hump distribution for all other new luminaires. Compared to HPS 250W luminaires, the GE LED 258W luminaires were capable of producing a larger lighted area and the Philips LED 270W luminaires were capable of producing an equivalent lighted area in terms of the area size. The areas lighted by the Horner LED 200W and EcoLuminator induction 200W luminaires were both less than the areas lighted by the HPS 250W luminaire. However, the areas lighted by the HPS 400W luminaires are greater than those lighted by all LED luminaires and the plasma 295W luminaires, particularly the Horner LED and plasma luminaires.

All LED, plasma, and induction luminaires produced measureable illuminance, i.e., 0.05 foot-candles or greater between the lighting poles. The percentages of grid points with illuminance of 0.2 foot-candles are 71%~98% for HPS 400W, 73%~98% for HPS 250W, 88%~96% for GE LED, 68%~94% for Philips LED, 52%–60% for Horner LED, 49% for Stray Light plasma and 45% for EcoLuminator induction.

In high mast lighting, both HPS 1000W and SoLtice 392W LED luminaires produced a symmetrically lighted, circular area covered with illuminance measurements 100% greater than 0.20 foot-candles. The light illuminance produced by the 1000W HPS luminaires was greater than that by the SoLtice 392W luminaires.

Illuminance Metrics

Compared to HPS 250W luminaires, both the GE 258W and Philips 270W LED luminaires produced similar minimum illuminance and the Horner LED and EcoLuminator induction 200W luminaires produced smaller minimum illuminance. The maximum illuminance values produced by all LED and induction luminaires are all greater than the corresponding maximum illuminance value by the HPS 250W luminaires. The GE LED produced the greatest average illuminance and the Horner LED produced the smallest average illuminance. The average illuminance produced the Philips LED is close to the by the HPS luminaires. The illuminance uniformity ratio produced by Philips LED is slightly better than that by the HPS 250W. The illuminance uniformity ratio produced by the GE LED luminaires is slightly greater than that by the HPS 250W. The illuminance uniformity ratios produced by both the Horner LED and EcoLuminator induction luminaires are much greater than those produced by the GE LED, Philips LED and HPS luminaires.

Compared to HPS 400W luminaires, both LED and plasma luminaires produced smaller minimum, maximum and average illuminance values. The illuminance uniformity ratios produced by the LED and plasma luminaires are greater than those by the HPS luminaires. In addition, both GE and Philips LED luminaires produced greater average illuminance and smaller illuminance ratio values than the Horner LED and Stray Light plasma luminaires.

It was demonstrated that in the urban street lightings, both LED and plasma luminaires are capable of providing better light performance, including illuminance level and uniformity ratio, with appropriate lighting layout.

For high mast lighting, the SoLtice 392 E LED luminaires produced smaller illuminance levels but better uniformity than the HPS 1000W luminaires.

The rankings through field observations by the SAC members agreed well with the field illuminance measurements and indicated that the new lighting sources produced sufficient light levels and GE and Philips provided better light performance in terms of light level and uniformity.

Power Metrics

The measured electric currents for LED, plasma and induction luminaires varied around 1.0 A, regardless of the lamp watts, and are less than the electric currents for not only the HPS 400W luminaires, but the HPS 250W luminaires as well. For high mast lighting, the electric currents for the LED 392W luminaires are much less than those for the HPS 1000W luminaires.

Compared to the HPS 250W luminaires, the calculated energy saving is 12% to 20% for LED luminaires, 12% for the 295W plasma luminaire, and up to 25% for the 200W induction luminaire. Notice that the GE LED, Philips and Stray Light plasma luminaire sizes are all greater the HPS 250W luminaire. Compared to the HPS 400W luminaires, the energy savings produced by the new luminaires varied between 44% and 52%. For high mast lighting, the energy consumed by the SoLtice LED 392W luminaires is 70% much less than the by the HPS 1000W luminaires.

Life Cycle Costs

The lower life cycle costs of the alternative lighting devices are attributed to their relatively lower electricity usages and longer lamp/emitter replacement cycles. All of the alternative new luminaires, including LED, plasma, and induction, are more cost effective than the existing 400W HPS lights under various discount rates and lamp replacement cycles. In comparison with the existing 250W HPS lights, only the 200W induction luminaire among the six alternative lighting devices is more cost effective. For high mast lighting, the 392W LED luminaires are more cost effective than the 1000W HPS luminaires. With the huge difference in electricity usages between the 392W LED and 1000W HPS luminaires, the LED luminaires will break even within 4 years.

The discount rate and the lamp/emitter replacement cycle affect the life cycle costs as well as the return periods as shown in this study. An MS Excel based worksheet, INDOT Lighting LCCA, has been developed in this study. The software makes it easy for INDOT engineers to perform life cycle cost analysis. The software can be used beyond this study by INDOT to conduct life cycle cost analysis for new lighting systems. It is recommended that the software be used to conduct thorough cost evaluations for possible new lighting systems in addition to other types of field evaluation.

Implementation

The GE 258W, Philips 270W and Horner 200W LED luminaires are capable of producing light levels equivalent to the HPS 250W luminaires. The light levels produced by these three types of LED luminaires may be lower than those by the HPS 400W luminaires, but all meet the light level requirements for most roadway lighting applications. The GE 258W and Philips 270W LED luminaires are capable of producing an illuminance uniformity ratio equivalent to that by the HPS 250W luminaires. While the illuminance uniformity ratios produced by the GE 258W and Philips 270W LED luminaires are greater than those by the HPS 400W luminaires, neither the HPS nor the new alternative luminaires could meet the illuminance uniformity requirements. In reality, the Cooper 232W LED luminaires on an urban street demonstrated satisfactory light performance in terms of both light level and uniformity. No failures arose with any of the LED luminaires over the study period. The energy savings ranged from 16% to 49% with the LED luminaires. Seemingly, the

LED lighting has matured to the point where roadway lighting can start to take advantages of all that LED lighting offers. It is recommended that GE 258W, Philips 270W, and Horner 200W LED luminaires may be used to replace the HPS 250W luminaires with the existing lighting poles. The GE 258W and Philips 270W LED luminaires may also be used to replace the HPS 400W luminaires.

The Stray Light plasma 295W luminaires are also capable of producing light levels close to that by the HPS 250W. However, this type of plasma luminaire may be unable to provide light performance. In particular, the plasma luminaires may produce very poor light uniformity compared to that produced by the HPS 400W luminaires. Early failures, as indicated in the roadway lighting surveys, also arose with the plasma luminaires in this study after around 12 months in service. However, the test results on the plasma street lighting in a local city indicated that the plasma lighting is capable of producing satisfactory light performance with appropriate lighting layout and eliminating early failure with appropriate design and integration. It is recommended that plasma may be used in lighting applications for minor streets, residential areas, and parks. However, special care should be exercised about the quality of luminaire products due to the manufacturing variations.

Failures with induction luminaires were not only indicated in the roadway lighting surveys, but observed with the induction luminaires in the early stage of this study as well. There is no doubt that the induction technologies themselves are probably reliable. However, the integration of those technologies into a luminaire for roadway lighting in an outdoor environment may not be mature. While it is evident that induction lighting has the potential to achieve great energy savings, its early failures make induction lighting not live up to expectations if taking into consideration the high initial cost. Therefore, it is recommended that at present, more field evaluation is needed on more induction light products before the adoption lighting in roadway lighting applications.

The SoLtice LED 392W luminaires for high mast lighting not only produced satisfactory light performance, but also produced up to 70% energy savings. It is recommended that the SoLtice LED 392W luminaires may be used to replace the HPS 1000W luminaires in high mast lightings with the existing lighting poles.

The potential concern associated with use of the new lighting is the light uniformity. While it was demonstrated that both LED and plasma lighting technologies are capable of producing satisfactory illuminance uniformity ratio with appropriate lighting layout in urban street lighting, it is recommended that the further efforts should be made by manufacturers to enhance the light uniformity for roadway lighting applications with the existing lighting poles.

The new lighting technologies have just started to find a way into roadway lighting applications and their effects on driving are not fully understood yet. There is no urgent need to change the lighting design criteria at present to adopt the new lighting technologies for roadway lighting applications. Field application data on the long term performance and reliability is still needed for future revision of the design criteria for the new lighting technologies.

The light performance data was collected over a 12-month period and it may be too early to evaluate the new lighting technologies thoroughly. However, early indications are that the new lighting sources are inherently energy-saving, particularly for high mast or area lightings.

Based on the life cycle cost analysis, the return or payback period is 13 years or more for replacing HPS 250W luminaires, between 6 and 9 years for replacing HPS 400W luminaires, and 1 year for replacing HPS 1000W luminaires. Currently, the warranty provided by most of the manufactures is five years, which does not match the above return periods. It is recommended that the manufacturers shall warrant the LED and plasma luminaires to be free from defects in materials and workmanship for a period of at least 8 years for conventional roadway lighting. For high mast lighting, the current warranty of 5 years provided by the manufacturers should be sufficient to protect the investment.

Technical specifications for the new lighting products are necessary for their successful applications. Appropriate technical specification should include but are not limited to the following aspects:

- Lamp/Luminaire
  - Photometric properties: lamp watts, initial lumen, CRI, CCT, light distribution type
  - Performance: lumen maintenance, service life
  - Safety: UL1029, UL1598
  - LM-79, LM-80 and ANSI C78.377 tests and reports
  - IP rating: IP65 or better (ANSI C136.25)
- Electrical
  - Voltage
  - Power factor
  - Surge protection: IEEE/ANSI C62.41
  - Ballast sound rating: A
  - Electromagnetic Interference (EMI): Class A (Title 47 CFR Part 15)
  - Photo electric sensor
- Housing
  - Vibration resistance: 2G or better (ANSI C136.31)
  - Material: Die cast aluminum housing (A360)
  - Slipfitter mount: Adjustable ($\pm 5^{\circ}$) for leveling
  - Wildlife instruction protection
- Others
  - Materials: RoHS compliant
  - Upward light output ratio (ULOR) rating: 0
  - Temperature rating: $-40^{\circ}C \sim 50^{\circ}C$
  - Warranty: 8 years for conventional lighting, and 5 years for high mast lighting

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1. INTRODUCTION

1.1 Problem Statement

There is an increasing interest in using new lighting technologies in roadway lighting. The new lighting technologies include light emitting diode (LED), induction and plasma lighting systems. The most commonly claimed benefits of the new lighting systems are increased reliability, improved efficiency, and reduced maintenance costs. Due to this growing interest and demand, the American Association of Highway and Transportation Officials (AASHTO) is developing a "subcommittee on lighting" to look specifically at developing LED standards. Consequently, an NCHRP Task 305 study, "Analysis of New Highway Lighting Technologies," has been proposed, and is currently ongoing (*1*). The objective of the NCHRP study is to evaluate the potential and proper application of LED lighting technology and, if applicable, other new roadway lighting technologies to determine if and what additional research is required to properly establish guidance for utilizing the new lighting technologies in roadway lighting applications. In the event the research establishes that sufficient acceptable research has already been performed to provide guidance on use of the LED lighting or other alternate lighting technologies, the NCHRP Task 305 study shall develop design guidance.

The Indiana Department of Transportation (INDOT) has been contacted by vendors requesting possible application of the new light sources for roadway lighting. Currently, the usages of the new lighting systems in Indiana are only limited to the lights for urban street, residential streets, walkway or other non- roadway applications. Before adopting the new lighting systems, INDOT would like to determine if the new lighting systems meet required light output and if they are cost effective. Moreover, it is necessary for INDOT to establish standardized guidelines for evaluating the new lighting systems prior to the formal adoption. This study was conducted to evaluate some select lighting devices in roadway lighting. The major effort of this study was to address engineering issues, such as light levels, life cycle cost (LCC), maintenance, traffic safety, and approval procedures for new lighting technologies based on field evaluations.

1.2 Research Objective

To address the concerns on the new lighting technologies, this study focused on the light properties, benefits, costs, and effectiveness of the new lighting systems applied in roadway lighting. The objective of this study was to review INDOT's current roadway lighting and compare with LED, induction and plasma lightings. A thorough literature review was performed to obtain necessary information on the applications of the new lighting technologies in roadway lighting. A questionnaire survey was conducted to investigate the status of the new lighting systems in other state DOTs and local agencies. Efforts were also made to obtain the specifications, standard drawings, and other relevant design and installation information from the places where the new lighting systems have been installed. Test sites and new types of lighting devices were selected for a filed evaluation to address the issues associated with the new lighting systems, including field photometric testing, installation, costs, maintenance, and the decision procedures for adopting the new lighting systems.

1.3 Research Approach and Main Tasks

Before adopting the new lighting systems, it is rationale for INDOT to evaluate if the new lighting systems meet required light output and if they are cost effective. This study was to obtain the needed information for INDOT to rationally address the concerns on the new roadway lighting systems. This study was performed to compare the new lightings with the existing lightings in terms of performance and cost effectiveness. In order to fulfill the research objectives and accomplish the main research tasks, the main tasks and research approach are summarized as follows:

a. First, it was necessary to summarize INDOT's current practice and requirements for roadway lighting. The average service lives and costs of the existing roadway lighting devices were identified so that they could be compared with the new roadway lighting systems to be studied. In addition to the input provided by the study advisory committee (SAC) members, information was gathered from INDOT districts, Indiana cities and towns after consulting with SAC members. Then the status of applications of the new roadway lighting in other states was investigated. The research team located, assembled, and reviewed studies, technical reports and papers, and other information on LED, induction and plasma lighting applications, criteria, and effectiveness. The main effort focused on the performance and economic aspects of the new lightings. The performance of the new lighting systems includes illuminance, color contrast, uniformity ratios, effective mounting heights, and degradation factors. The economic aspects include the initial cost, maintenance cost, electricity cost, and service life.
b. A questionnaire survey was conducted to obtain the status of the new lighting technologies adopted in Indiana cities and towns and other states highway agencies (SHAs). Documents related to the new lighting technologies were identified and obtained from other state DOTs, and Indiana cities and towns. Follow-up phone calls were made to get responses for the questionnaire, to clarify information on the completed questions, and to obtain any necessary details of lighting information. Efforts were made to obtain specifications, standard drawings, and other relevant design and installation information from other states who have installed alternative lighting technologies. The information on expected service lives and LCCs of the lighting devices were searched and documented.
c. To better evaluate the performance of new lighting technologies, also reviewed were the technical publications by other professional lighting organizations, including American Association of State Highway and

Transportation Officials (AASHTO), Illuminating Engineers Society of North America (IESNA), and Lighting Research Center (LRC) at Rensselaer Polytechnic Institute.

d. Field evaluations were conducted on the new lighting systems at the I-74/US-231 interchange. Some other sites established by local agencies on the state highway system were also studied. Through the field evaluation, the illumination levels, light distribution, and light uniformity were measured and calculated. Prior to making the site visits the researchers acquired road plans in order to have the geometry and determine the appropriate spots on the roadway to take measurements. In addition to the photometric readings, the researchers ascertained installation issues, costs, maintenance issues, safety issues, and factors that influence decision-making.

e. Life cycle cost analysis was conducted to determine if the new lighting systems were cost effective as compared to the existing lighting systems. Life cycle cost analysis can be utilized to compare various alternatives to select the most cost effective lighting system.

2. ROADWAY LIGHTING AND TECHNOLOGY OVERVIEW

2.1 FHWA Policy, Guidance and Recommendations on Roadway Lighting

In August, 2012, Federal Highway Administration (FHWA) released the 2012 FHWA Lighting Handbook (*2*). This handbook is an update to the 1978 FHWA Lighting Handbook 78–15. The 2012 FHWA Lighting Handbook provides guidance lighting designers and State, city, and town officials concerning the application of roadway lighting. This handbook is primarily used as a resource for policy makers and design and construction community to evaluate potential needs and benefits of a roadway or street lighting system. The 2012 FHWA Lighting Handbook is divided into six areas of discussion. The first area discusses the guidance, recommendations and references used by FHWA in evaluating and administering funds for roadway and street lighting projects.

FHWA guidance and recommendations regarding roadway lighting basically focus on determination of lighting need, system maintenance, and design for special situations. The projects under Section 148 of Title 23, United States Code, Highway Safety Improvement Program, are qualified for FHWA funding. These projects are eligible for the increased Federal share under 23 U.S.C. 120(c). When Federal aid is used for a roadway or street lighting project, the need can be supported by the following items:

- Warranty analysis showing that lighting is a warranted safety feature.
- A document showing that the design criteria established by AASHTO or the Illuminating Engineering Society (IES) are met as part of the design.

A safety analysis or study showing that a lighting system is a cost-effective alternative for the project may also be considered. The FHWA review process requires maintenance plan and MOU. A State DOT may provide a formal agreement with adequately equipped county, municipality, or other governmental instrumentality, but such an agreement shall not relieve the State DOT of its responsibility for the system maintenance. For the lighting design for special situations, such as consideration of old drivers, railroad grade crossings, crosswalks, and roundabouts, this handbook specifies the documents as guidance.

The 2012 FHWA Lighting Handbook does not discuss use of the new lighting technologies. This handbook is not intended to be a detailed design but supplements to the guidance provided by AASHTO or IES. It is believed that when lighting is warranted, agencies may select any lighting system that meets the AASHTO design criteria and is cost-effective.

2.2 INDOT Highway Lightings

There are three types of lighting sources that have been widely used for indoor and outdoor lighting applications, including incandescent, fluorescent, and high intensity discharge (HID) lights. For highway facilities, lighting is commonly provided at interchanges, rest areas, weight stations, tunnels, and parking lots. For some time INDOT has been using only an HID light source due to its availability, size, power requirement, and cost effectiveness. There are several advantages to the HID light lamps. First, HID light lamps are commercially available in small physical size. Second, HID light lamps usually have relatively long life (5,000 to 24,000 hours). Third, HID light lamps demonstrate relatively high lumen output per watt. The HID light source family consists mainly of four members, including mercury vapor (MV), low-pressure sodium (LPS), high pressure sodium (HPS), and metal halide (MH) lights. However, HPS is the light source that INDOT has been using for each new installations of conventional or high-mast lighting due to its excellent luminous efficiency, power usage, and long service life (*3*).

Recently, revolutionary changes have occurred in lighting technologies. New lighting sources are receiving increasing use in all indoor and outdoor lighting areas. Of those new roadway lighting sources, light-emitting diode (LED), induction, and plasma luminaires have been reported to be the most promising alternatives to traditional roadway lighting luminaires. LED, induction, and plasma luminaires are envisioned to provide better color, reduce hazardous waste, and decrease carbon emissions. LED, induction, and plasma luminaires have demonstrated great potentials in energy efficiency, reduction in long-term maintenance, and longevity with the innovations achieved in optics, electronics, and design. Accordingly, INDOT Office of Traffic Administration and Traffic Standards Subcommittee are committed to keeping abreast of the new lighting technologies. The INDOT Standard Specifications are being revised through a recurring special provision to compliment the use of light sources other than HPS as determined and specified by the designer (*4*).

2.3 Highway Lighting Sources

2.3.1 HPS Lamps

HPS lamps were introduced in the 1960s. An HPS lamp commonly consists of four basic components, including a sealed, translucent, ceramic arc tube, main electrodes, an outer bulb, and a base (*5,6*). The arc tube ceramic contains a mixture of a small amount of xenon gas and sodium-mercury amalgam and is used to provide a proper environment for producing light. The Xenon at a low pressure is used as a "starter gas" in the HPS lamp. Lying at the coolest part of the lamp, the sodium-mercury amalgam provides the sodium-mercury vapor that is needed to draw an arc. The main electrodes are made of tungsten and carry a high-voltage, high-frequency pulse to strike the arc and vaporize the mercury and sodium. The outer bulb, typically elliptical in shape and made of hard glass, protects the arc tube from damage and prevents oxidation of the internal parts. It also contains a vacuum that reduces convection and heat losses from the arc tube to maintain high efficacy. The lamp base, either medium or mogul, is typically a screw base made of brass or nickel and provides a socket for electrical connection. Shown in Figure 2.1 is a photo that demonstrates HPS lighting for an on-ramp acceleration lane in one of the test zone at the interchange of I-74 and US-231 in Indiana.

An HPS lamp requires an inductive ballast to regulate the arc current flow and deliver the proper voltage to the arc. Unlike MV or MH lamps, an HPS lamp does not contain a starting electrode. It is the electronic starting circuit within the ballast that generates a high-voltage pulse to the main electrodes. An HPS lamp is powered by an alternating current (AC) source. When the HPS lamp is turned on, the voltage is applied across the main electrodes and the xenon gas is easily ionized. The ionized xenon gas strikes the arc and generates heat. The heat then vaporizes the mercury and sodium. The resultant mercury vapor raises the gas pressure and operating voltage to a point so that the sodium vapor produces golden light. Compared to incandescent lamps, fluorescent lamps or other HID family members, HPS lamps have exhibited both advantages and disadvantages (*5,6*). The identified advantages are as follows:

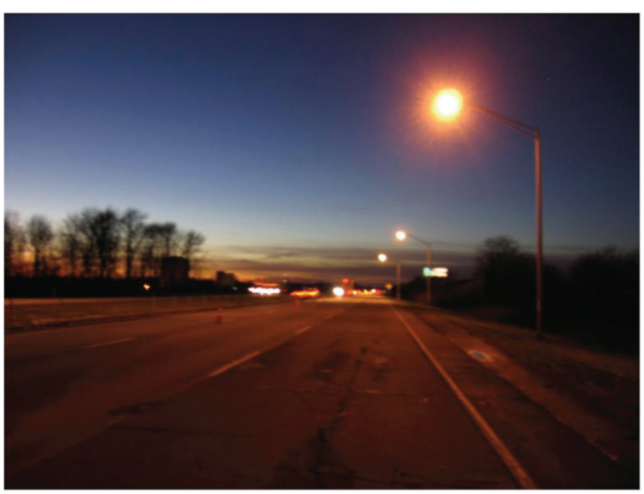


Figure 2.1 HPS lighting at I-74/US-231 interchange.

a. Low lamp price. HPS lighting technologies have been developed for decades. Currently, the costs for manufacturing HPS lamps have dropped to reasonably low level. For example, the price for a 250W, ED28 HPS lamp is about $40.
b. High efficacy. Currently, HPS lamps have very high efficacy, commonly ranging between 38 and 150 lumens per watt.
c. Long life. HPS lamps typically have a rated life of 24,000 hours. Special HPS lamps may provide a rated life of 40,000 hours.
d. High availability. HPS lamps are commercially available in various sizes between 35 and 1,000 watts.
e. Broad applications. HPS lamps can be easily controlled and meet demands for various lighting applications, from indoor to outdoor, and from residential homes to roadway infrastructures.

The identified disadvantages are summarized below:

a. Poor color rendering. HPS lamps typically have a color rendering index (CRI) between 20 and 30 and a correlated color temperature (CCT) less than 3000 K. Therefore, HPS lamps commonly give off a yellowish color and a small amount of natural light, which makes it difficult to identify the object’s true color.
b. Higher wattage lamps. HPS luminaires typically require a higher wattage lamp to achieve necessary lighting levels. As an example, INDOT requires use of 400Watt lamps when mounted at 40 ft high. Therefore, HPS luminaires may consume more electricity, resulting in higher operating costs.
c. Ballast needed. Like other HID lamps, HPS lamps require a ballast to start and operate. The function of the ballast is to provide starting voltage, and then regulate the current and match the line voltage to the arc voltage. The operation of the ballast will cause efficiency loss.
d. Slow starting and re-starting. When an HPS lamp is powered, it may take up to 6 minutes for it to achieve the full lumen output. When a momentary power loss occurs, the HPS lamp must cool first before re-striking.

Currently, HPS lamps are the only light source that INDOT is using for each new installations of conventional or high-mast lighting due to its excellent luminous efficiency, and long service life.

2.3.2 MH Lamps

MH lamps are also a member of HID lamp family. However, MH lamps can offer an excellent combination of quality and performance. MH lamps not only present more natural blue-white light compared to HPS lamps, but also provide increased efficacy compared to MV lamps. The MH technology evolved from the first probe-start quartz developed in 1960 to the latest pulse-start ceramic in late 1990s. Similar to other HID lamps, a standard MH lamp consists of four basic components, including a quartz arc tube, main electrodes, outer bulb, and base. The operation of metal halide lamps is similar to HPS lamps in that they produce light by way of an arc tube contained within a glass bulb. When an MH lamp is energized, the electric current is passed through the arc tube which ignites an electric arc through a gaseous mixture of vaporized mercury and metal halides, which are compounds of metals with bromine or iodine. Similar to HPS lamps, inductive ballast is used to regulate the current and the voltage to the lamp.

MH lamps share the many advantages with HPS lamps, including efficacy, availability and service life. Nevertheless, MH lamps have also exhibited both advantages and disadvantages as compared to HPS lamps. The advantages include the following:

a. Better color rendering. Metal halide lamps have a CRI of about 65 and a CCT of about 4000 k. MH lamps have a broader output spectrum than HPS lamps and produce an intense white light rather than the yellowish light from HPS lamps.
b. High efficacy. MH lamps produce more light than mercury vapor lamps. Also, the efficacy of low-wattage HM lamps is greater than that of HPS lamps.

The main disadvantages are as follows:

a. Higher initial cost. Low prices may be available for some MH lamps, but in general, MH lamps are more expensive that HPS lamps.
b. Less service life. For example, the service life is typically 15,000 for a Pulse-Start Quartz 250W MH lamp and 24,500 for a 250W HPS lamp.
c. More hazardous substance. MH lamps are based on the MV technology. Therefore, mercury plays an important role in MP lamps. The mercury content may be close to 50 mg for a standard 250W MH and only 15 mg for a 250W HPS lamp.
d. Longer start time. MH lamps can take up to 30 minutes to start back up and reach full brightness when restarting from a hot state due to the high pressure in the hot arc tube that prevents the arc from being reignited immediately.
e. More glare. MP lamps typically more glare due to the blue light component.

Currently, MH lamps are not used for roadway lighting applications by INDOT. Figure 2.2 presents a photo showing the MH lighting (the front luminaire) in one of the lighting test zones employed in this research study.

2.3.3 LED Lighting

LED lighting is a type of solid-state lighting. It is a semiconducting device that produces light when an electrical current passes through it. Multiple LEDs can be combined into LED arrays. LED lamp, as defined by IES (*7*), is an LED device with an integrated driver

Figure 2.2 MH lighting on US-231.

and a standardized base that is designed to connect to the branch circuit via a standardized lamp holder/socket. LED luminaire refers to a complete lighting unit consisting of a light source and driver together with parts to distribute light, to position and protect the light source, and to connect the light source to a branch circuit. The practical visible-spectrum LED was first developed in 1960s (*8*). With the advancements in optics and semi-conducting technologies, LED technologies become more reliable, and LED product prices have been falling in the past decades. As a result, LED lighting applications have become more financially attainable. Figure 2.3 shows the LED lighting in one of the test zones utilized for this study.

A basic LED lamp consists of several components, including optical, electrical, and mechanical and thermal components (*6,8*). An LED is essentially a p-n junction semiconductor. When an LED is energized, the electrical current flows from one end of the diode to the other. Charge carriers electrons and holes flow into

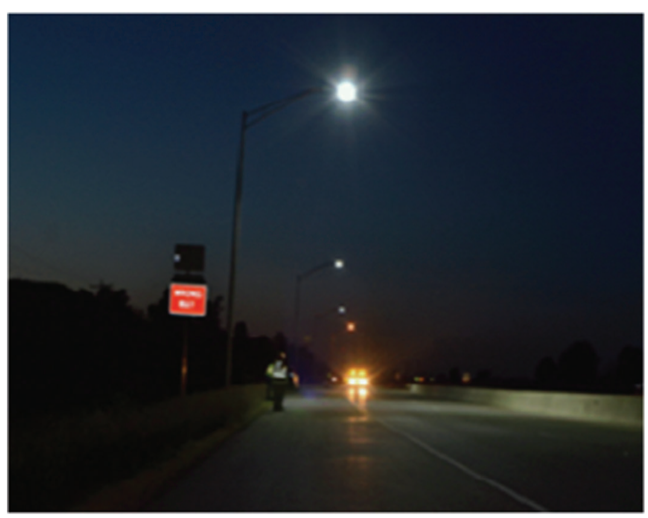


Figure 2.3 LED lighting in test zone.

the diode in the direction of the current flow. When an electron meets a hole, the electron falls into a lower energy state and releases a particle known as a photon, which is where the visible light comes from. A heat sink is needed to draw the heat away from the LED array to cool them and prevent premature failure of one or all of the LEDs. The heat sink is typically integrated into the outer housing of the fixture to maximize heat dissipation.

Several advantages have been identified with LED lighting:

a. High efficacy. LEDs do not have a filament, and therefore do not generate heat which is usually radiated into space like an incandescent lamp. Theoretically, LEDs can achieve an energy conversion efficiency of 100%.
b. Good color rendering. LED lamps typically use a combination of LEDs of varying wavelengths of light they are able to have superior color rendering abilities and produce a very clean white light requiring a lower powered light source. Currently, LED lamps have a CRI of about 70 and a CCT in the range of 4000 K to 6000 K. The white LEDs used in LED street lamps have wavelengths ranging from about 450 nm up to about 650 nm.
c. Less energy consumption. Because LEDs generate less heat, they are able to provide comparable lighting performance in the same task to conventional lighting sources while using significantly less power.
d. High reliability. An LED is powered by an electronic driver which converts alternating current (AC) voltage into direct current (DC) voltage and then regulates the voltage and current to keep it constant and protects the system from surges in the current and the voltage which could cause a catastrophic failure of the system. Therefore, LED lamps are typically more resistant to shock and vibration.
e. Long service life. LEDs do not burn out and last much longer than conventional lighting sources. An LED's service life is measured by lumen depreciation and is defined as L70, i.e., the point at which its light output has declined to 70% of the initial lumens.
f. Easy control and programming. LED street lights are able to have their light projection controlled very well which enables the direction and pattern of light to be much more precise. This enables them to have very good uniformity of light while also significantly reducing light pollution.
g. No sudden failure. LEDS typically fail by dimming over time, rather than sudden burn-out. This makes the replacement foreseeable and eliminates potential adverse driving conditions due to sudden burn-out at nighttime.
h. No warm up. LEDs can achieve full brightness instantly.
i. Environmentally friendly. LEDs contain no mercury, and therefore no additional costs associated with their disposal.
j. Dimmable.

The main disadvantages associated with LED lighting are as follows:

a. High initial cost. With the advancements in optics and semi-conducting technologies, LED product prices have been falling in the past decades. However, at present it is still costly to produce LEDs.
b. Need for thermal management. LEDs' performance, such as color consistency, light output, and service life, depends heavily on the ambient temperature of the operating temperature. LEDs do not radiate heat into space and therefore require adequate heat-sinking to keep the ambient temperature down. High ambient temperature may result in overheating of LEDs.
c. Photobiological safety concern (*9*). An increasing concern associated with powerful LED lights is that the white and blue LED components may exceed the safety limits specified by IESNA (*10*) and be harmful to human eyes.
d. Expensive replacement. Driver or any other component(s) failure may require replacement of the entire luminaire.

2.3.4 Plasma Lighting

Plasma, also known as lighting emitting plasma (LEP), is an ionized gas with equal number of positive and negative charges. Plasma lamps are electrodeless lamps, meaning there are no electrical connections inside of the bulb, which use radio frequency (RF) waves to excite plasma within the bulb. Plasma lamps were invented by Nikola Tesla in 1894 and became popular in the 1970s and 1980s (*11*). A plasma lamp typically consists of four basic components, including lightron, waveguide, cavity resonator and bulb assembly (*12*). The lightron is an advanced version of magnetron similar to that used in a microwave oven. The waveguide is designed to guide the microwaves generated by the lightron and direct them over to the cavity resonator. The cavity resonator is a wire mesh housing that contains the bulb and prevents the microwaves from escaping from the housing. The quartz bulb has a size of approximately ¼″ × ¼″ and contains several milligrams of sulfur at the end of a thin glass rod. When a plasma lamp is powered, RF waves or microwaves are produced. RF waves guided toward the bulb energize the plasma gas inside the bulb. The gas (usually noble gas) becomes ionized causing some electrons to be excited and collide with the gas and metal particles inside bringing some electrons to a higher energy state. When the electrons return to their original state they emit a photon that gives off visible light. Figure 2.4 shows a photo showing the plasma lighting installed in one of the test zones utilized in this study.

Plasma lighting is a category of high-intensity, electrodeless lighting. However, plasma lighting is not LED lighting or HID lighting. Like LEDs, a plasma lamp is a point light source that utilizes solid-state devices. The fundamental difference is that LEDs use the solid-state device itself to generate light and plasma lamps use the solid-state device to generate RF waves that is used energize the plasma light source. Like induction lamps, plasma lamps do not need metal electrodes to power the light source. However, plasma lamps are point light sources. Like HID lamps such as

Figure 2.4 Plasma lighting installed in test zone.

metal halide lamps, a plasma lamp uses similar materials to ionize gasses to create bright plasma. However, plasma lamps are electrodeless lamps and use solid-state device. Therefore, plasma lamps have been envisioned to combine many of the best attributes of induction, LED, and metal halide sources. The main advantages associated with plasma lighting are the following (*13,14*):

- High efficacy
- High light output
- High (good) color rendering
- Long service life
- Consistent spectrum of light
- Rapid start
- Dimmable

The main disadvantages of plasma lighting are as follows:

- High initial cost
- Technology still under development
- Expensive replacement: failure of a component may require replacement of the entire luminaire

2.3.5 Induction Lighting

Induction lamps are another form of an electrodeless lamp. Like plasma lamps, the induction lamp was invented by Nikola Tesla in 1890s (*15*). In the late 1960s, John Anderson who was working with General Electric applied for patents for electrodeless lamps for commercial use. However, it was not until the 1990s when several major lighting manufacturers started to promote induction lighting into the marketplace around the world. An induction lamp consists of three major components, including ballast (known as HF generator), power coupler, and lamp bulb (*16,17*). The ballast contains an oscillator and preconditioning and filtering circuits. It first converts AC to DC, and then DC to AC. The power coupler contains an antenna which is made of a primary induction coil and ferrite core. It transfers energy from the ballast to the discharge inside the lamp bulb. The lamp bulb is a sealed glass bulb containing a low pressure inert gas with a small amount of mercury vapor.

When an induction lamp is powered, the ballast generates HF current. The HF current is sent through the electromagnet and a strong magnetic field is produced. The energy is transferred from the magnet to the mercury in the tube via the antenna and excites the mercury atoms. The mercury vapor emits UV light which is changed into visible light by the phosphor coating on the inside of the glass. Induction lamps are electrodeless lamps, which results in long service life and reliable performance. The main advantages with induction lighting include:

- High efficacy
- Long service life
- High (good) color rendering
- Instant start and hot re-strike
- Dimmable capability with some units

The disadvantages with induction lighting are as follows:

- High initial cost
- High ballast failure rate
- Bulky design, not a compact light source
- Applications still under development
- Environmental concerns with mercury amalgam

Figure 2.5 presents a photo showing a decorative induction light installed a bridge on Ohio Street in Indianapolis.

2.4 Luminaire Performance

2.4.1 Performance Indicators

The performance of a light source is usually measured in terms of multiple indicators (or parameters), rather than a single indicator. Typically, the evaluation of luminaire (or lamp) performance for

Figure 2.5 Induction lighting on Ohio Street.

roadway lighting applications is made by taking into account photometrics, energy efficiency, lamp life, costs, operation, and maintenance. Photometrics affect illumination quality and commonly include color rendering index (CRI) and correlated color temperature (CCT). Energy efficiency is mainly measured with luminous efficacy. Costs are typically estimated over the lifespan and include initial cost, operation cost, and maintenance cost. Operation factors cover the start time and re-strike time, and resistance to the effect of climate condition. In practice, the commercial availability of lamp size or lamp watts also plays an important role in roadway light applications, particularly in the selection of light sources.

CRI is a measure of the degree of color shift an object undergoes when illuminated by the light source as compared with those same objects when illuminated by a reference source of comparable color temperature on a scale of 0 to 100 (*18*). The maximum CRI is 100 for a black body. A low CRI value indicates that some colors may appear unnatural when illuminated by a lamp. However, CRI is the average shift of eight standard colors and does not indicate which color will shift. Therefore, CCT is used together with CRI to characterize the color appearance of a light source. CCT is defined as the absolute temperature of a black body whose chromaticity most nearly resembles that of the light source. CCT is a measurement of the dominant color tone from warm (yellow and red) to cool (blue). A CCT value below 3200 K usually indicates a warm light source and a CCT value above 4000 K indicates a cool light source. Therefore, both CRI and CCT are commonly used as indicators of the quality of a light source.

Efficacy is defined as the quotient of the total emitted luminous flux and the total lamp power and expressed in lumens per watt. It indicates the efficiency for a lamp to convert energy into visible light. A lamp with higher efficacy requires less electrical energy to produce a certain amount of light. Lamp life or life expectancy is defined as the number of hours when 50% of a sample group of lamps have failed. For LED, plasma and induction lamps, lamp life is the number of hours when the lumen outputs for 50% of lamps have declined to 70% of the initial lumens. Lamp start time is the time required for a lamp to reach the full initial light output of the lamp after the lamp is powered. Lamp re-strike time is the time required for a lamp to return to its full initial light output of the lamp. Lamp start and re-strike times are two important parameters for emergency lighting. Also, less re-strike time can reduce the potential interruption to traffic. High availability of lamp size (wattages available) provides a wide range of choice.

2.4.2 Typical Performances

The authors reviewed luminaire products for highway lighting applications on publicly accessible websites for the major lamp manufactures and suppliers (*19–29*). Presented in Table 2.1 are the typical performance values for different light sources, including HPS, MH, LED, plasma, and induction lights which may be used in highway lighting applications. Plasma, induction and MH lights have equivalent CRI values which are greater than those for LED and HPS lights. HPS light has the lowest CRI values. LED light provides in-between CRI values. With a CCT value of 4,000 K or above, LED and plasma lights are both cool lights. HPS light has a CCT value of 2,700 K or less, and is warm light. Both MH and induction lights produce a wide range of CCT values. In reality, induction light is basically equivalent to the high quality fluorescent light. LED and plasma lights demonstrate the greatest efficacy. While some HPS lamps may also provide very high efficacies, the corresponding CRI values are commonly very low. Induction luminaires provide a service life up to 100,000 hours. The start time is about 2–5 minutes for HPS, MH and induction lamps, and 45 seconds for plasma lamps. However, LED lamps can start and re-strike instantly.

Also presented in Table 2.1 is the information on the lamp size, warranty and application of the luminaires that are currently commercially available. While reviewing the lamp products for street and highway lightings, the authors noticed that many LED manufacturers are able to provide a wide range of LED lamp

TABLE 2.1
Typical Luminaire Performance for Highway Lightings

	Luminaire Type				
Indicator	**HPS**	**MH**	**LED**	**Plasma**	**Induction**
CRI	20–65	70–90	65–75	75–95	80–90
CCT	2,200–2,700	3,000–6,000	4,000–6,500	5,000	2,700–6,500
Efficacy*	80–125	50–100	115	115	85
Lifespan	12,000–24,000	10,000–15,000	50,000	50,000	100,000
Start time	2–5 min.	2–5 min.	Instant	45 s	2–5 min.
Lamp size**	70–1,000 watts	32–2,000 watts	55–560 watts	160–500 watts	40–200 watts
Application	Conventional & high mast	Conventional & high mast	Conventional & high mast	Conventional & high mast	Conventional
Warranty	5 years	5 years	5–10 years	5 years	5–10 years

*Measured at source.

**Roadway lighting applications.

sizes. Plasma lamp sizes currently available are limited to 160, 200, 280, 295, 300, and 500 watts. The largest induction lamp size is 200 watts. Therefore, the three new light sources are all available for conventional roadway lighting, but only LED and plasma light sources are currently available for high mast lighting. The majority manufacturers of LED, plasma, and induction luminaires commonly provide a 5-year warranty which is also common for HPS and MH luminaires. Some of the LED and induction luminaire manufacturers may provide up to 10 years of warranty.

3. STATE HIGHWAY AGENCY AND LOCAL CITY SURVEYS

3.1 Description of Survey

3.1.1 Survey Purpose and Questionnaire

As one of the main tasks of this study, a survey was conducted to gather information on the status of new lighting technologies, including the current use, lighting performance, cost/benefit, life expectancy, potential issues in installation, operation and maintenance, and possible impact on travel safety in state highway agencies nationwide and in local cities in Indiana. The survey participants include traffic engineers, electrical engineers, illuminating engineers and design engineers from state highway agencies, and city engineers, street light coordinators and traffic supervisors from local cities. The participants were asked to provide technical specifications, drawings, and approval methodologies for new lighting technologies if currently available. In addition, they were asked to identify their perceptions on the future use of the new lighting technologies by their organizations and main barriers to adoption of the new lighting technologies.

The survey contained a total of fourteen questions (see Appendix A). Four questions were designed to map out the current use of new lighting technologies by SHAs nationwide and local cities statewide, such as whether the organizations surveyed have utilized LED, plasma, and induction lighting technologies, years of experience in using the new lighting technologies, main reasons to use the new lighting technologies, and critical barriers for their organizations to use new lighting technologies. One question was asked to determine the types of roadway (interstate, U.S. highway, state road, or local streets) and locations (urban or rural area, parking lot, rest area or intersection) where the new lighting systems have been installed. Six questions focused on technical aspects of the new lighting technologies, such as lighting performance, life expectancy, issues in installation, operation, maintenance and safety. The remaining questions helped determine the availability of specifications and approval procedures of new lighting technologies.

3.1.2 Survey Methods and Execution

The survey was conducted primarily via email. The main advantages of email survey over other survey methods include low cost, quick response, flexible time, and easy tracking. The email addresses of respondents were either provided by the Study Advisory Committee (SAC) members or identified in the contacts for the AASHTO Joint Technical Committee (JTC) on Roadway Lighting (*30*). For SHAs, the first attempt was made in November 1, 2011. Due to retirement, job change or organization reshuffle, new respondents were added to the list of survey respondents and additional attempts were made in the following weeks. For local cities, the survey questionnaire was sent out in June 5, 2012. Follow-up phone calls were made to clarify the information received in the survey. Reminder phone calls were made to make sure the representatives in the neighboring states to provide responses to the survey. Phone calls were also made to get in-depth information from some representatives, particularly states with climatic condition similar to that in Indiana, and states that have adopted new lighting technologies.

A total of sixty two representatives, including 49 SHAs and 13 local cities, were contacted, and 19 SHAs and 6 cities responded to the survey. Presented in Table 3.1 is the summary of survey returns and response rates. It is shown that the response rate for SHAs is slightly greater than that for local cities. This is most likely due to the timing of the email survey. In reality, it was indicated by the follow up phone calls that the city representatives were willing to participate in the survey and provide information as much as possible. It was also found that most responses were received within one week after the original surveys were sent out. Approximately 50% of responses from SHAs were received within the same day. The response rate for local cities is higher than that for SHAs. Overall, the response rate is 40.3% that is much higher than the average response rate for those email surveys conducted to collection information by the researchers in various fields nationwide (*31*).

TABLE 3.1
Summary of Survey Returns and Response Rates

Organizations	No. of Representatives Contacted	No. of Surveys Completed	Response Rate
SHA	49	19	38.8%
Local city	13	6	46.2%
Total	62	25	40.3%

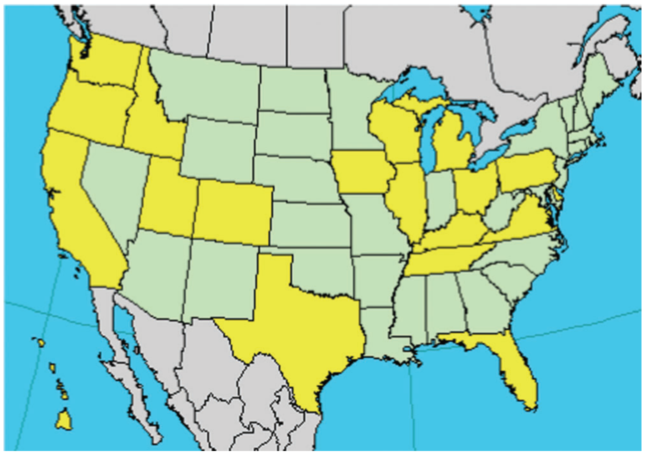


Figure 3.1 Geographical locations of SHAs responded to the survey.

3.2 State Highway Agency Survey Results

3.2.1 Adoption of New Lighting Technologies

As indicated in the previous sections, the survey questionnaire was sent to forty nine SHAs. A total of nineteen SHAs have responded to the survey. Illustrated in Figure 3.1 are the geographical locations (in yellow) of these nineteen SHAs. Apparently, these SHAs responded to the survey are mainly distributed in two regions of the country, the Midwest region and the West region. The real reason for the responses from the SHAs in the Midwest is that the research team made extra effort, including follow-up phone calls and emails, to get the responses from them. These states, such as Wisconsin, Illinois, Michigan and Ohio, are the neighboring states of Indiana. They are all close to the Great Lake and have the climatic condition very similar to that in Indiana. Therefore, their experiences may be more suitable for the environmental condition in Indiana as perceived by the SAC members and the research team. The reason for the responses from the SHAs in the West and other regions responded to the survey is probably that these SHAs have already used or are currently experimenting with new lighting technologies to some extent and are willing to share their experiences.

Figure 3.2 Geographical locations of SHAs.

Figure 3.2 demonstrates the geographical locations (in yellow) of the eleven respondents who indicated that their SHAs have used new lighting technologies (Question 1). In the Midwest states, only Ohio and Michigan have used new lighting technologies. Michigan has used both LED and induction lighting technologies, and Ohio has only used LED lighting technology. The reaming SHAs (besides Texas and Florida) that have used the new technologies are mainly located in the West region. Table 3.2 shows the exact type of new lighting technology that has been used by these SHAs. Florida DOT and Texas DOT have used all three types of new lighting technologies. Colorado, Michigan, and Utah DOTs have used two types of new lighting technologies. The remaining six SHAs have used one type of new lighting technologies. Of these nineteen SHAs surveyed, approximately 47.4% have used the LED lighting source, 36.8% have used the induction lighting source, and 10.5% have used the plasma lighting source, as shown in Figure 3.3. Obviously, LED is the most attractive new lighting source followed by induction lighting source, which has been used and is probably being considered by SHAs across the country. This agrees well with the finding in another survey conducted by AASHTO JTC on Roadway Lighting (*32*), which indicated that 44.4% of SHAs has used LED lighting.

When asked about the main barriers to use new lighting technologies (Question 2), the representatives from ten SHAs that have not used new lighting technologies returned responses. To simplify the analysis, these responses were grouped into three categories such as performance, cost/benefit, and technology. The category of performance covers lighting performance such as light level, luminous efficacy, and life span. Cost/benefit includes costs in installation, maintenance and energy consumption. Technology covers the science behind new lighting sources and the skill and specifications to apply new lighting sources. As illustrated in Figure 3.4, 70% of the respondents picked performance, 60% of the respondents picked technology, and 50% of the respondents picked cost/benefit. For lighting performance, two respondents indicated their concerns about light level and two respondents indicated their concerns about luminous efficacy. One respondent mentioned light color, and one respondent mentioned effect of temperature. For lighting technology, four respondents indicated the new lighting technologies are not proven or are still developing. Deficiencies associated with new lighting sources have been identified in some technical areas. For cost/benefit, two respondents indicated that the savings claimed are not convincing. Two respondents indicated that LED lighting requires more poles and is more costly.

The respondents from the SHAs in the Midwest, Wisconsin and Illinois indicated that a specification is necessary for their agencies to adopt new lighting

TABLE 3.2
Adoption of New Lighting Technologies by SHAs

SHA	CA	CO	FL	ID	MI	OH	OR	PA	TX	UT	WA
LED	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No
Induction	No	Yes	Yes	No	Yes	No	Yes	No	Yes	Yes	Yes
Plasma	No	No	Yes	No	No	No	No	No	Yes	No	No

technologies. Illinois further indicated that the standards and technology for new lighting sources are not on the same level and they are developing their own specifications regarding LED lighting. Wisconsin is also developing specifications for LED lighting and had concerns over the performance of induction lighting. For cost/benefit, Illinois indicated that the savings with LED lighting were virtually non-existent. High initial cost and the need for more luminaires spaced closer together have negated the other benefits of LED l.

The respondents were asked in the survey to provide the primary reasons for their SHAs to adopt the new lighting technologies (Question 4). While the responses varied from respondent to respondent, they are mainly related to costs and performance. Figure 3.5 shows the distribution of grouped responses from the respondents. The top three reasons include maintenance savings, energy savings, and better performance. The majority (77.8%) of respondents selected maintenance savings, 55.6% of respondents selected energy savings, 33.3% of respondents selected better performance, and 22.2% of the respondents picked either lamp life or other costs (such as installation cost). On the whole, SHAs have adopted the new lighting technologies mostly for savings, followed by better performance and lamp life. For the respondents from the Midwest, Michigan indicated that they adopted new lighting technologies mainly for energy savings. Ohio stated that they have used LED lighting for both maintenance savings and longer lamp life. As indicated that in the previous section, the top barrier for SHAs to use new lighting technologies is lighting performance rather than costs, the top reason to use new lighting

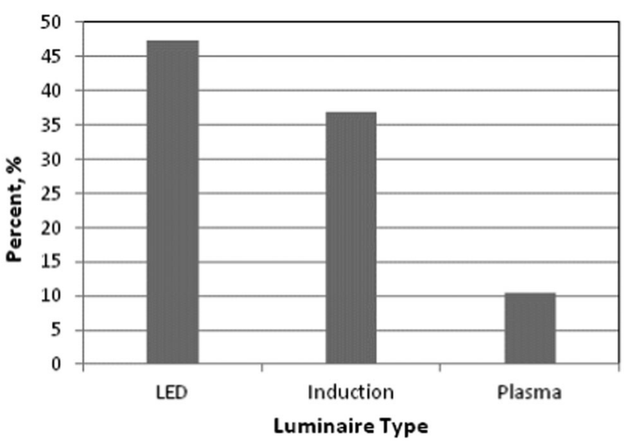


Figure 3.3 Distribution of new lighting technology adoption by SHAs.

technologies. Combining the responses to Questions 2 and 4 together, it simply implies that SHAs have never intended to pursue savings by sacrificing lighting performance.

3.2.2 Current Use of New Lighting Technologies

In response to the question of how many years the respondent's agency has adopted new lighting technologies (Question 3), a total of nine respondents provided answers as shown in Table 3.3. It is very surprising that induction lighting was used much earlier than LED lighting which is probably today's most popular new lighting technology. Colorado started to use induction lighting around 10 years ago; Texas started about 5 years ago. Utah has used induction lighting for 5 years. However, all these three SHAs just started to use LED lighting recently. LED lighting has been used for no more than 3 years. Michigan started to use LED lighting around 2 years ago. For plasma lighting, Texas indicated that they have started using this new lighting source for 1 year.

A question (Question 5) was posed in the survey to identify on what types of roadways (interstate, US routes, state roads, local roads, etc.) and at what locations (urban, rural, intersection, rest area, etc.) new lighting technologies have been utilized by SHAs. Table 3.4 presents the summary of responses from these eleven SHAs that have utilized new lighting technologies. LED lighting has been used in various types of roadways, including interstate, US highway, and State route for both conventional and high-mast light standards. LED lighting has also been used at interstate interchange, conventional roadway intersection, and parking lot. For the two SHAs in the

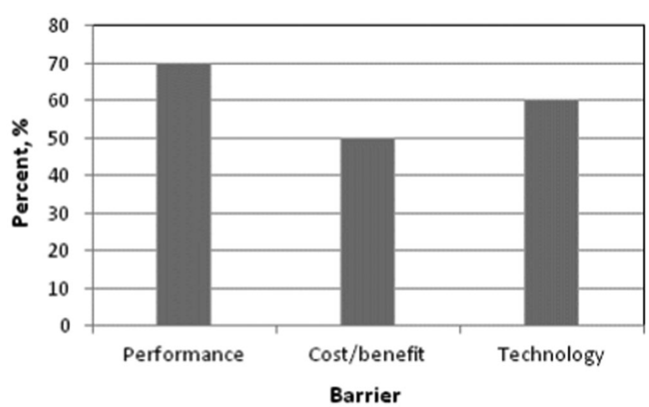


Figure 3.4 Barriers to use new lighting technologies by SHAs.

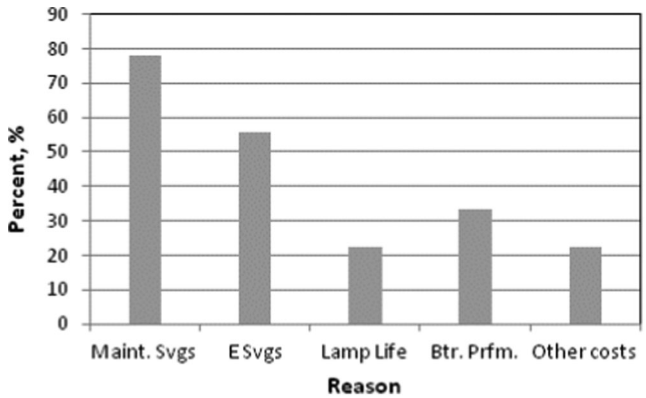


Figure 3.5 Reasons for adopting new lighting technologies by SHAs.

Midwest, LED lighting has been used on interstate and US highway in Michigan, but only on off-highway locations in Ohio. Induction lighting has been used on interstate by Michigan and Colorado. In addition, Texas and Utah have used induction lighting in tunnel or underpass. Florida, Utah and Washington have used induction lighting for sign lighting. Plasma lighting has been used for conventional roadway lighting and high mast lighting by Florida. In Texas, plasma lighting has been used only in parking lots. Apparently, both LED and induction lightings have been used for a wide range of applications. LED lighting has received increasing use recently. Nevertheless, plasma lighting has not received much attention for roadway lighting to date.

3.2.3 Expected Performance of New Lighting Technologies

One question (Questions 7) was asked of the respondents about the expected service lives and LCCs of new lighting luminaires. For LED lighting, seven SHAs, five from the West region, one (Texas) from the southern region, and one (Michigan) from the Midwest, returned their responses. The shortest service life is 10 years expected by Idaho and Texas and the longest service life is 21 years expected by Utah. For induction lighting, five SHAs, including Colorado, Michigan, Oregon, Texas and Utah, responded. The shortest service life is 10 years indicated by Oregon and Texas and the longest service life is 21 years by Michigan. For plasma lighting, two SHAs, Michigan and Texas, responded. The expected service life is 10.5 years by Michigan and 10 years by Texas. Figure 3.6 shows the average expected service lives computed from responses. The average expected service life is 13.2 years for LED lighting, 14.8 years for induction lighting, and 10.3 years form plasma lighting. Two main conclusions can be drawn from the above discussion. First, the expected service life was assumed to be greater than 10 years for these three new lighting technologies. Second, the service life for induction lighting is expected to be longer than LED and plasma lightings. It was also noted that no regional patterns of the expected service life were identified at this time.

For the expected LCCS of new lighting luminaires, the responses from different SHAs varied dramatically. It was also indicated that the LCCs depended on the lamp wattage. For LED lighting, the expected LCC varies between $38 (Utah) and $125 (California). It was indicated that California used either 163 or 216 watt LED bulbs, and Utah used either 140 or 220 or 225 watt bulbs. One reason why the LCC for Utah is so low is probably that Utah utilized a service life of 20 years. The LCCs range between $15 and $113 for induction lighting. The lowest LCC occurred in Colorado and was estimated in terms of 80 watt bulb and 15 year service life. For induction lighting, the greatest LCC occurred in Michigan, which was estimated using 146 watt bulbs by assuming a 25-year service life. For plasma lighting, the estimated LCC is $163 in Michigan, and $80 in Texas. As indicated in Table 3.4, Texas is using plasma lighting in parking lot. Figure 3.7 shows the expected LCCs for new lighting technologies. The average LCC values for LED, induction, and plasma lighting are approximately $80, $70, and $122 for LED. The plasma lighting was expected to have the greatest LCC, followed by LED lighting and induction lighting.

TABLE 3.3
Number of Years Using New Lighting Technologies by SHAs*

SHA	LED	Induction	Plasma
CA	2 years	N/A	N/A
WA	N/A	1 year	N/A
CO	3 years	10 years	N/A
ID	1 year	N/A	N/A
MI	2 years	1 year	N/A
OR	N/A	1 year	N/A
TX	1 year	9 years	1 year
UT	3 months	5 years	N/A
WA	N/A	1 year	N/A

*Baseline year: 2012.

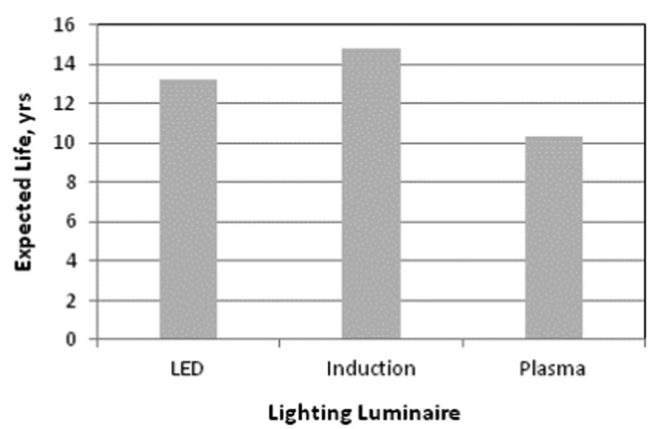


Figure 3.6 Expected service lives for new lighting luminaires by SHAs.

TABLE 3.4
Applications of New Lighting Technologies to Roadway Lighting by SHAs

SHA	LED	Induction	Plasma
CA	Interstate, US highway and State route in rural & urban	—	—
CO	Interstate, US highway, State route, parking lot	Interstate, US highway, tunnel	—
FL	Conventional roadway, high mast lighting	Sign, convention roadway, and high mast lighting	Conventional roadway, high mast lighting
ID	Interstate interchange, US intersection	—	—
MI	Interstate, US highway	Interstate	—
OH	Off-highway	—	—
OR		Turnpike, bike path	—
PA	Decorative lighting (retaining wall)	—	—
TX	All types of roadways	Underpass	Parking lot
UT	State route, rest area	Sign and underpass lighting	—
WA	—	Sign lighting (interstate)	—

3.2.4 Current Issues Associated with New Lighting Technologies

Four questions (Questions 8, 9, 10, and 11) were posed in the survey to identify the current issues in the use of new technologies by the respondents' agencies, such as installation, safety, light performance, and maintenance. Eight SHAs responded. Figure 3.8 shows the percent distribution of the issues in using the new lighting technologies. Half of the respondents indicated that they have issues associated with the performance and 25% of the respondents have issues associated with installation. The issues on safety and maintenance were indicated by 12.5% of the respondents. There is no doubt that the top issue in using these new lighting technologies is currently still about the performance.

For the issues about the performance, two respondents mentioned light patterns, one respondent mentioned surge protection, and one respondent mentioned the uncertainty about the claimed performance. For installation, one respondent indicated that the current AASHTO foot-candle level could be reduced if the new lighting technologies are utilized, and however, they had issues to determine the optimal food-candle level. Another respondent indicated that the electronic drivers were not as robust as the magnetic ballast and more surge protection was needed. For safety, one respondent indicated that safety is the top concern when moving to a new lighting system that is distinctly different from what the traveling public used to see. Safety concerns should be evaluated using lighting design software such as AGi32 and any safety concerns not found in the Agi32 model should be corrected through field verification. For maintenance, one respondent indicated that some problems were observed with failures of electronic drivers in induction fixtures.

One further question (Question 12) was asked about the respondents to rank the performance of the new lighting technologies currently in use: Excellent, Satisfactory, Unsatisfactory, or Not Applicable. The answer, "Not Applicable" was intended for those respondents who have not used the related lighting technology. Plotted in Figure 3.9 is the distribution of the respondents' satisfactions with LED and induction lightings. No response was available about plasma lighting. This may be due to the fact that the plasma lighting has been used just for a short period of time (one year as indicated in Table 3.3) at parking lot, and therefore, the respondents were still not 100% sure about its performance. For the performance of LED

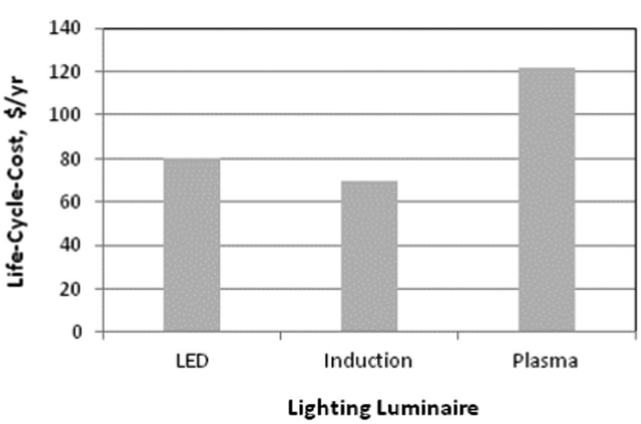


Figure 3.7 Expected LCCs for new lighting luminaires by SHAs.

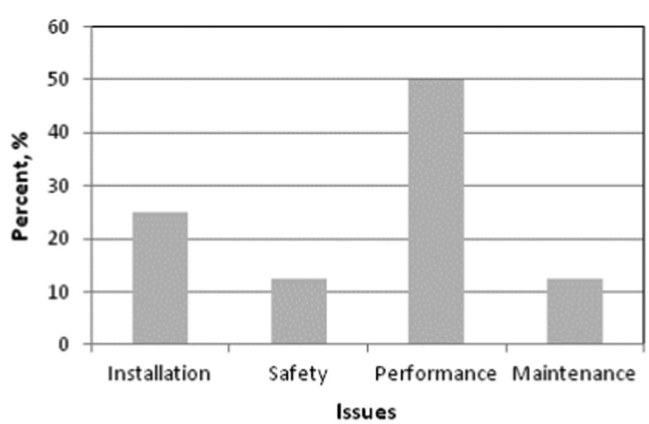


Figure 3.8 Distribution of issues in using new lighting technologies by SHAs.

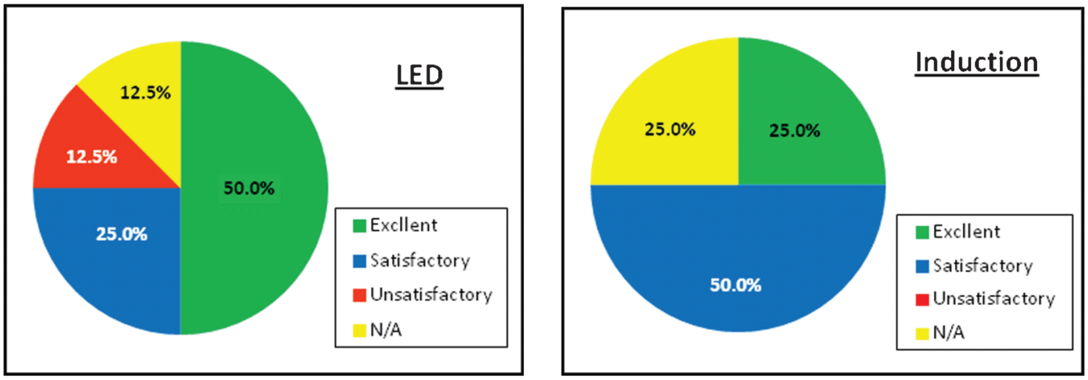


Figure 3.9 Percent satisfaction with new lighting technologies by SHAs.

lighting, 50% of the respondents selected "Excellent", 25% of the respondents selected "Satisfactory", 12.5% the respondents selected "Unsatisfactory", and 12.5% the respondents selected "Not Applicable". For the performance of induction lighting, 25% of the respondents selected "Excellent", 50% of the respondents selected "Satisfactory", 25% the respondents selected "Unsatisfactory", and no respondents selected "Not Applicable". The above observations can be extended to conclude that the new lighting technologies have made great progress in roadway lighting. Moreover, LED lighting has outperformed induction lighting for roadway lighting. However, issues still remain for these new lighting technologies.

3.2.5 Needs for Successful Adoption of New Lighting Technologies

New lighting technologies, particularly LED lighting, are evolving rapidly and have demonstrated great potentials for roadway lighting. However, it should be understood that new lighting technologies have distinctive features that may significantly vary from the conventional lighting technologies and many important aspects for their use in roadway applications must be understood and addressed in design procedure and construction standards. To enable successful application of new lighting technologies, one of the highest priority tasks is to establish appropriate approval procedures for adopting new lighting technologies and develop technical specifications for guiding the proper site application of new lighting technologies as promised. In the survey, three questions (Questions 6, 13, and 14) were designed to map out the status of the development of the necessary procedures and specifications by SHAs.

Table 3.5 presents the responses related to the specifications the respondent's agency has used. It is indicated that most of SHAs that have used the new lighting technologies are currently using specifications from the manufacturers or vendors. Three SHAs, including Idaho, Illinois and Wisconsin, are currently in the process of developing LED lighting specifications. Washington has specifications for the use of induction lighting for interstate sign lighting. The above indicates that the development of specifications for the use of new lighting technologies is lagging behind the advance of new lighting technologies. Also, it is possible that while SHAs are very receptive to new lighting technologies, they are waiting for national guidance provided by AASHTO or FHWA to address the potential issues on both technical and application aspects.

3.3 Local City Survey Results

3.3.1 Adoption of New Lighting Technologies

The investigators contacted 19 local cities and 9 cities responded. Table 3.6 lists the responses to the question (Question 1) about the adoption of new lighting technologies. Three cities have adopted both LED and induction lightings, four cities have adopted LED lighting, and one city has adopted plasma lighting. Overall, 88.9% of cities that responded to the survey have adopted at least one new lighting technology. While the sample size is small, two observations can certainly be made from Table 3.6. First, local cities seem very receptive to new lighting technologies. One city, Evansville, has not adopted any of the new lighting technologies, the respondent indicated that the municipality's street lights are owned, operated, and maintained by the area's sole utility provider and the adoption of any such roadway lighting technologies cannot be accomplished without the establishment of new tariffs through the Indiana Utility Regulatory Commission (IURC). Second, local cities are more experienced with LED lighting than induction or plasma. In particular, plasma lighting has just started to find a way into the application for street lighting.

When asked about the reasons for local cities to adopt the new lighting technologies (Question 4), eight cities returned responses as shown in Table 3.7. It is evident that the top three reasons for local cities to adopt new lighting technologies are energy saving, maintenance saving, and light property. All eight respondents indicated perceived energy savings from new lighting technologies, six respondents perceived maintenance savings from new lighting technologies, and three respondents selected natural light from new lighting technologies. Fort Wayne has observed a 50% or more energy reduction with LED lights. Greenfield has metered HPS, metal halide and LED lights, and found a 40% to 70% energy savings with the LED lights. The third reason as indicated by Valparaiso, Lafayette and Scottsburg is better light or more natural light provided by the new lighting technologies. The respondent from Greenfield also indicated that the public likes the white light look. Indianapolis indicated that LED and induction have better performance. Carmel pointed out the environmental benefit due to use of the new lighting technologies. Greenfield provided another reason, i.e., the federal grant. The availability of federal grants that provide complete or partial funding also has played a role in local agencies adopting new lighting technologies.

3.3.2 Current Use of New Lighting Technologies

As demonstrated in Table 3.8 are the responses to the question regarding how many years the respondent's city has used the new lighting technologies (Question 4). It is shown that local cities started to use new lighting technologies just recently. Valparaiso and Carmel have used LED lighting for 3 years, earlier than any of the other cities that responded to the survey. Generally, local cities started using LED lighting a little earlier than using induction and plasma lightings, while Fort Wayne started using induction lighting 6 months earlier than using LED lighting. As indicated in the responses, Huntingburg converted all street lights to LED in 2011. Greenfield has already installed LED lights for new installation and replaced the conventional cobra head lights with LED lights on all city streets. In addition to roadway lighting, LED lighting technology has long been utilized for signal lights as indicated by Lafayette.

Summarized in Table 3.9 are the responses to the question about the types of streets and locations where the new lighting technologies have been utilized (Question 5). In Fort Wayne and Huntingburg, LED lighting has been used almost everywhere, including corridors, and streets in industrial park and neighborhoods. Huntingburg has used LED lights for illuminating streets, interchanges and intersections in both rural and urban areas, a total of 720 fixtures. It was also indicated that in the responses by Greenfield, a total of 1400 LED light fixtures have been installed for all street lighting applications. In Valparaiso and Lafayette, LED lighting is majorly used on main streets. For induction lighting, its applications are still limited. Fort Wayne has used it for illuminating intersections. Valparaiso is currently conducting induction light testing on one street light. Evidently, LED lighting has been used on urban roadways of different classifications at different locations. Use of the induction or plasma lighting is still limited in urban street lighting. In particular, plasma lighting is still limited to minor urban streets or residential streets so far.

3.3.3 Performance and Issues Associated with New Lighting Technologies

Table 3.10 shows the responses to the question regarding the adoption of specifications on the use and performance of new lighting technologies provided by these nine cities (Question 6). It is implied that by the responses, the majority of local cities have used the specifications developed by either the manufacturers or vendors. When asked about the expected service lives for new lighting luminaires, the responses varied significantly from city to city and from light to light (see table 3.11). For LED lights, the service life perceived by the respondents varies between 10 and 20 years with an average of 15.7 years. For induction lighting, it seems that the service life did not live up to the expectation as indicated in the response by Fort Wayne. Overall, the cities perceived that LED lights may be capable of providing longer service life than induction and plasma lights.

Summarized in Table 3.12 are the responses to the questions about the issues associated with the use of new lighting technologies, such as installation, safety, performance, and maintenance (Questions 8–11). Three observations can be made through careful review of these responses. First, surge protection is necessary for

TABLE 3.5
New Lighting Technology Specifications Adopted by SHAs

SHA	LED	Induction	Plasma
California	Yes (mfr/ven)*	No	No
Colorado	Yes (mfr/ven)	Y (mfr/ven)	No
Idaho	Ongoing	No	No
Illinois	Ongoing	—	—
Michigan	Yes (mfr/ven)	Yes (mfr/ven)	No
Oregon	No	Yes (mfr/ven)	No
Texas	Yes (mfr/ven)	Yes (mfr/ven)	Yes (mfr/ven)
Utah	Yes (mfr/ven)	Yes (mfr/ven)	No
Washington	No	Yes**	No
Wisconsin	Ongoing	—	—

*mfr/ven = manufacturer or vendor.
**Interstate sign lighting.

TABLE 3.6
Adoption of New Lighting Technologies by Cities

City	LED	Induction	Plasma
Fort Wayne	Yes	Yes	No
Evansville	No	No	No
Valparaiso	Yes	Yes	No
Lafayette	Yes	No	No
Huntingburg	Yes	No	No
Greenfield	Yes	No	No
Indianapolis	Yes	Yes	No
Carmel	Yes	No	No
Scottsburg	No	No	Yes

TABLE 3.7
Reasons for Adopting New Lighting Technologies by Cities

City	Responses
Fort Wayne	(1) Energy reduction, and (2) virtually zero maintenance required
Valparaiso	(1) Energy savings, (2) maintenance savings, and (3) more natural light
Lafayette	(1) Energy savings, (2) maintenance savings, and (3) more natural light
Huntingburg	(1) cost savings, (2) low maintenance
Greenfield	(1) Federal fund, (2) energy savings, and (3) maintenance saving
Indianapolis	(1) Energy efficiency, and (2) better performance
Carmel	(1) Cost saving, and (2) environmental benefits of reduced energy consumption
Scottsburg	(1) Less energy consumption, (2) lower maintenance, and (3) full spectrum light

TABLE 3.8
Number of Years Using New Lighting Technologies by Cities*

City	LED	Induction	Plasma
Ft. Wayne	1.5 years	2 years	—
Valparaiso	3 years	2 years	—
Lafayette	2 years	—	—
Huntingburg	2 years	—	—
Greenfield	1 year	—	—
Indianapolis	1 year	2 years	—
Carmel	3 years	—	—
Scottsburg	—	—	2 years

*Baseline year: 2012.

TABLE 3.9
Applications of New Lighting Technologies to Street Lighting by Cities

City	LED	Induction	Plasma
Fort Wayne	Interchange, corridors, intersections, industrial park, neighborhoods	Intersections	—
Valparaiso	Main streets	Streets (test)	—
Lafayette	Urban streets	—	—
Huntingburg	All street lights (720 fixtures), interstate and local, urban and rural intersection	—	—
Greenfield	All city streets (1400 fixtures)	—	—
Indianapolis	Urban and residential streets	Urban streets	—
Carmel	Local urban and residential streets, interchange	—	—
Scottsburg	—	—	Side and residential streets

TABLE 3.10
New Lighting Technology Specifications Adopted by Cities

City	LED	Induction	Plasma
Fort Wayne	Yes (mfr/ven)	Yes (mfr/ven)	—
Valparaiso	Yes (mfr/ven)	—	—
Lafayette	Not sure	—	—
Huntingburg	Yes (mfr/ven)	—	—
Greenfield	Yes (mfr/ven)	—	—
Indianapolis	Yes (mfr/ven)	Yes (mfr/ven)	—
Carmel	Yes (mfr/ven)	—	—
Scottsburg	—	—	Yes (mfr/ven)

TABLE 3.11
Expected Service Lives for New Lighting Luminaires by Cities

City	LED	Induction	Plasma
Fort Wayne	20 yrs or more	Not sure	—
Valparaiso	20 yrs	—	—
Lafayette	10 yrs	—	—
Huntingburg	20 yrs ($30/yr)	—	—
Greenfield	15 yrs	—	—
Indianapolis	10 yrs or more	5–10 yrs	—
Carmel	15 yrs (LCC = $1410)	—	—
Scottsburg	—	—	11 yrs

TABLE 3.12
Issues in Using New Lighting Technologies by Cities

City	Installation	Safety	Performance	Maintenance
Fort Wayne	Complaint about the universal mounting system. Some models are easier to level than others.	No	Induction has not served us well. Driver failures are apparently common. They do not survive voltage spikes as well as LED fixtures. We have had to service the majority of the induction lights. We don't have many of these in service.	No issues with any of the LED fixtures to date.
Valparaiso	Need surge protectors	No	First street lights in LED had no surge protectors, lighting hit and took out 50%	No
Lafayette	No	No	No	No
Huntingburg	No	No	No	No
Greenfield	Need new support arms on some of older parts of town	No	No	Need to replace the drivers in the some fixtures
Indianapolis	No	No	No	No
Carmel	No	No	No	No
Scottsburg	Early designs difficult to install, and now more user friendly	No	No	No

TABLE 3.13
Satisfaction Ranking for New Lighting Technologies by Cities

City	LED	Induction	Plasma
Fort Wayne	Satisfactory	Unsatisfactory	—
Valparaiso	Excellent	Excellent	—
Lafayette	Excellent	—	—
Huntingburg	Excellent	—	—
Greenfield	Excellent	—	—
Indianapolis	Excellent	Satisfactory	—
Carmel	Excellent	—	—
Scottsburg	—	—	Satisfactory

both LED and induction lightings. Second, electronic driver failures might be one of the common failure modes for the new lighting technologies. Third, issues may arise in the installation, particularly the use of the existing pole infrastructure. Four cities, including Lafayette, Huntingburg, Indianapolis, and Carmel, indicated that they had no issues at all in using LED lighting. Three cities, including Fort Wayne, Valparaiso, and Indianapolis, provided mixed responses on induction lighting. Scottsburg has encountered problems in installing the plasma light. Overall (see Table 3.13), local cities were very satisfied with the performance of LED street lighting. Induction street lighting has not worked as promised so far. Plasma street lighting is just getting started. It is likely that to date, LED lights can provide consistent and satisfactory performance in street lighting.

4. FIELD EVALUATION OF HPS AND ALTERNATIVE LUMINAIRES

4.1 Test Site

4.1.1 Site Selection

Figure 4.1 shows the test site selected for evaluating the performance of new light sources. The test site is located at the interchange of I-74 and US-231, a partial cloverleaf interchange in Crawfordsville, Indiana. This site was chosen due to two main reasons. First, the current lighting applications consist of almost all possible roadway lighting applications for INDOT, such as interstate lighting, conventional roadway lighting, interchange lighting, HM (tower) lighting, and conventional lighting pole (standard). Therefore, the results can be used not only to evaluate the performance of new lighting technologies, but also to assess the use of existing lighting fixtures and poles. Second, the test site is close to the INDOT Crawfordsville District and approximately 28 miles away from the INDOT's Division of Research and Development (R&D). This makes it very convenient for the District Signal and Lighting unit to install and maintain the lighting luminaires and easier for the Personnel from R&D Division to conduct field footprint measuring. Another reason is that, as indicated by the SAC members, this site may be used as a permanent test site for evaluating lighting technologies in the future.

The test site was divided into 5 test zones as shown in Figure 4.1. The first test zone is located on US-231 northbound, consisting of Poles 1, 2 and 3. The second and third test zones are located on US-231 southbound with Poles 4, 6 and 7 in Zone 2 and Poles 8, 9 and 10 in Zone 3. The fourth test zone is located on I-74 westbound with Poles 14, 15, and 16. The fifth test zone is the upper quadrant of the interchange with a single high mast tower lighting pole, Pole T-2. Based on the traffic volume reports in 2010 (*33*), the AADT was 13,090 in Zone 1, 10,670 in Zone 2, and 15,902 in Zone 3. The AADT on the ramps in Zone 4 was 3,160.

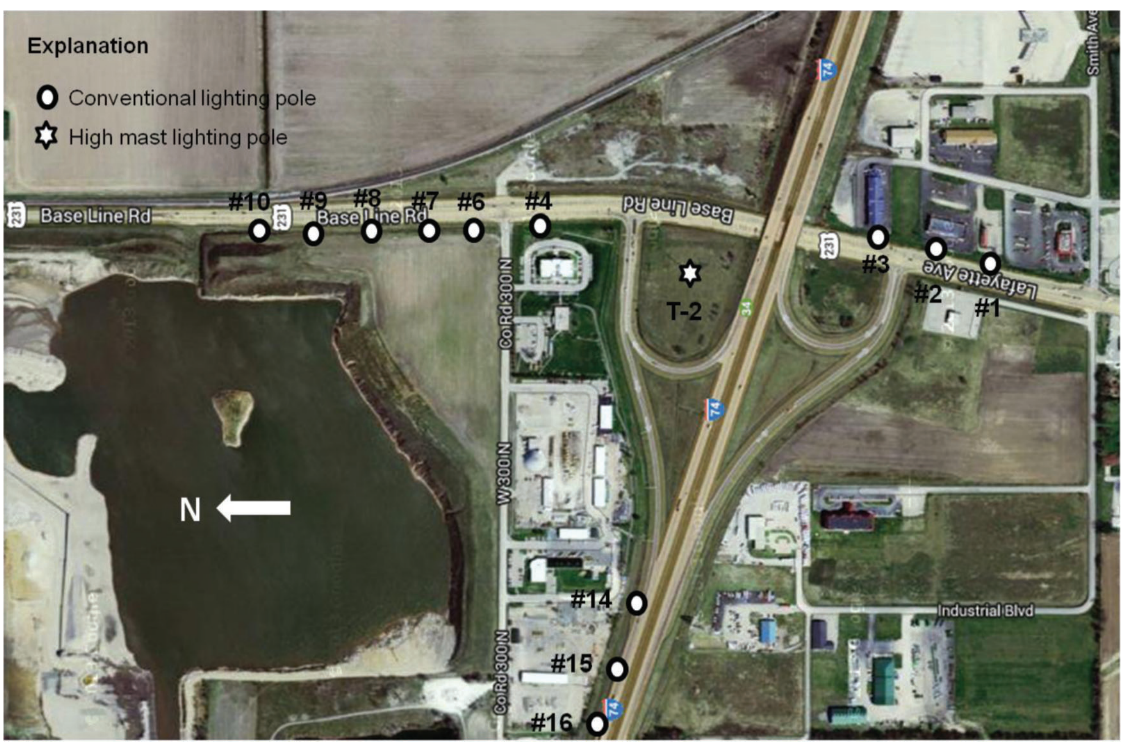


Figure 4.1 Map of test site.

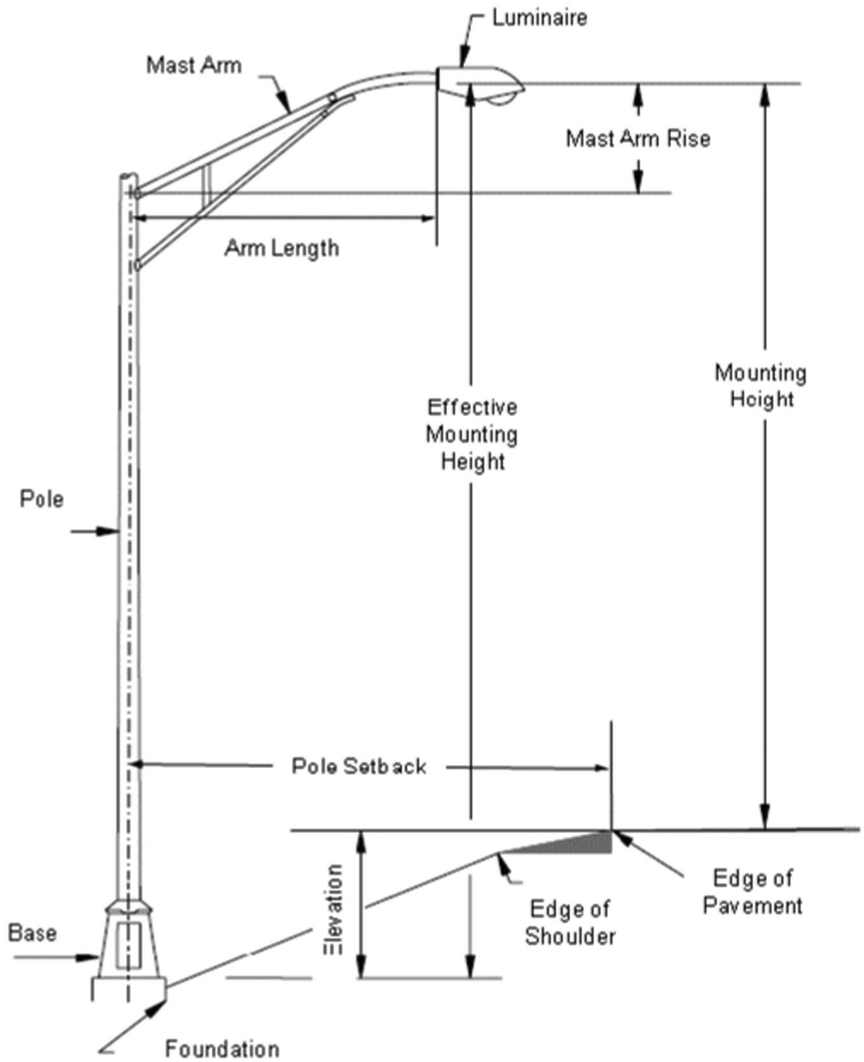


Figure 4.2 Design parameters for light pole.

4.1.2 Existing Light Infrastructures

One of the major factors affecting roadway lighting performance is the selection of light pole, particularly mounting height, arm length, and pole setback as defined in Figure 4.2 (*3*). For HM poles, the mounting high ranges from 80 ft to 200 ft in height. A higher mounting height reduces the number of poles required. For conventional light poles, the mounting height may vary from 30 ft to 50 ft. However, the practice of INDOT is to use a light pole with a mounting height between 40 ft and 50 ft and the recommended minimum mounting height is 40 ft. The arm type depends on its length. For single-member design, the arm length is usually less than 8 ft. For truss-type design, the arm length is commonly 8 ft or longer. The arm rise ranges between 4 ft and 8 ft, depending on the arm length. The greater the arm length is, the greater the arm rise is. The pole spacing or luminaire spacing depends on the light requirement, roadway geometry, light output (lamp lumens), and lamp depreciation. As the required light level and pavement width increases, the required pole spacing decreases. A higher light output will result in larger pole spacing. For conventional roadway lighting, the INDOT's practice is to use a 40-ft height pole with HPS lamps of 250 watt or 400 watt. For HM lighting, 1000 watt HPS bulbs are commonly used. Currently, HPS is the only light source used by INDOT for each new installations of conventional or high-mast lighting.

Presented in Table 4.1 are the geomertic dimensions of the current light poles in these five test zones at the test site. Field visits were conducted to verify the design dimensions of the light poles using a measuring wheel. Most measured dimensions agree well with the desing dimensions, except for the pole spacing between poles 4 and 6. Discrepancies can be observed between the desing mast arm length (MAL) and measured MAL. In addition, discrepancies exist between the measured pole setback and the design pole setback. The exisitng light poles at the test site were installed in 1993. In the past 20 years, both US-231 and I-74 have undergone resurfacing, adding turning lane or pavement re-striping. As a results, some poles might have been relocated and the roadway dimensions may have been

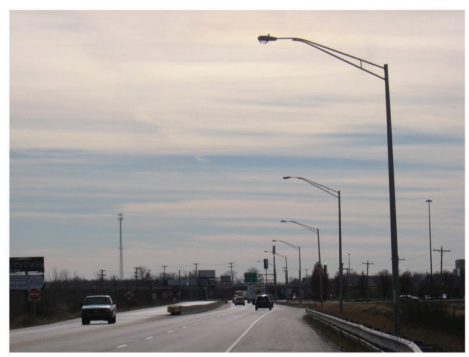
TABLE 4.1
Geometric Dimensions of Light Poles

Test Zone	Pole #	Pole Spacing		EMH (ft)	MAL (ft)		Pole Setback (ft)	
		Design	Measured		Design	Measured	Design	Measured
1	1	—	—	42	15	18	20	20.0
	2	275	273					19.5
	3	280	277					20.6
2	4	—	—	42	15	16	20	8.7
	6	300	340					20.4
	7	280	280					21.0
3	8	—	—	42	15	15	20	20.4
	9	290	289					22.4
	10	290	287					20.6
4	14	—	—	42	15	18	20	23.5
	15	270	270				20	24.3
	16	270	274				15	21.1
5	T-2	N/A	N/A	125	—	—	225 (offset from US 231)	

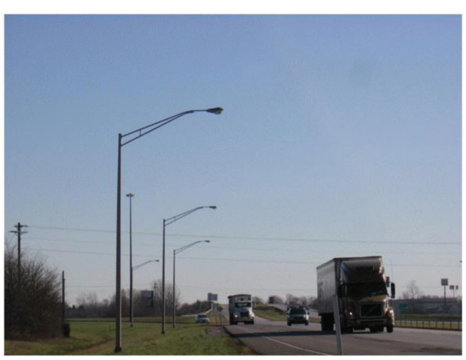
altered. Thus it is recommended that the design parameters of light poles should be verfiifed periodically or after some major road works. The effective mounting height (EMH) is 42 ft for all conventional lighting poles and 125 ft for the HM lighting pole.

In Zone 1, the test section on US-231 consists of 2 through lanes and 1 turning lane. In Zones 2 and 3, the test sections on US-231 consist of 1 through lane and 1 turning lane. In Zone 4, the test section of I-74 consists of 2 through lanes and 1 acceleration lane. For the HM lighting in Zone 5, the area to be lighted covers a 2-way ramp, part of interchange and a signalized, 3-leg intersection of US-231 and the ramp. Figure 4.3 shows the photos of the light poles and fixtures in these four test zones. It can be seen that for the conventional lightings in Zones 1, 2, 3 and 4, the mast arms of the light poles are all truss-type arm and the the light fixtures are all cobra-head fixtures. The luminaires are

(a) Zone 1



(b) Zones 2 and 3



(c) Zone 4

(d) Zone 5

Figure 4.3 Photos of light poles at test site.

(a) 250 W (b) 400 W (c) 1000 W

Figure 4.4 Photos of HPS Cobra Head luminaires.

placed on the side of the roadway and designed to produce a long, narrow, oval-shaped lighted area (IES Type II, III or IV) which is commonly applicable to 2- to 3-lane roadways. The spacing of light poles varies bewteen 6 to 7.5 mounting heights and is capable of producing a medium vertical light distribution. For the high mast lighting in Zone 5, the luminaire is placed at an offset of 225 ft from US-231 to produce a circular, lighted area, i.e., a lateral light distribution of IES Type V. Again, it is shown that in Figure 4.3, the setbakc of light pole on I-74 in Zone 4 is greater than that in Zone 1, 2 or 3. The luminaires are almost right above the pavement edge painting in Zones 1, 2, and 3, about 3 ft away from the should edge.

4.2 Installation of Luminaires

4.2.1 Selected Luminaires

The final selections of luminaires were made by taking into consideration the objectives of this study, the availability of the luminaires currently commercially available, and the promotions from manufacturers and vendors, and were approved by the SAC members. In order to compile the first-hand information and original data on new lighting sources to INDOT electrical, lighting and design engineers, and in order to compare the photometric and economic performances between HPS lighting and the new lighting sources, a total of 10 types of luminaires, including 3 HPS luminaires, 4 LED luminaires, 1 plasma luminaire, 1 induction luminaire, and 1 MH luminaire, were formally selected for field evaluation and monitoring. Summarized in Table 4.2 is the information on these selected luminaires. The 3 HPS luminaires, as shown in Figure 4.4, consist of 250W and 400W cobra head luminaires for conventional lighting and 1000W cobra head luminaires for HM lighting typically utilized by INDOT. The 4 LED luminaires include GE ERS4 258W luminaires (*34*), Philips RVM 270W LED luminaires (*35*) and Horner 200W LED luminaires for conventional lighting (*36*), and Global Tech 392W LED luminaires for HM lighting (*37*). The

TABLE 4.2
Information on Selected Luminaries

Lamp Type	Manufacturer	Initial Lumens	Lamp Efficacy	Power Factor	CCT (K)	CRI	Average Life (h)	Vibration Resistance	IP Rating	Warranty (yrs.)	Price ($)
250W, HPS	GE LU250	27500	110		2100	22	40000				54.40*
400W, HPS	GE LU400	50000	125		2000	22	40000				68.58*
1000W, HPS	GE LU1000	130000	130		2100	22	24000				105.70*
320W, MH	EcoReady Firebird	30000	94		4100	65	20000				80.10*
258W, LED	GE Evolve ERS4	20500	79	≥0.90	5700	70	50000 (L85)	2G	IP65	5	800.00**
270W, LED	Philips RoadView RVM	20775	77	≥0.90	4300*	70	100000 (L70)	3G	IP66	—	950.00**
200W, LED	Horner ETG	19400	97	—	5000	70	100000 (L70)	—	IP66	3	850.00**
392W, LED	Global Tech SoLtice LED	27136	81	—	4998	67	100000	—	IP66	5	1750.00**
295W, Plasma	Stray Light Optical Technologies, TESLA II	23000	78	0.99	5500	75	50000	—	IP67	—	850.00**
200W, Induction	EcoLuminator: PMX-ILS-200SL	20000	100	0.95	5000	86	100000	—	IP65	5	500.00**

*Per lamp.
**Per fixture.

Figure 4.5 Photos of LED, induction, plasma, and MH luminaires.

induction luminaries are EcoLuminator 200W induction luminaires for conventional lighting (*38*). The plasma luminaires are Stray Light 295W plasma luminaires and are also used for conventional lighting (*39*). The MH luminaires are GE 320W MH luminaires for conventional lighting (*40*). The photos of the selected luminaires are shown in Figure 4.5. The HM light pole was retrofitted with the Global Tech Solstice LED modules.

The GE Evolve™ LED is promoted to meet recommended luminance and illuminance requirements for local to major roadway/street classifications and can yield up to a 50% reduction in system energy compared with standard HID systems, depending on roadway applications, and can also be paired with programmable dimming options for even greater savings and control. Philips RoadView LED series are created to offer exceptional performance and value, and enhanced energy efficiency, and can be tailored to the unique specifications of each project, while being easy to install and maintain. The TESLA II plasma is claimed to be an ideal lighting fixture for streets, parking lots and other high illuminance applications and is designed to replace 400W metal halide and HPS, 1000W mercury vapor, and 1500W incandescent lighting fixtures without the need for new poles or changed spacing. Powered by the Luxlite induction lamps, the EcoCobra induction street lights are designed to provide bright white, high efficient lighting for streets and roadways while reducing the power consumption (40%~60%) and maintenance & disposal costs. The EcoReady Firebird MH luminaires offer high-efficiency and crisp white light and deliver exceptional long life (*41*).

It can be observed that from Table 4.2, HPS lamps provide the highest lamp efficacy (110 lm/W~130 lm/W). A lamp with higher luminous efficacy tends to provide radiant power within a narrow range of wavelengths, resulting in limited color rendering. Both the MH and induction lamps provide relatively high luminous efficacy, and also maintain good color rendering. The LED and plasma lamps demonstrate similar lamp efficacy and CRI, and are equally effective. It is very interesting to note that the Horner LED fixtures are designed to provide a luminous efficacy of 97, which is greater than that provided by other LED fixtures and close to that by HPS. Based on the information summarized in Table 4.2, the following aspects should be considered while selecting new lighting sources:

- Lamp/fixture
  - Photometric properties: lamp watts, initial lumen, CRI, CCT, light distribution type
  - Performance: lumen maintenance, service life
  - Safety: UL1029
  - LM-79, LM-80 and ANSI C78.377 tests and reports
  - Safety: UL1598
  - IP rating: IP65 or better (ANSI C136.25)
- Electrical
  - Voltage
  - Power factor
  - Surge protection: UL 1449 or IEEE/ANSI C62.41
  - Ballast sound rating: A
  - Electromagnetic Interference (EMI): Class A (Title 47 CFR Part 15)
  - Photo electric sensor
- Housing
  - Vibration resistance: 2G or better (ANSI C136.31)
  - Material: Die cast aluminum housing (A360)
  - Slipfitter mount: Adjustable ($\pm 5^{\circ}$) for leveling
  - Wildlife intrusion protection
- Others
  - Materials: Restriction of hazardous substances (RoHS) compliant
  - Upward light output ratio (ULOR) rating: 0
  - Temperature rating: -40°F~122°F
  - Warranty: 5–7 years

4.2.2 Field Installation

The selected luminaires were installed on the existing lighting poles at the test site during the study period by the Traffic Signal Unit of INDOT Crawfordsville

TABLE 4.3
Manpower, Time and Cost for Installing Selected Luminaires

Luminaire Type	No. of Luminaires	No. of Technicians	Hours	Costs ($)
EcoCobra induction	3	3	7.5	604.07
Philips RVM LED	3			
Tesla II plasma	3	3	7.5	476.75
GE LED ERS4	3			
Horner LED	3	3	2	106.96
High Mast LED	6	2	4	149.04
EcoReady metal halide	3	3	2	106.96

District. The field luminaire installation required a minimum of 4 technicians, one aerial/bucket truck, two attenuator trucks, and traffic cones, and consisted of the following steps:

a. Traffic control: Traffic control was set-up using traffic cones and two attenuator trucks in accordance with the INDOT Work Zone Traffic Control handbook (*42*).
b. Removal of existing fixture: Two technicians were required.
c. Installation of new fixture: Two technicians were required.
d. Testing of luminaire.

Summarized in Table 4.3 are the manpower, time, and cost utilized in the new luminaire installations. The EcoLuminator induction and Philips RVM LED fixtures were installed on February 8, 2012. It took approximately 7.5 hours to install a total of 3 induction fixtures and 3 LED fixtures. The installation of 3 Tesla II plasma and 3 GE LED ERS4 fixtures were completed on February 9, 2012. It also took the technicians 7.5 hours. The Horner LED and HM LED fixtures were installed on May 16, 2012. The MH fixtures were installed on September 6, 2012. The total cost for installing the lighting fixtures consisted of the manpower and equipment required not only for the installation of the fixtures, but also for traffic control. Because the numbers of lanes on the roads are different in these four test zones, it is hard to compare the costs for traffic control in different test zones. For example, the traffic control for a multi-lane road requires more attenuator trucks than a 2-lane road. Therefore, the costs for traffic control were not included in the final comparison. Also, the installation of HM lighting fixtures does not require any bucket truck and traffic control. Therefore, only those costs associated with the manpower in installing the lighting fixtures were considered in this study.


Figure 4.6 Field luminaire installation.

Presented in Figure 4.6 is a photo of field luminaire installation. When asked about the possible issued in installing the luminaires, the comments from the technicians involved in the installation were summarized below:

- Phillips RVM LED: Basically every aspect was user friendly. The fixtures are lighter and easier to hold and level.
- GE ERS4 LED: The fixtures are a little heavier and a little difficult to level. They were a solid unit and the internal access was user friendly.
- Stray Light Telsa II plasma: The fixtures were easy to install and level. The electrical connections are very user friendly and easy to access.
- EcoLuminator EcoCobra induction: These fixtures were the most time consuming and difficult to install. They were the heaviest of the four. The terminal block is more difficult to access and has a small screw termination.
- Other fixtures: No issues were identified in installation.

4.3 Field Light Measurements

4.3.1 Light Illuminance Testing

Testing instrument. During the light illuminance testing, the standard light illuminance was measured using an illuminance meter, i.e., Konica Minolta T-10 (*43*), as shown in Figure 4.7. This illuminance meter can be operated at −10°C to 40°C, which allows possible light illuminance testing throughout the entire

Figure 4.7 Konica Minolta illuminance meter T-10.

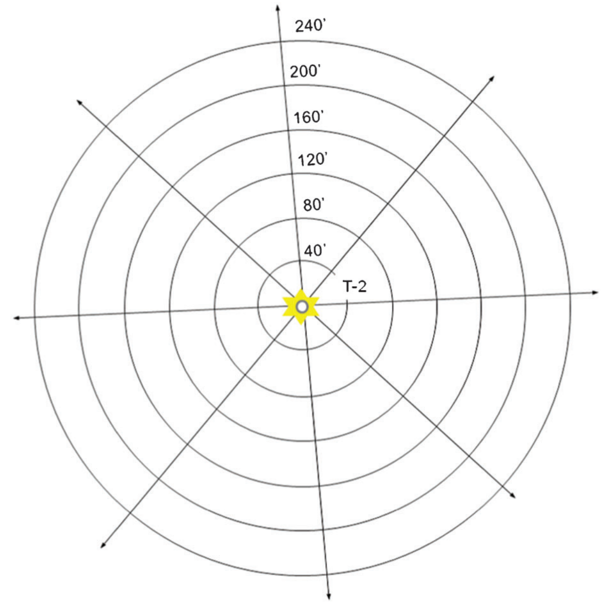


Figure 4.9 Schematic of measurement grid for HM lighting.

year. It also has functions to calculate the average illumination, compare the measured illuminance with the target value, and display the results on the LCD screen. In addition, this illuminance meter has the ability to automatically perform calibration after switching on the device. It can be used to measure continuous and intermittent light sources. Users can also enter color correction factors for adaptation to certain light sources. This illuminance meter provides a wide measuring range of 0.001 fcd to 29,990 fcd.

Measurement grids. In the four conventional lighting test zones, i.e., Zones 1, 2, 3 and 4, each consists of 3 light poles, i.e., 2 luminaire cycles. Initially, it was intended to measure the light illuminance for all 2 luminaire cycles in each test zone. However, field visits revealed that it was not practical due to the nature of the test site and many unexpected restrictions as follows:

- Effect of roadside objects. In Zone 1, Pole 1 is very close to the traffic signal and commercial street lightings, and the light on pole 3 was partially blocked by a large guide sign on US-231.
- Variation of light pole installation. In Zone 2, the spacing between Poles 4 and 6 is much greater than that between poles 6 and 7. The pole setback also varies dramatically from pole to pole in Zone 2 and 4.
- Traffic control. Lane closure is not allowed after 2:00am in Zone 4, which limits the time available for light testing.

Therefore, the measurement grid setup could only follow the IESNA guide (*44*) as closely as possible and was determined in light of the surrounding condition in each zone. Figure 4.8 shows the basic setup of measurement grid for illuminance testing in Zones 1, 2, 3 and 4. The midpoint of the measurement grid was longitudinally aligned with the middle pole of the three poles. The measurement points were set on a 10' × 12' grid in zones 1, 2, 3 and 4. In Zone 5 on I-74, the measurement points were set on a 10' × 12' grid in the driving lanes and on a 6' × 12' grid in the shoulder. This grid setup made it possible to place the measurement points on the lane markings and easier for field testing. In Zone 5 (HM lighting), the measurement grid was laid out on a grid at 40' spacing in radial direction (see Figure 4.9).

During testing, the measurement grid in each zone was modified according to field conditions, such as adjacent lights, ground objects and roadway geometrics. In Zones 1, 2, 3, and 4, the measurement grid

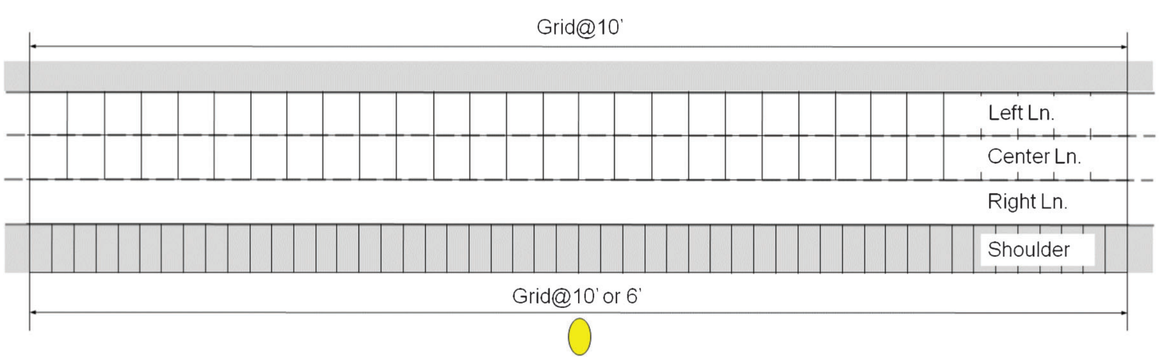


Figure 4.8 Schematic of measurement grid for conventional lighting.

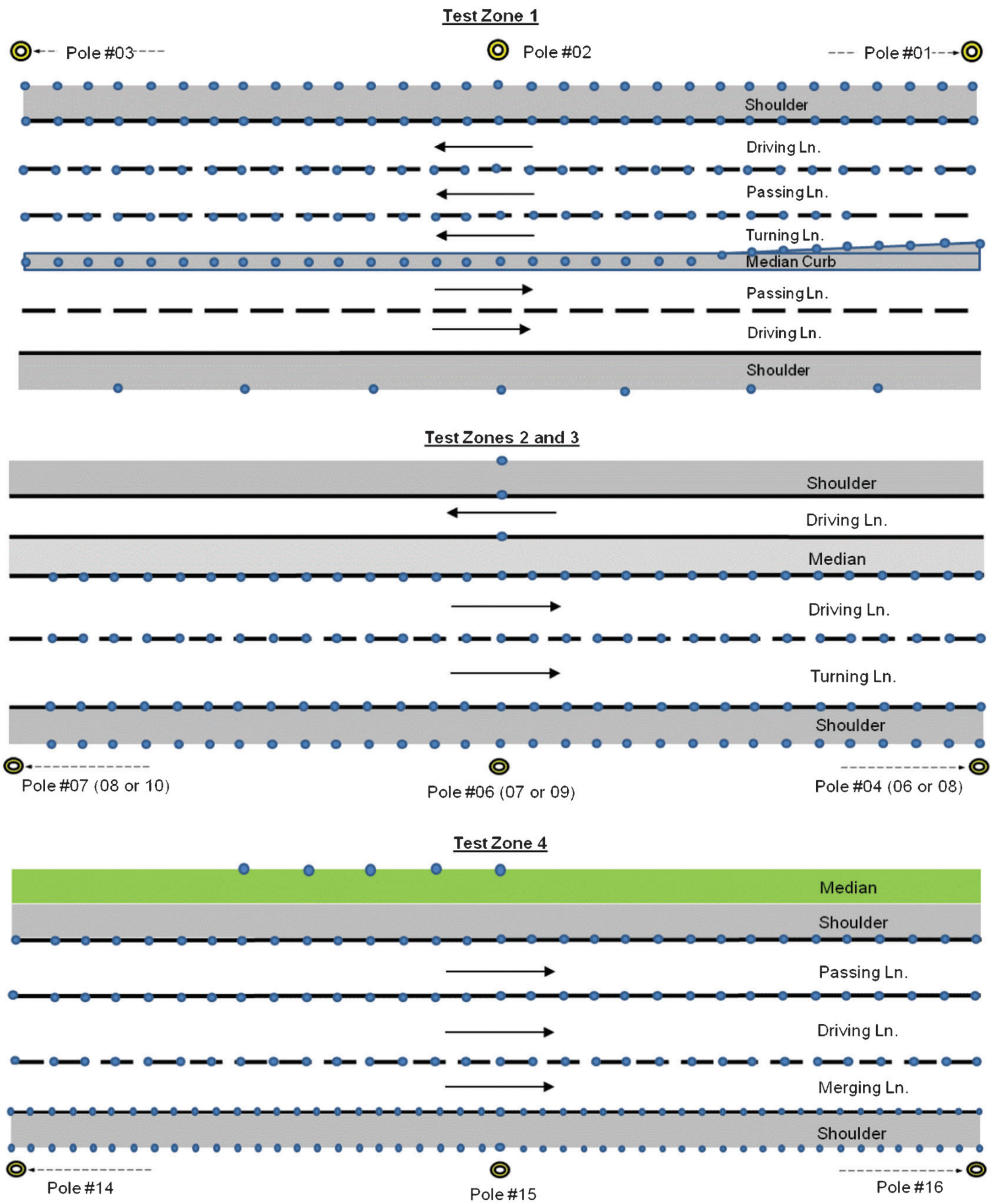


Figure 4.10 Field measurement points in Test Zones 1, 2, 3 and 4.

setup covered all travel lanes and the shoulder to provide four rows of measurement points in Zones 2 and 3 (2 travel lanes), and five rows of measurement points in Zones 1 and 4 (3 travel lanes). In Zone 5 (HM lighting), the measurement grid setup covered the whole quadrant, providing eight rows of measurement points. Additional measurement points were also added to determine the light levels in the medians on I-74 in Zone 4 and on the interchange ramp in Zone 5.

Illuminance testing. In the field illuminance testing, traffic control setup started approximately 1 hour before it got dark. Once the traffic control setup was completed, a 100-ft measuring tape and permanent paint were used to mark the locations for measurements. All light illuminance measurements were made after sunset and when the sky had become dark. In Zones 1, 2, 3 and 4, the illuminance measuring started at the middle pole and ended when the illuminance reading rose. A total of 162 measurements were taken in Zone 1, 123 measurements in Zone 2, 123 measurements in Zone 3, and 196 measurements in Zone 4 (Figure 4.10).

In Zone 5, a total of 40 measurements were taken around the high mast light pole. The illuminance

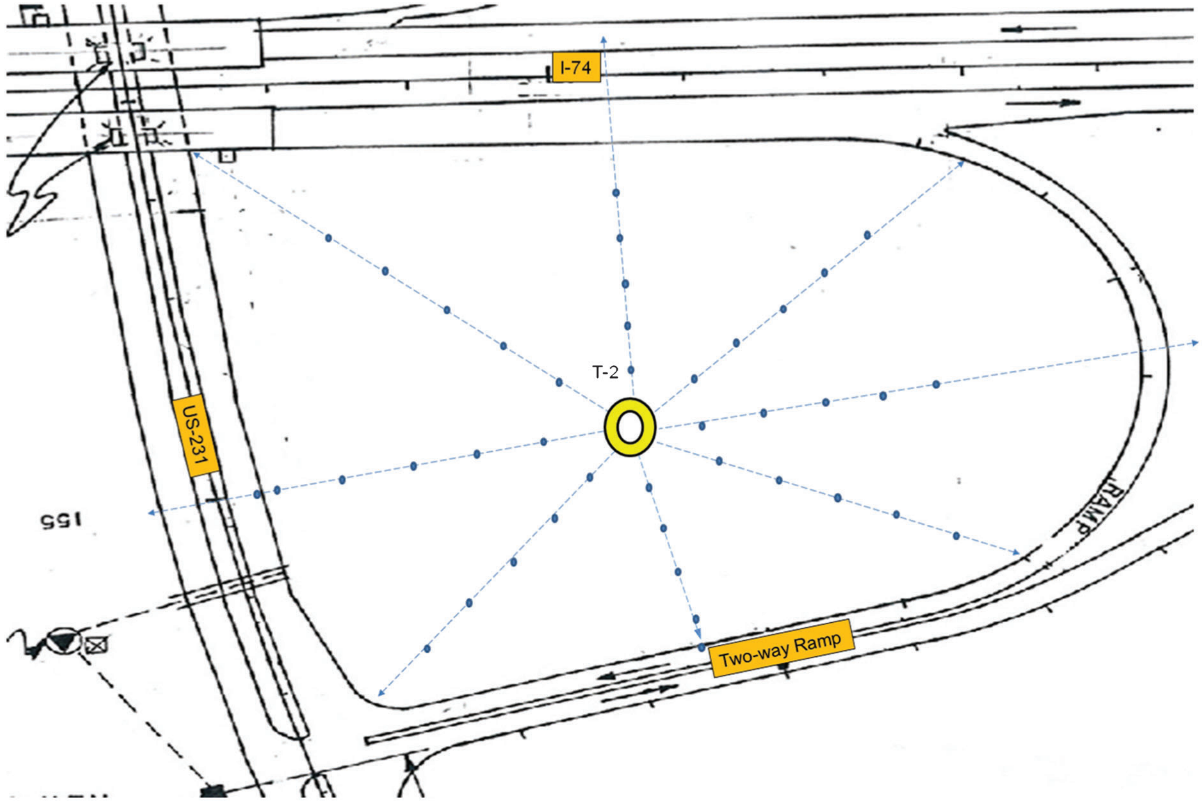


Figure 4.11 Field measurement points in Test Zone 5.

measuring started from the HM pole and ended at the edge of roadside ditches as illustrated in Figure 4.11.

4.3.2 Power Measuring

The power measurements were made while the power supply was switched on. Only amperage readings were taken by using a digital multi-meter. While taking the reading, the clamp on the red probe was set on one open end and the clamp on the black probe set on the other open end. For the HPS luminaires, the amperage readings (cold) were first taken as the light was powered and the luminaire was heating up, usually within first 5 to 15 minutes of being energized. After the luminaire had been energized all night, the amperage readings (hot) were taken again as soon as the technicians came in the morning. For the LED, plasma and induction luminaires, the trial measurements did not demonstrate any differences between the cold and hot readings. As a result, the amperage readings were taken once in the morning.

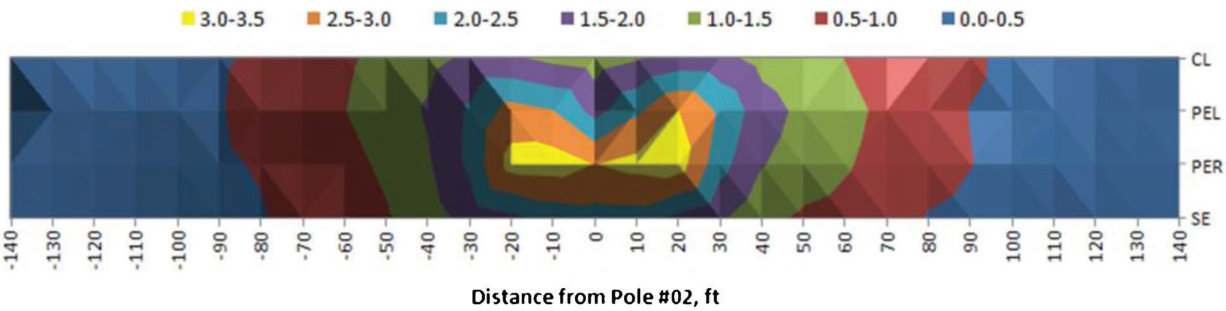
5. COMPARISONS OF FIELD TEST PERFORMANCES

5.1 Light Distributions

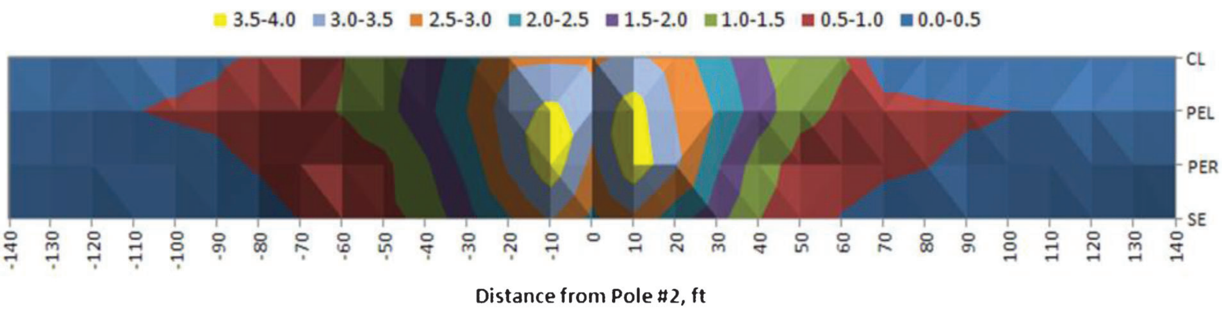
5.1.1 Conventional Lighting in Zone 1

Figure 5.1 shows the illuminance footprints for the luminaires measured in Zone 1, including HPS 250W, GE 258W LED (ERS4), Philips 270W LED (RVM), and Horner 200W LED. Notice that each of the footprints represents only part of the corresponding lighted road surface area. Three observations can be made through careful inspection of the footprints. First, the HPS, GE LED and Philips LED luminaires produced oval-shaped lighted areas, while the lighted area by GE LED demonstrates two angles, one at each end. The Horner LED produced a circular lighted area. Second, the areas lighted by the HPS and GE LED luminaires are very close in size and greater than those by the Philips and Horner LED luminaires. The Horner LED luminaire produced the smallest lighted area. Third, all four different luminaires produced measureable illuminance, i.e., 0.05 foot-candles or greater (*45*), over the pole spacing. The percentages of grid points with illuminance of greater than 0.2 foot-candles for the HPS, GE LED, Philips LED, and Horner LED luminaires are 98%, 96%, 94%, and 60%, respectively.

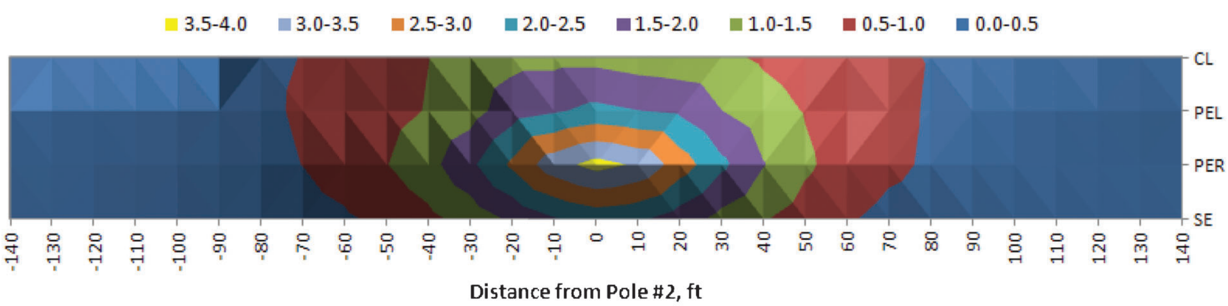
The light distributions are different directly under the luminaires. For both the HPS and GE LED luminaires, the illuminance measurements demonstrate a double-hump distribution. The greatest illuminance occurred at two locations symmetrical to the luminaire. For the Philips LED and Horner LED luminaires, the illuminance measurements show a single-hump distribution. The greatest illuminance occurred only at one location, i.e., the pavement surface directly under the luminaire. Therefore, the resulting contour plot peaked at the



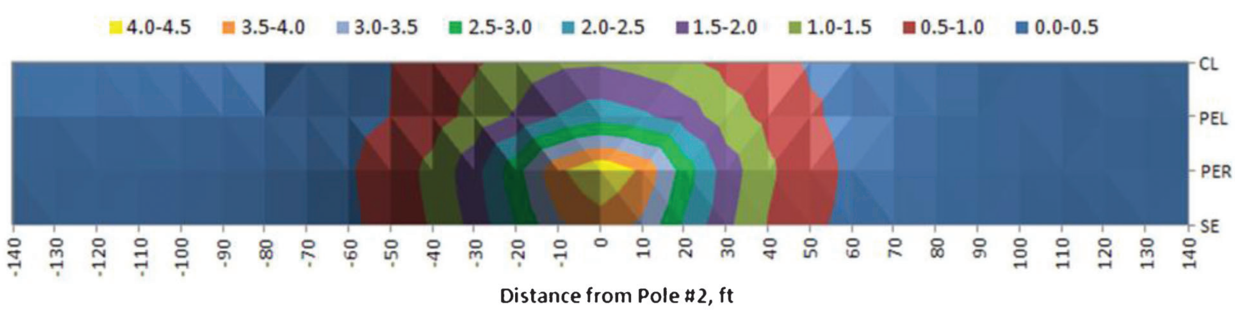
(a) 250 W HPS



(b) GE 258 W LED (ERS4)

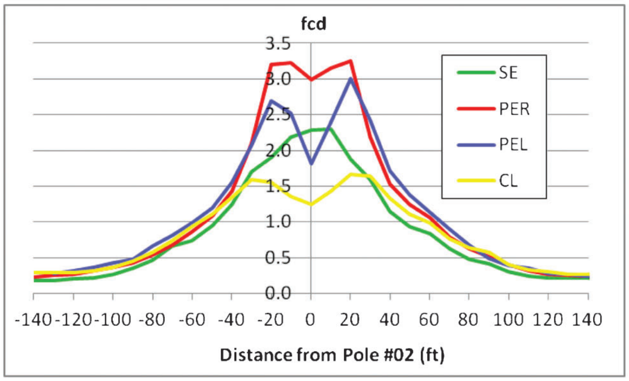


(c) Philips 270 W LED (RVM)

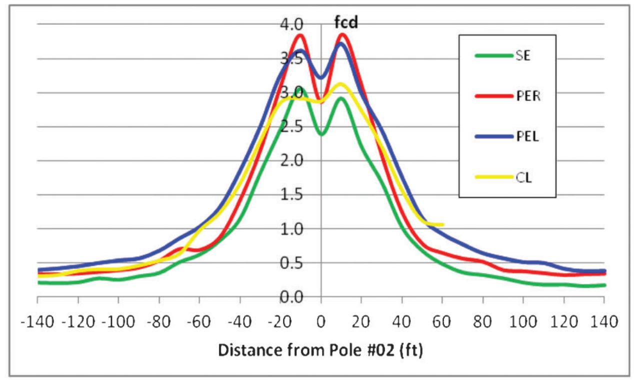


(d) Horner 200 W LED

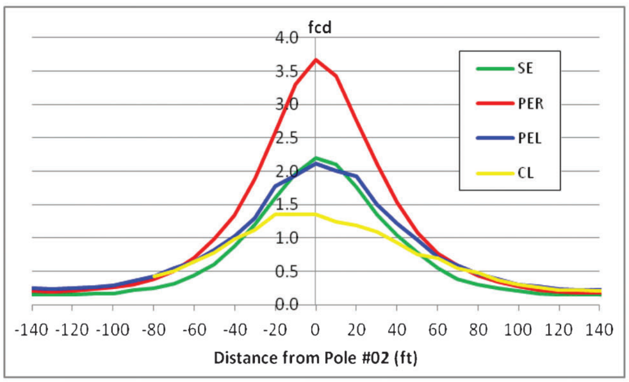
Figure 5.1 Illuminance footprints measured in Zone 1 (Pole #02). (NOTE: SE = shoulder edge, PER = pavement edge on right, PEL = pavement edge on left, and CL = center line).



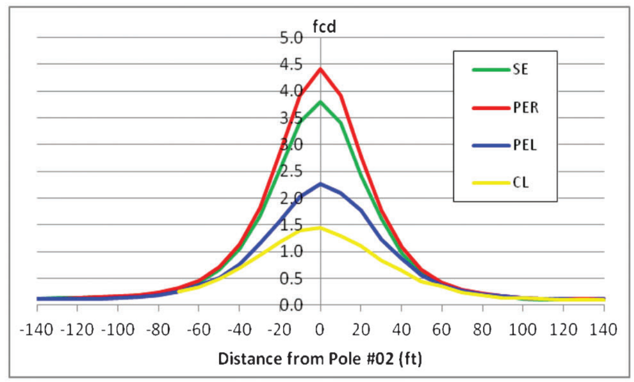
(a) 250 W HPS



(b) GE 258 W LED (ERS4)



(c) Philips 270 W LED (RVM)



(d) Horner 200 W LED

Figure 5.2 Illuminance variations in roadway direction (Pole #02).

center of the lighted area. All LED luminaires produced a maximum illuminance greater than that produced by the HPS luminaire. The GE and Philips LED luminaires produced a lighted area greater than that produced by the Horner LED luminaire. However, the maximum illuminance produced by the Horner luminaire was greater than those by the GE or Philips LED luminaires, while the Horner LED lamp size in terms of rated power was smaller than both the GE and Philips LED lamp sizes.

Figure 5.2 shows the variations of the illuminance measurements of the four luminaires in longitudinal direction. Seemingly, the illuminance variation of the HPS luminaires is flatter than those of the GE and Philips LED luminaires, particularly in the area within 40 ft of the luminaire. However, the illuminance distributions for the HPS luminaire were not consistent in longitudinal direction. The illuminance along the shoulder edge (SE) shows a single-hump distribution. The illuminance measurements of the Horner LED luminaire demonstrated the greatest variation. In order to evaluate the illuminance variations in the transverse direction, Figure 5.3 presents the illuminance variations across the pavement cross-section directly under the luminaire for the four types of luminaires. The illuminance variations for HP, Philips LED and Horner LED luminaires follow a similar pattern. However, the illuminance variation for the GE LED luminaire demonstrates a different pattern and is much flatter than those for the other luminaires.

5.1.2 Conventional Lighting in Zones 2 and 3

Figures 5.4 and 5.5 show the illuminance footprints for the luminaires evaluated in Zones 2 and 3,

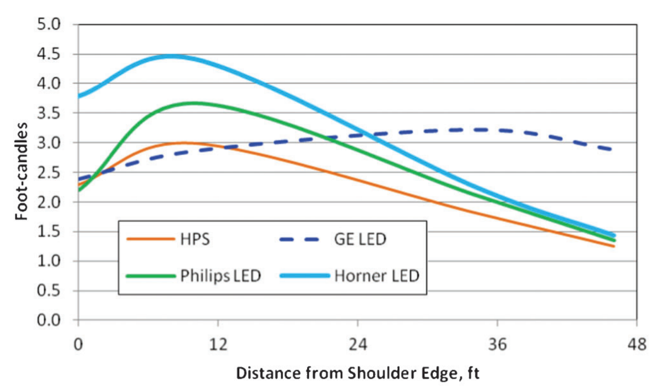
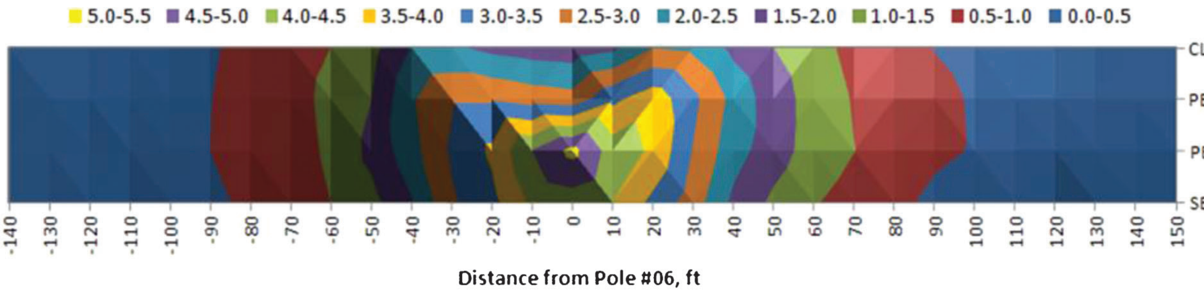
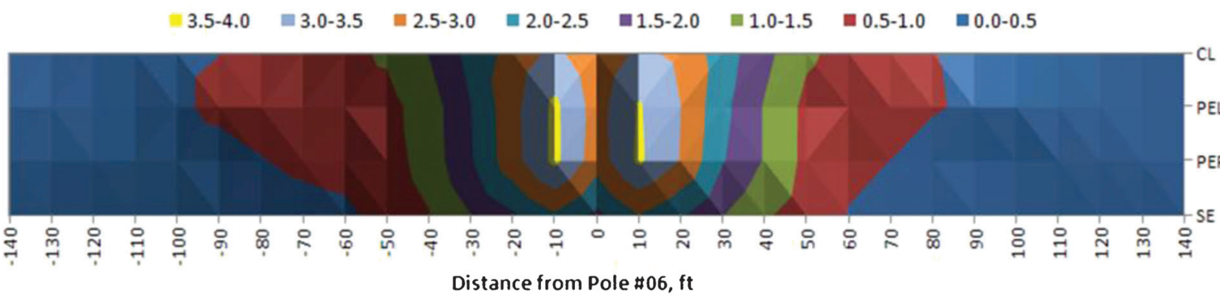


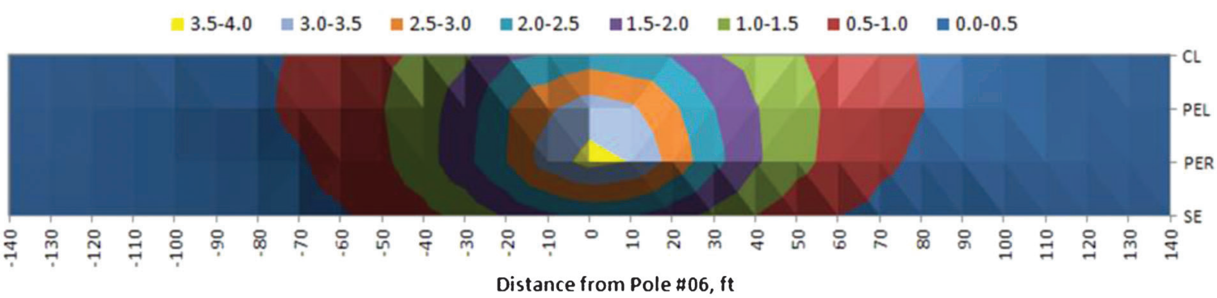
Figure 5.3 Illuminance variations across pavement cross-sections (Pole #02).



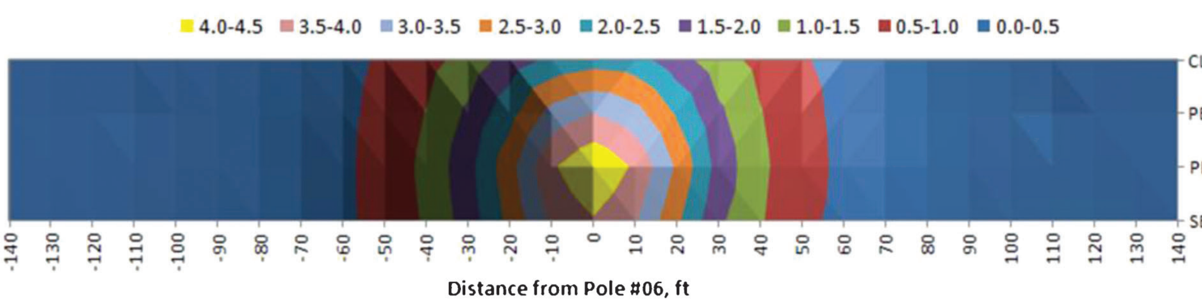
(a) 400/400/250 W HPS



(b) GE 258 W LED (ERS4)

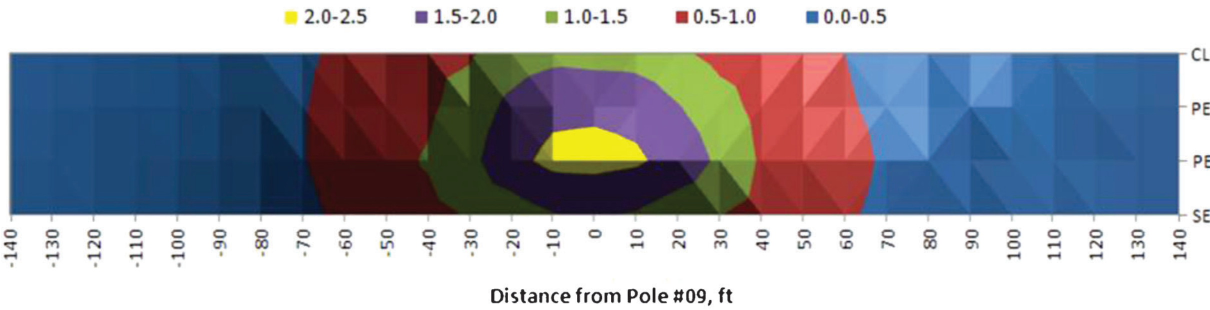


(c) Philips 270 W LED (RVM)

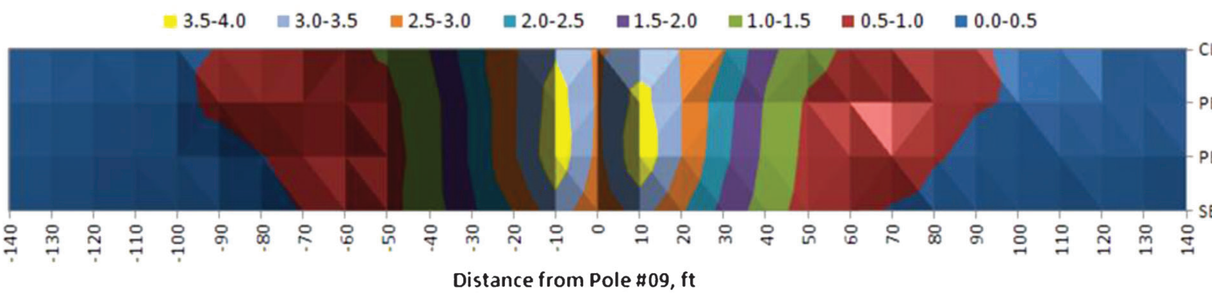


(d) Horner 200 W LED

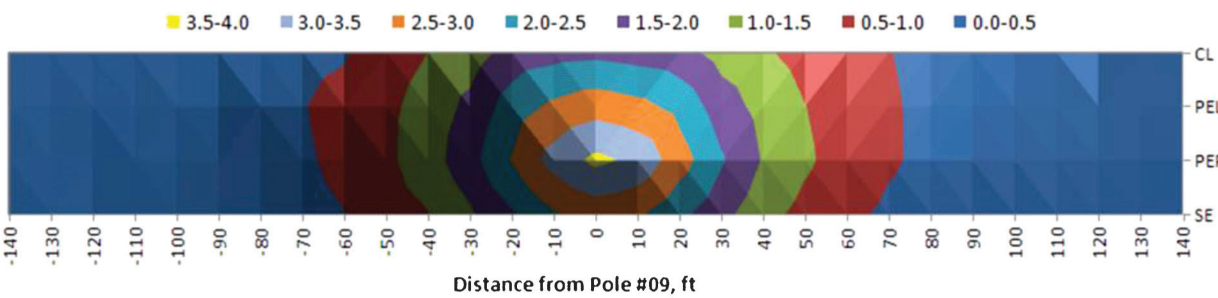
Figure 5.4 Illuminance footprints measured in Zone 2 (Pole #6).



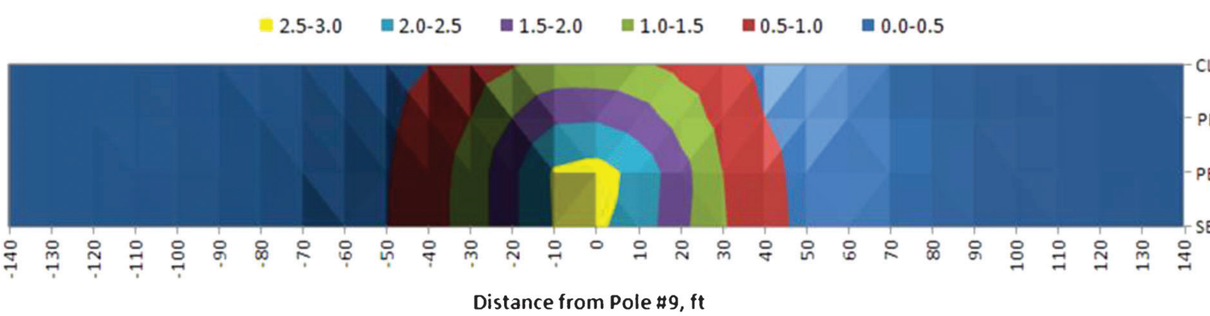
(a) 250/250/400 W HPS



(b) GE 258 W LED



(c) Philips 270 W LED (RVM)



(d) EcoLuminator 200 W Induction

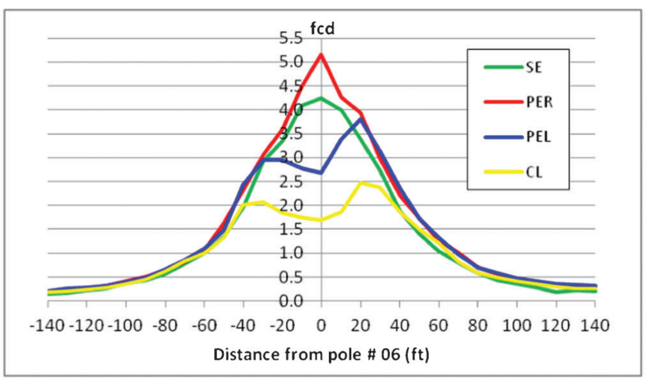
Figure 5.5 Illuminance footprints measured in Zone 3.

respectively. Zones 2 and 3 consisted of similar lighting infrastructures in terms of the pole height, spacing, arm length, and setback. One of the differences between these two zones is that the spacing between Poles 4 and 6 in Zone 2 is 340 ft, instead of 280 ft. Another difference is the HPS lamp sizes. In Zone 2, the three HPS lamps consisted of two 400W lamps and one 250W lamp, with one of the 400W lamps installed on the middle pole. In Zone 3, the three HPS lamps consisted two 250W lamps and one 400W lamp, with one of the 250W lamps installed on the middle pole. It is shown that in general, all luminaires in Zones 2 and 3 produced measurable illumination over the areas between the lighting poles.

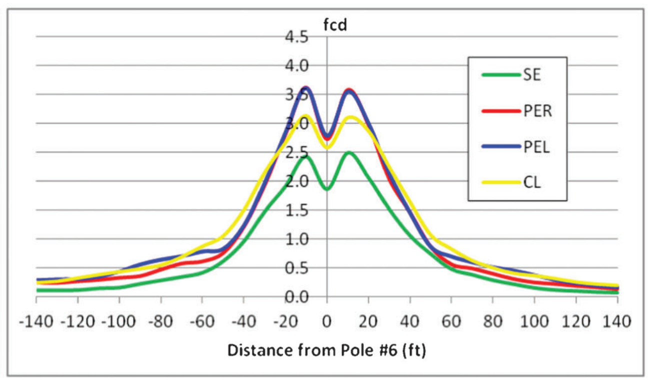
In Zone 2, the HPS, GE LED and Philips LED luminaires produced oval-shaped lighted areas, and the Horner LED luminaire produced a circular lighted area. The percentages of grid points with illuminance of greater than 0.2 foot-candles for the HPS, GE LED, Philips LED, and Horner LED luminaires are 98%, 88%, 78%, and 52%, respectively. The luminaires in descending order of their lighted areas are HPS, GE LED, Philips LED, and Horner LED. The HPS luminaire produced not only the largest lighted area, but also the greatest illuminance due to the 400W lamps. In addition, the HPS light distribution is different from that in Zone 1. Observations similar to those in Zone 1 can be made about the three different LED luminaires. The GE LED luminaire produced a double-hump illuminance distribution, and both the Philips and Horner LED luminaires produced a single-hump illuminance distribution. The maximum illuminance produced by Horner LED is greater than those by GE and Philips LEDs.

In Zone 3, the EcoLuminator induction luminaire produced a circular lighted area and the other luminaries produced oval-shaped lighted areas. The percentages of grid points with illuminance of greater than 0.2 foot-candles for the HPS, GE LED, Philips LED, and EcoLuminator induction luminaires are 73%, 94%, 68%, and 45%, respectively. The GE LED produced the largest lighted area with a double-hump illuminance distribution. The illuminance footprints by the HPS, Philips LED and EcoLuminator induction show a single-hump distribution. The lighted areas by HPS and Philips LED are very close in terms of area size and shape. The EcoLuminator induction luminaire produced the smallest lighted area. Both the GE and Philips LEDs produced a maximum illuminance greater than that produced by either the HPS or EcoLuminator induction luminaire. The maximum illuminance by the EcoLuminator induction luminaire is slightly greater than that by the HPS luminaire. It is also interesting to note that the lighted areas in Zone 1 are greater than the lighted areas produced by the same luminaires in Zones 2 and 3. This is probably due to the effect of ambient light from the restaurants adjacent to Zone 1.

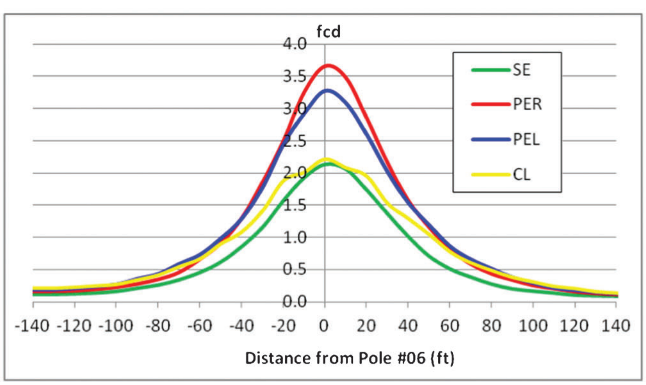
Figures 5.6 and 5.7 show the variations of the illuminance measurements of the three different luminaires



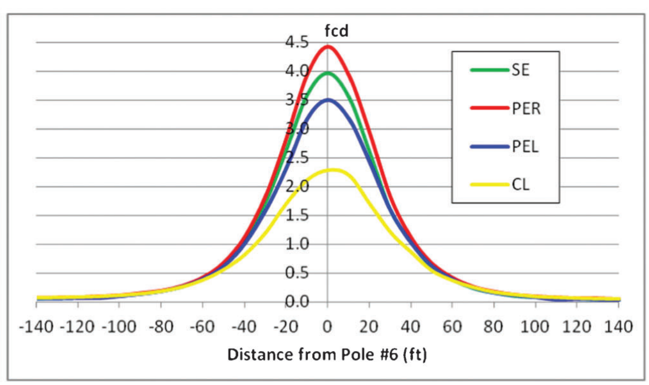
(a) 400/400/250 W HPS



(b) GE 258 W LED (ERS4)

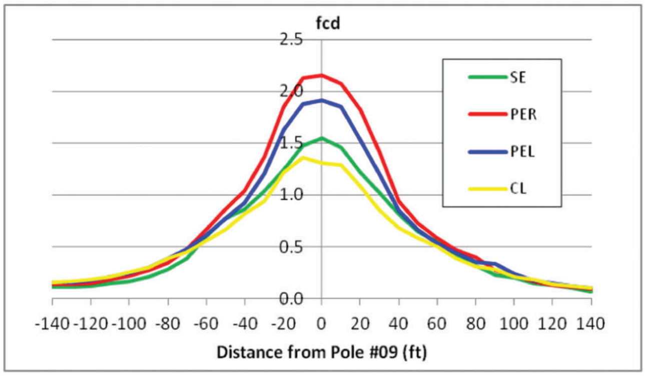


(c) Philips 270 W LED (RVM)

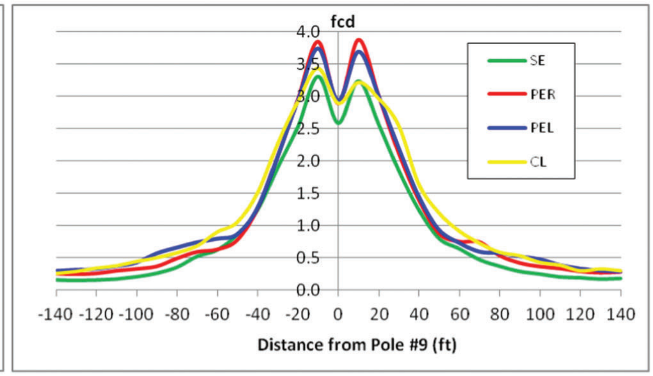


(d) Horner 200 W LED

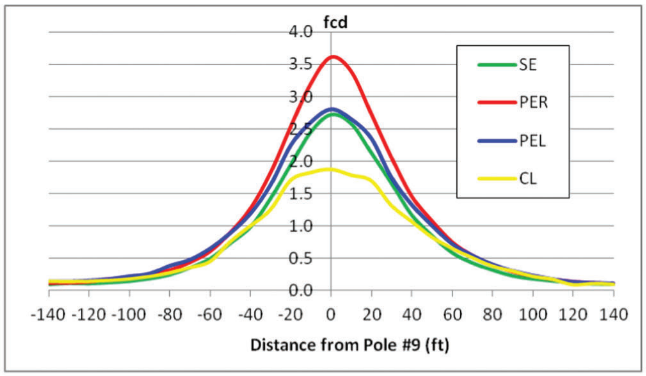
Figure 5.6 Illuminance variations in roadway direction in Zone 2 (Pole #6).



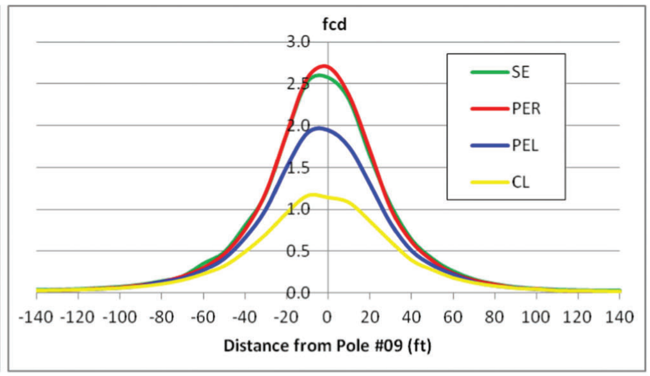
(a) 250/250/400 W HPS



(b) GE 258 W LED



(c) Philips 270 W LED (RVM)

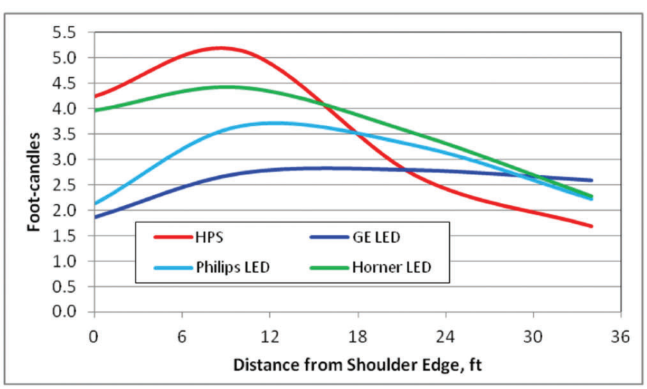


(d) EcoLuminator 200 W Induction

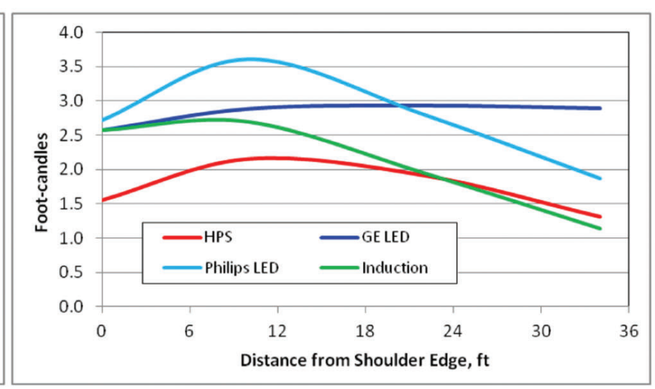
Figure 5.7 Illuminance variations in roadway direction in Zone 3 (Pole #9).

in the roadway or longitudinal direction in Zones 2 and 3. It is shown that the illuminance variations are all approximately symmetrical to the y-axis. In the case of HPS luminaire in Zone 2, the illuminance variations are not consistent. They demonstrate a single-hump distribution along the shoulder edge (SE) and right pavement edge (PER), and a double-hump distribution along left pavement edge (PEL) and center line (CL). In other cases, the illuminance variations are consistent along different locations, including shoulder edge, pavement edge and center line.

Plotted in Figure 5.8 are the illuminance measurements across the pavement cross-section right at the center of footprint for each type of the luminaires in Zones 2 and 3. Again, the illuminance measurements of the GE LED luminaire demonstrated the least

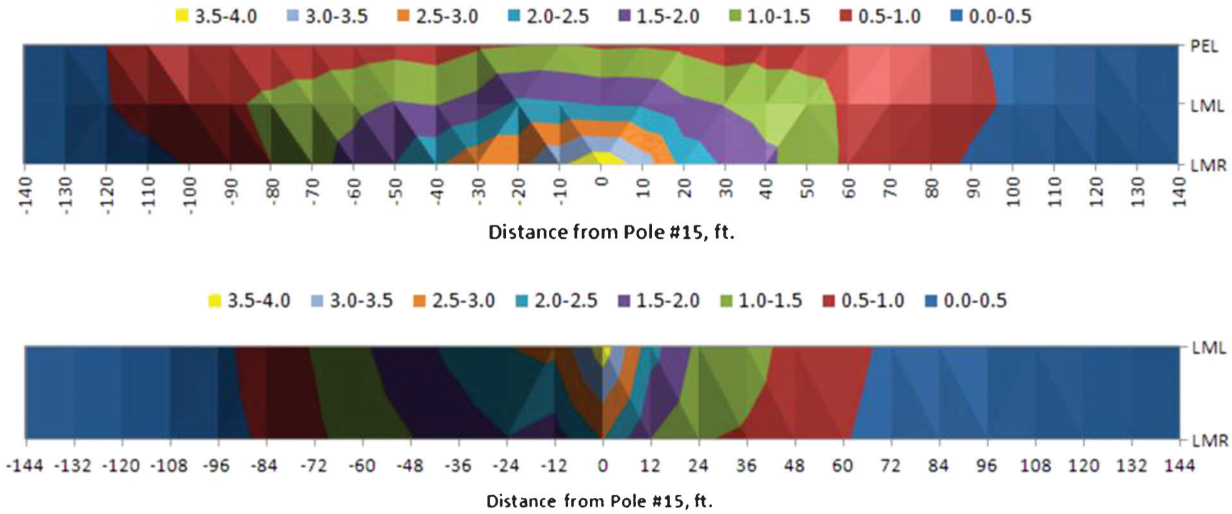


(a) Zone 2 (Pole #6)

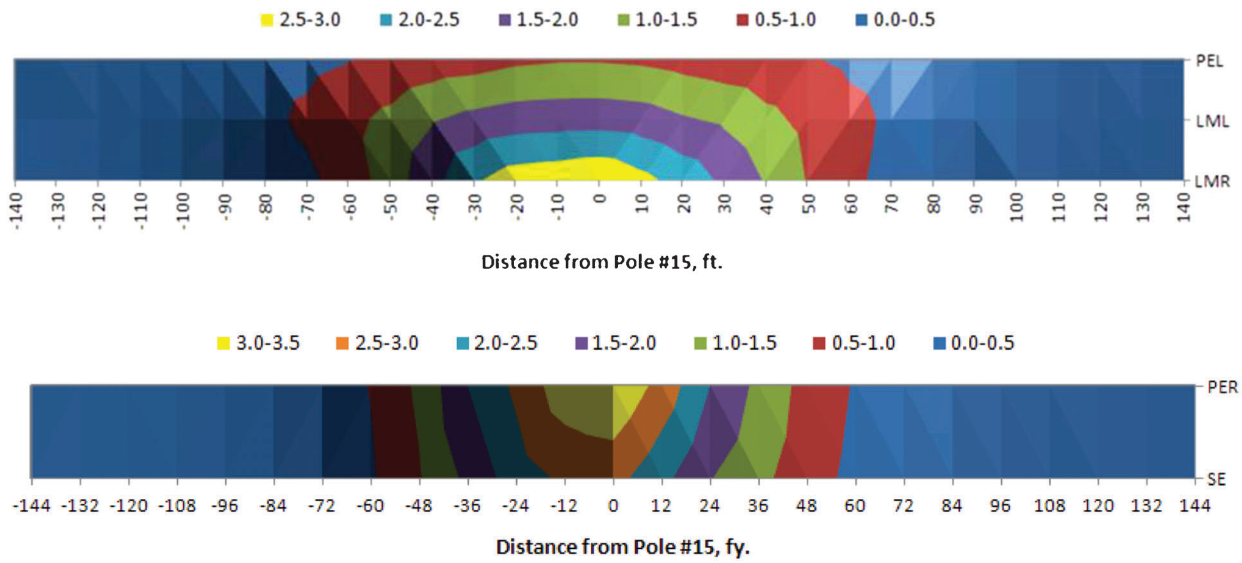


(b) Zone 3 (Pole #9)

Figure 5.8 Illuminance variations across pavement cross-sections in Zones 2 and 3.



(a) 400/400/400 W HPS



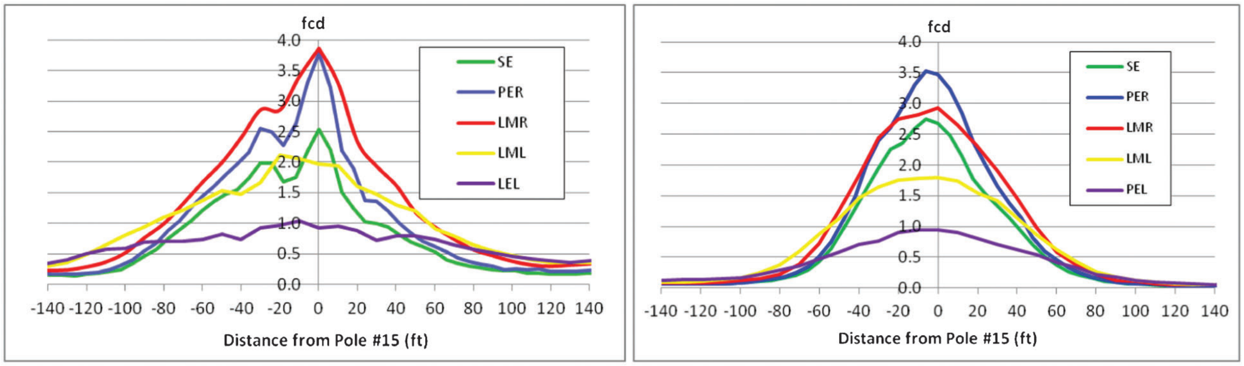
(b) Stray Light Tesla II 295 W Plasma

Figure 5.9 Illuminance footprints measured in Zone 4 (Pole #15). (NOTE: LML = lane marking on left; LMR = lane marking on right.)

variation and its light distribution is relatively uniform across the pavement cross-section, regardless of the test zone. In Zone 2, the illuminance of HPS luminaire demonstrates the greatest variation across the pavement cross-section. The illuminance variations appeared to be relatively similar with the Philips and Horner LEDs. In Zone 3, the induction luminaire produced lights with the greatest variation across the pavement cross-section. The illuminance variation of Philips LED is slightly greater than that produced by the HPS luminaire. It is also shown that in Zones 2 and 3, the variations decrease as the distance increases.

5.1.3 Conventional Lighting in Zone 4

Figure 5.9 presents the footprints of the 400W HPS and Tesla II 295 plasma luminaires in Zone 4 on I-74. Due to the different measurement grids utilized in the shoulder and in the driveway, the footprints were plotted separately. It is shown that in general, these two different luminaires produce measurable illumination over the 270-ft spacing. Both the HPS and Tesla II plasma luminaires produced oval-shaped lighted areas. Both the footprints peak at the center. However, the lighted area produced by the HPS luminaire is much greater than that by the plasma luminaire. Approximately 71% of the lighted area was covered with 0.20 foot-candles or greater with the



(a) HPS in Roadway Direction (b) Plasma in Roadway Direction

Figure 5.10 Illuminance variations in roadway direction in Zone 4 (Pole #15).

HPS luminaire and only 49% of the lighted area was covered with 0.20 foot-candles or greater with the plasma luminaire. In addition, the HPS luminaire produced greater illuminance than the plasma luminaire.

Presented in Figure 5.10 are the illuminance variations in the roadway direction. It is shown that the greatest illuminance reading occurred on the right lane marking with the HPS luminaire and on the edge of pavement with the plasma luminaire. It appears that the illuminance variations along the right edge of pavement and the first lane marking with the HPS luminaire are greater than those with the plasma luminaire. However, the illuminance variations along the left edge of pavement and the left lane marking with the HPS luminaire are smaller than those with the plasma luminaire. This indicates that in the roadway direction, the differences in the light distributions produced by the HPS and plasma luminaires lie mainly in the shoulder area. Presented in Figure 5.11 are the illuminance variations in the transverse direction, i.e., across the pavement cross-section at the center of the footprint. It is demonstrated that the illuminance variation with the plasma luminaire is slightly less than that with the HPS luminaire. Also, the HPS luminaires produced a broader area of relatively high illumination at the center. The main differences between the light distributions produced by the HPS and plasma luminaires occurred in the driveway area across the pavement cross-section.

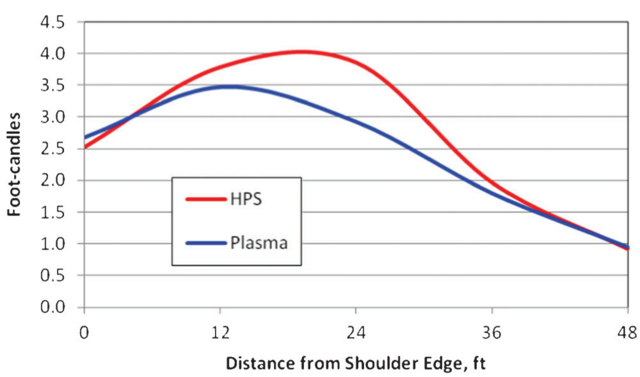


Figure 5.11 Illuminance variations across pavement cross-section in Zone 4 (Pole #15).

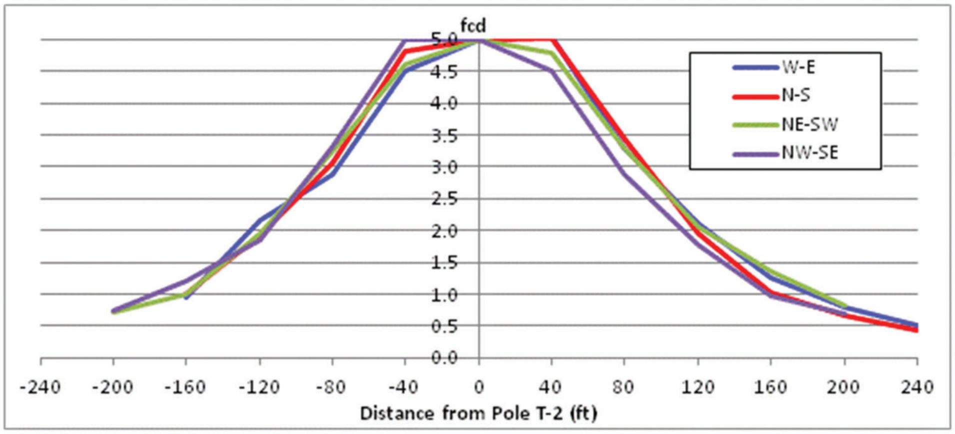
5.1.4 High Mast Lighting in Zone 5

Figure 5.12 shows the illuminance measurements taken in those eight radial directions (see Figure 4.11). The blue W-E line indicates the illuminance measurements taken in both the west and east directions. The red N-S line indicates the illuminance measurements taken in both the north and south directions. The olive green NE-SW line indicates the illuminance measurements taken in both the northeast and southwest directions. The purple NW-SE line indicates the illuminance measurements taken in both the northwest and southeast directions. Two major observations can be made through careful inspections these illuminance curves. First, both types of luminaires produced a symmetrically lighted, circular area with relatively large foot-candles. The illuminance measurements greater than 0.20 foot-candles covered 100% of the lighted area with both the HPS and SoLtice LED luminaires. Second, the light illuminance produced by the 1000W HPS luminaires was much greater than that by the SoLtice 392W luminaires.

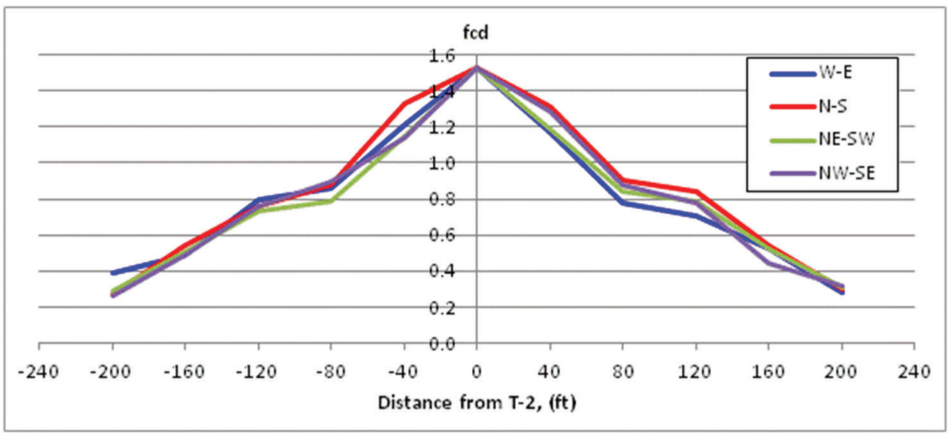
5.2 Illuminance Metrics

5.2.1 AASHTO Roadway Lighting Illuminance Metrics

In order to compare the illuminance performances with all luminaires evaluated in this study, the illuminance metrics, such as average illuminance, minimum illuminance and illuminance uniformity ratio (average-to-minimum illuminance ratio) as defined in the AASHTO lighting design guide (*46*), were calculated for each type of luminaire in each test zone. It should be pointed out that the illuminance metrics were calculated for photopic levels. The average illuminance indicates the average light level over the calculated area. The minimum illuminance is the single lowest illuminance measurement over the lighted area and is commonly used to verify the illuminance threshold that is required to ensure traffic safety at night. The illuminance uniformity ratio is calculated by dividing the average of illuminance measurements by the single lowest illuminance measurement over the entire lighted area. A lower uniformity ratio indicates a better lighting condition.



(a) Six 1000 W HPS Luminaires



(b) Six SoLtice 392 W LED Luminaires

Figure 5.12 Illuminance distributions of high mast lightings.

Illuminance uniformity is an important factor in roadway lighting applications. It directly affects the driver's ability to detect differences in brightness level. Uniform lighting can not only eliminate eye discomfort, but also allow continuous perception of the roadway condition.

The illuminance metrics, particularly the minimum illuminance may vary with the size of measured, lighted area. As the measured area increases, the minimum illuminance decreases and the uniformity ratio increases. Also, the light distributions presented in the previous sections indicate that the position of the maximum illuminance varies from luminaire to luminaire and from test zone to test zone. The measured maximum illuminance may not be the true maximum illuminance. To provide more comparable information on the lighting performances with the selected luminaires, the calculation of illuminance metrics in this study was performed over the same lighted of equal size in each test zone, roughly the entire shoulder and driveway surface within 140 ft on each side of the middle pole for the conventional lighting. For the high mast lighting in Zone 5, the illuminance metrics were calculated roughly over a circular area with a radius of 200 ft centered at the light pole.

5.2.2 Measured Illuminance Metrics

Table 5.1 presents the measured illuminance metrics for all luminaires evaluated in this study. In Zone 1, the HPS, GE LED and Philips LED produced similar minimum illuminance values, and the Horner LED produced the smallest minimum illuminance. All three different LED luminaires produced a maximum illuminance greater than that by the HPS. The GE LED produced the greatest average illuminance, and the Horner LED produced the smallest average illuminance. The HPS produced the smallest uniformity ratio and the Horner LED produced the greatest uniformity ratio. The uniformity ratio produced by the Philips LED is very close to that by the HPS. In Zone 2, the minimum, maximum and average illuminance values produced by the HPS are greater than those by the three LEDs. The Horner LED produced the greatest illuminance uniformity ratio that is much greater than those with the other luminaires. In Zone 3, the induction luminaires produced the smallest minimum and average illuminance values but the greatest uniformity ratio. The metal halide luminaires produced

TABLE 5.1
Measured Illuminance Metrics in Different Test Zones

Test Zone	Lamp Type	Illuminance (fc) Min	Max	Avg	Avg/Min*	Test Date
1	HPS (250/250/250W)	0.17	3.25	1.00	5.8:1	11/29/2011
	GE LED (258/258/258W)	0.16	4.03	1.20	7.6:1	4/2/2012
	Philips LED (270/270/270W)	0.15	3.67	0.87	5.9:1	5/22/2012
	Horner LED (200/200/200W)	0.10	4.42	0.80	8.2:1	5/8/2013
2	HPS (400/400/250W)	0.15	5.15	1.33	8.8:1	11/28/2011
	Philips LED (270/270/270W)	0.09	3.66	0.89	10.2:1	4/3/2012
	Horner LED (200/200/200W)	0.04	4.42	0.82	19.1:1	5/22/2012
	GE LED (258/258/258W)	0.08	3.62	1.00	12.8:1	5/8/2013
3	HPS (400/250/250W)	0.07	2.15	0.63	9.0:1	11/28/2011
	EcoLuminator induction (200/200/200W)	0.02	2.70	0.50	22.7:1	4/3/2012
	GE LED (258/258/258W)	0.15	3.87	1.11	7.6:1	5/22/2012
	Philips LED (270/270/270W)	0.09	3.61	0.84	9.2:1	5/8/2013
	EcoReady metal halide (320/320W)	0.08	1.94	0.55	6.6:1	10/3/2012
4	HPS (400/400/400W)	0.14	3.86	1.00	7.1:1	11/29/2011
	Stray Light plasma (295/295/295W)	0.04	3.52	0.77	21.9:1	4/2/2012
5	HPS 6 × 1000W)	0.66	5.05	2.88	4.4:1	12/1/2011
	Global Tech LED (6 × 392W)	0.26	1.53	0.80	3.1:1	5/22/2012
	Global Tech LED (6 × 392W)	0.24	1.75	0.79	3.3:1	5/8/2031

*Avg/min = uniformity ratio.

the smallest illuminance and uniformity ratio. During the testing period, the metal halide lamp on Pole #10 burned out and thus the illuminance metrics were calculated from the illuminance measurements between Poles # 9 and #8. The minimum, maximum and average illuminance values produced by the GE and Philips LEDs are all greater than those by the other luminaires. Also, the two LED luminaires produced a uniformity ratio either smaller than or similar to that by the HPS luminaires. In Zone 4, the 400W HPS luminaires produced greater minimum, maximum and average illuminance values than the plasma luminaires. However, the illuminance uniformity ratio with the HPS luminaires is much less than that with the plasma luminaires. In Zone 5, the minimum, maximum and average illuminance values produced by the 392W Tech LED luminaires are much smaller than those by the 1000W HPS luminaires. However, the illuminance uniformity ratio with the Tech LED luminaires is smaller than that with the HPS luminaires.

5.2.3 Illuminance Metrics Measured on Urban Streets

Test sites and lighting facilities. This study also conducted field lighting testing at two urban street sites, one on Washington Blvd in City of Fort Wayne, Indiana, and the other on US-31 in City of Scottsburg, Indiana. The test site on Washington Blvd is located at the interchange of Washington Blvd to Coliseum Blvd. The lamp type is Cooper 232W LED. The twin-arm light poles are located in the median and spaced 300 ft apart. The arm length is about 8 ft and the luminaire mounting height is 45 ft. The lighted road section consists of two through lanes and one merging lane (from the ramp). The test site on US-31 is located close to the intersection of US-31 and SR-56. The lamp type is Stray Light Tesla II 280W plasma. The lighted road section is a two-lane section with only one shoulder (8-ft wide) in southbound. The lighting layout is a staggered layout with single-arm light poles spaced 200 ft apart. The plasma luminaires are mounted 35 ft high on an 8-ft long arm. Presented in Figure 5.13 are two photos that show the LED and plasma lightings at these two test sites.

Results and analysis. Figure 5.14 shows the measurements of illuminance produced by the Cooper 232W LED luminaires on Washington Blvd. As shown in Figure 5.14(a), the lighted area demonstrates with a double-hump distribution with an irregular-shape, particularly in the areas around the luminaire. The illuminance distribution becomes more symmetrical as it gets closer to the luminaire. It is also shown that in Figure 5.14(b), the maximum illuminance in the driveway is about 2.27 fc, which occurred on the pavement surfaces on both sides of the luminaire. The illuminance distribution is relatively flat between the poles, i.e., in the driving direction. Presented in Figure 5.15 are the measurements of illuminance produced by the Stray Light Tesla II 280W plasma luminaires on US-31. Apparently, the lighted area is oval-shaped with a single hump. The maximum illuminance, roughly 5.85 fcd, occurred at the middle of pavement edge on the right side. The illuminance distribution is every symmetrical in the roadway

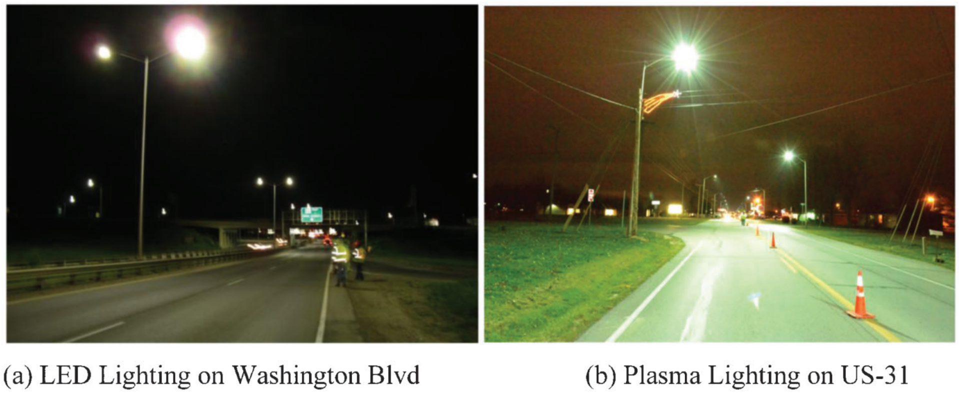


Figure 5.13 Lighting test sites on urban streets.

direction, regardless of the distance in the direction of cross-section as demonstrated in Figure 5.15(b). The illuminance on the road center line is approximately 4 fcd.

Based on the illuminance measurements taken at these two sites, the average illuminance is 1.16 fc with a minimum illuminance of 0.43 fcd and a maximum illuminance of 2.27 fcd for the LED lighting on Washington Blvd. For the plasma lighting on US-31, the average illuminance is 2.0 fcd with a minimum illuminance of 0.52 fcd and a maximum illuminance of 5.85 fcd. Apparently, the minimum illuminance levels produced both the LED and plasma lights, are much greater than those produced by the LED and plasma luminaires in Zones 1, 2, 3 and 4 (see Table 5.1). In addition, the illuminance uniformity ratio is 2.72:1 for the LED lighting on Washington Blvd and 3.85:1 for the plasma lighting on US-31. It is obvious that both the LED lights on Washington Blvd and the plasma lights on US-31 produced better illuminance uniformities than the LED and plasma luminaire in Zones 1, 2, 3, and 4.

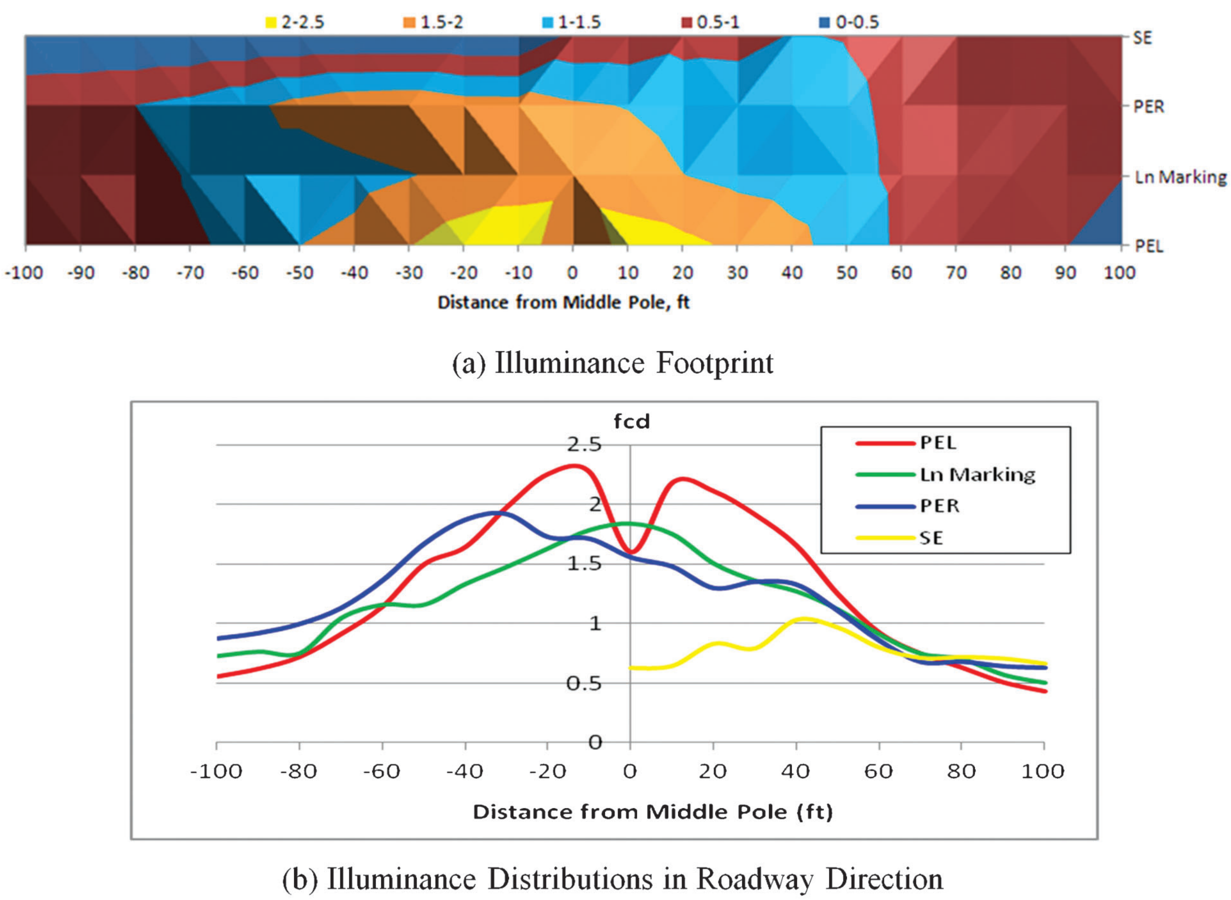
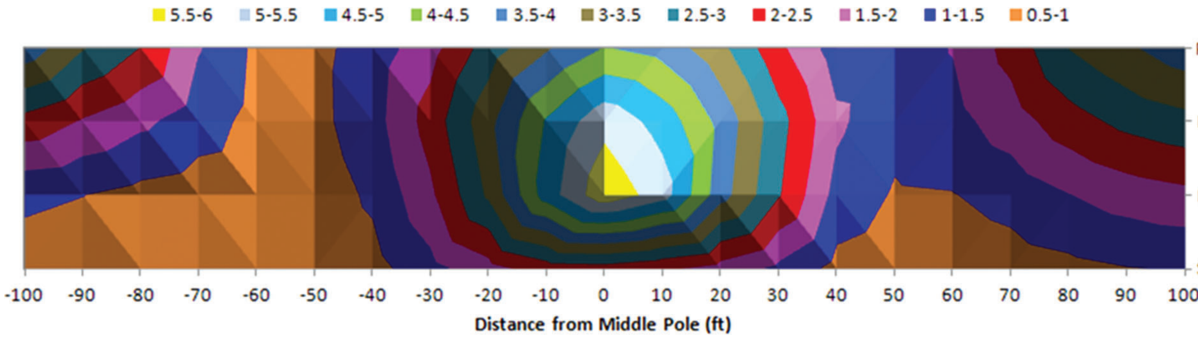
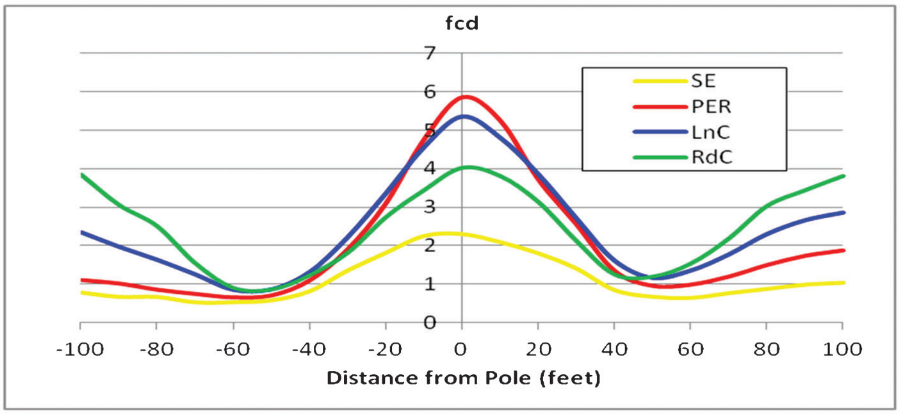


Figure 5.14 Illuminance measurements on LED lighting on Washington Blvd.



(a) Illuminance Footprints



(b) Illuminance Distributions in Roadway Direction

Figure 5.15 Illuminance measurements on plasma lighting on US-31. (NOTE: LnC = lane center; RdC = road center.)

5.3 SAC Member Ratings

The members of the Study Advisory Committee (SAC) conducted a field observation in the evening of March 14, 2012 to qualitatively rate the performances of the LED, plasma and induction luminaires in Zones 1, 2, 3 and 4. A total of eleven members participated in the field observation. To avoid possible biased ratings, the participants did not know the type of luminaire in each test zone prior to the observation. The members drove through the roadway sections and then rated the lighting performance of the luminaries based on their observations. The performance of the luminaries was assessed in terms of lighting level, lighting uniformity, glare, and overall performance. Presented in Table 5.2 are the SAC member ratings on the light level and uniformity in terms of the number of participants rated on each lighting effect. All participants rated the light level of Philips LED sufficient, 10 participants rated the light level of GE LED sufficient, 7 participants rated EcoLuminator induction sufficient, and 6 participants rated Stray Light plasma sufficient. This agrees very well with the illuminance measurements that indicated the new light sources produced sufficient light levels.

While rating uniformity, 9 participants observed dark spots under the induction lighting, 6 participants observed dark spots under the plasma and Philips LED lightings, and 2 participants observed dark spots under the GE LED lighting. This agrees well with the illuminance uniformity ratios (see Table 5.1), i.e., 22.7:1 for the induction in Zone 3, 10.2:1 for the Philips LED in Zone 2, 21.9:1 for the plasma in Zone 4, and 7.6:1 for the GE LED in Zone 1. Also, only a few participants observed glare. The ratings on the overall

TABLE 5.2
Number of Participants Rated in Field Observation

	Lighting Level		Uniformity		Glare
Lamp Type	**Sufficient**	**Insufficient**	**Dark Spots**	**Hot Spots**	**Yes**
EcoLuminator induction	7	3	9	4	4
Philips LED	11	0	6	2	3
Stray Light plasma	6	4	6	2	2
GE LED	10	1	2	3	3

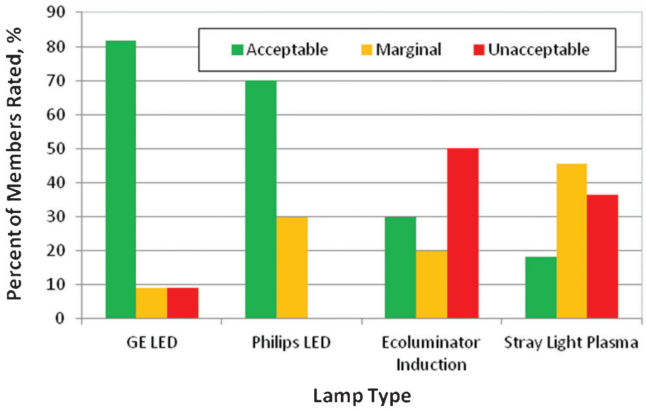


Figure 5.16 Overall performance ratings.

performance of these four new light sources are shown in Figure 5.16. The GE LED has the highest rating, followed by the Philips LED. Approximately, 50% of the participants rated the overall performance of the induction luminaires unacceptable and 36% of the participants rated the overall performance of the plasma luminaires unacceptable.

5.4 Power Consumption

5.4.1 Power Measuring

Electrical power is defined as the rate at which electrical energy is supplied to a circuit or consumed by a load, or simply the rate of doing work (*47*). For lighting applications, the electrical power represents the rate at which energy is converted from the electrical energy into light, a form of radiant energy. Electrical power is commonly denoted by P and measured in watts. Therefore, the term wattage is also colloquially referred to as electric power in watts. To calculate the power consumed by a lighting luminaire, the following equation is used:

$$P = I \times V \qquad (5.1)$$

where, I denotes electric current in amperes, and V denotes electric voltage in volts.

In this study, only amperage readings were taken by using a digital multi-meter. While taking the reading, the clamp on the red probe was set on one open end and the clamp on the black probe set on the other open end. For the HPS luminaires, the amperage readings (cold) were first taken as the light was powered and the luminaire was heating up, usually within first 5 to 15 minutes of being energized. After the luminaire had been energized all night, the amperage readings (hot) were taken again as soon as the technicians came in the morning and were used in power calculation. For the LED, plasma and induction luminaires, the trial measurements did not demonstrate any differences between the cold and hot readings. As a result, the amperage readings were taken once in the morning. Since no data was measured on the electric potential or voltage, an average voltage of 240 volts was utilized in the calculation.

5.3.2 Power Metrics

Electric current measurements for HPS luminaires were made before they were replaced with the new light sources, including LED, plasma and induction luminaires. Electric current measurements for the new light sources were repeated at the same point in the circuit in each test zone. Presented in Table 5.2 are the statistic summary of the electric current measurements, including average current and coefficient of variance (COV). For the conventional lightings, the average currents for LED, plasma and induction luminaires regardless of the lamp watts, varied around 1.0 A and are less than not only the average current for HPS 400W luminaires, but the average current for HPS 250W luminaires as well. For the high mast lighting, the average current for the LED luminaires is much less than that for the HPS 1000W luminaires. It is also shown that in Table 5.3, both GE and Philips LED luminaires demonstrated equivalent variability that is less than that for the other luminaires. The Horner LED, EcoLuminator induction and HPS 400W luminaires exhibited much greater variability. Electric current varies due to the effects of ballast, heat, corrosion at connections and type of lamp. A greater variability in electric current may affect power quality and lamp lifespan.

TABLE 5.3
Summary of Electrical Current Measurements

Luminaire Type	Lamp Watts	No. of Fixtures	Lighting Type	Current: Average (A)	Current: COV (%)
GE LU250, HPS	250	1	Conventional	1.26	6.4%
GE LU400, HPS	400	1	Conventional	1.97	13.0%
GE LU1000, HPS	1000	6	High mast	30.96	0.5%
GE Evolve ERS4 LED	258	1	Conventional	1.02	3.3%
Philips RoadView RVM LED	270	1	Conventional	1.00	4.2%
Horner ETG LED	200	1	Conventional	1.06	19.4%
Stray Light TESLA II plasma	295	1	Conventional	1.11	3.8%
EcoLuminator induction	200	1	Conventional	0.95	13.8%
Global Tech SoLtice LED	392	6	High mast	9.16	1.8%

TABLE 5.4
Calculated Usage of Energy

Luminaire Type	Luminaire Power (W)	Energy Consumption (EC) (kWh)	Saving (%)[d]
GE LU250 HPS 250W	302	1324	—
GE LU400 HPS 400W	473	2070	—
GE Evolve ERS4 LED 258W	244	1069	19[a]/48[b]
Philips RoadView RVM LED 270W	241	1056	20[a]/49[b]
Horner ETG LED 200W	254	1111	16[a] /46[b]
Stray Light TESLA II plasma 295W	267	1169	12[a]/44[b]
EcoLuminator induction 200W	227	996	25[a]/52[b]
GE LU1000 HPS 6 × 1000W	7430	32545	—
Global Tech SoLtice LED 6 × 392W	2196	9618	70[c]

[a]Compared to HPS 250W.
[b]Compared to HPS 400W.
[c]Compared to HPS 1000W.
[d]Saving is calculated as: $Saving(\%) = \frac{(EC_{HPS} - EC_{New})}{EC_{HPS}} \times 100$.

Table 5.4 shows the energy usage for these different luminaires calculated from the average currents shown in Table 5.3. The calculation was based on a nominal 240 V and an annual operation time of 4380 hours. Compared to the baseline luminaire of HPS 250W, the calculated energy saving is 12% to 20% for a LED luminaire depending on the lamp watts, 12% for a 295W plasma luminaire, and up to 25% for a 200W induction luminaire. Notice that the GE LED, Philips and Stray Light plasma luminaire sizes are all greater the HPS 250W luminaire. It is also interesting to note that the energy saving produced the 200W Horner LED luminaire is less than that produced by the 200W EcoLuminator induction luminaire. Compared to the baseline luminaire of HPS 400W, the energy savings varied between 44% and 52%, depending on the type of luminaire. The energy savings produced by LED, plasma and induction luminaires become very close regardless of the luminaire size and luminaire type. For high mast lighting, the energy consumed by the Global Tech SoLtice LED luminaires is much less than that by the HPS luminaires. The above observations indicate that while the luminaire size may affect the usage of energy, the new lighting sources are inherently energy-saving, particularly for high mast or area lightings.

5.5 Further Discussion

In the highway lighting design by INDOT, the illuminance design criteria is defined by AASHTO lighting design guide (*46*), INDOT design manual (*48*) and NCHRP Report 672 (*49*). While the AASHTO lighting design guide recommends a minimum illuminance for principal arterials, both the INDOT design manual and NCHRP Report 672 have only recommendations for the average maintained illuminance and uniformity ratio. The average maintained illuminance criteria promotes sufficient nighttime visibility for all possible users, including vehicles, bicycles, and pedestrians, to accurately assess roadway conditions within the lighted area and ensure safety and security. The criteria for illuminance uniformity ratio allow drivers to perceive roadway conditions continuously and avoid sudden drops of lighting level. It is indicated that frequent changes of contrasting high- and low-lighted roadway segments cause eye discomfort, leading to stress and tiredness (*50*). Consequently, poor illuminance uniformity may affect the driver's perception of roadway conditions and jeopardize travel safety. Summarized in Table 5.5 are the illuminance design criteria used to guide the INDOT highway lighting design. For roundabout lighting design, the average maintained illuminance ranges between 0.8 fcd and 3.4 fcd and the illuminance uniformity ratio ranges between 3:1 and 6:1, depending on the roadway classification and pedestrian volume.

As demonstrated earlier (see Table 5.1), the average illuminance varied between 1.00 and 1.20 fcd for GE 258W LED, 0.84 and 0.89 for Philips 270W LED, 0.80 and 0.82 for Horner 200W LED, depending on the test

TABLE 5.5
INDOT Illuminance Design Criteria

Roadway Classification	Average Maintained Illuminance (fcd)	Illuminance Uniformity Ratio
Interstate route or other freeway	0.7	4:1
Expressway	1.1	3:1
Intersection or city street	0.8	4:1
Weigh station or rest area ramp	0.6	3:1
Weigh station or rest area parking area	1.0	4:1
Roundabout	0.8~3.4	3:1~6:1

TABLE 5.6
Illuminance Measurements under Luminaire

Lamp Type	Illuminance (fcd)	
	New Installation	12 Months Later
GE LED (258/258/258W)	2.81/2.70	2.68
Philips LED (270/270/270W)	3.57/3.34	3.42
Horner LED (200/200/200W)	4.43	4.37
Global Tech LED (6 × 392W)	1.53	1.74
Stray Light plasma (295/295/295W)	1.97	2.07

zone. The HPS 250W luminaires produced an average illuminance of 0.63 to 1.00 fcd and the HPS 400W luminaires produced an average illuminance of 1.00 to 1.33 fcd. Evidently, the three LEDs produced light levels compatible to that by the HPS 250W luminaires and slightly less than that by the HPS 400W luminaires. However, the average illuminance values produced by the three LEDs meet the average maintained design criteria for most highway facilities. Both GE 258W and Philips 270W LEDs produced an illuminance uniformity ratio that is close to that by the HPS 250W luminaires and slightly greater than that by the HPS 400 luminaires. Neither the new light sources nor the HPS luminaires met the illuminance uniformity requirements for continuous lighting in Zones 1, 2, 3 and 4. However, the new light sources were capable of producing satisfactory illuminance uniformity as indicated by the LED lighting on Washington Blvd and the plasma lighting on US-31 in Scottsburg.

To evaluate the possible changes of the lamp performance over time, the authors also measured the illuminance over the pavement surface right under the lamp for each of the LED luminaires and the plasma luminaire right after the installation (i.e., new installation) and approximately 12 months later after going through four different seasons. The results are presented in Table 5.6. For both the GE and Horner LED luminaires, the illuminance decrease is negligible. For Philips LED luminaires, the illuminance measurements are almost the same. For the Global Tech LED and Stray Light plasma luminaires, the illuminance measurements increased slightly after 12 months, probably due to the potential testing errors. Overall, the performance loss after 12-month service can be neglected for the LED and plasma luminaires.

The LED, plasma, and induction luminaires have been installed only for around 12 months and it may be too early to evaluate their performance thoroughly. However, both the measured illuminance and power metrics have demonstrated that these LED and plasma luminaires can not only produce light performances equivalent to those by the HPS luminaires with current lighting infrastructures, but also produce significant energy saving, particularly the LED luminaires for high mast lighting. Early indications from the field measurements are that the LED luminaires can be utilized for both conventional and high mast roadway lighting applications. The plasma luminaires with proven product quality can be utilized for conventional roadway lighting applications. No conclusions could be drawn about the induction and metal halide luminaires due to their early failures. In the author's opinion, new lighting sources such as LED and plasma should be considered in roadway lighting applications. However, there is no urgent need to change the current lighting design values such as average maintained illuminance, minimum illuminance and illuminance uniformity ratio. The new lighting technologies are not yet fully mature. Field application data on the long term performance and reliability is still needed for future revision of the design criteria for the new lighting technologies.

6. LIFE CYCLE COST ANALYSIS

6.1 Methodology and Basic Data

The FHWA publication, "Economic Analysis Primer" (*51*), is a great source of economic analysis methods for highway projects. The FHWA publication indicates that Life Cycle Cost Analysis (LCCA) is applied when an agency must undertake a project and is seeking to determine the lowest life-cycle-cost (i.e., most cost-effective) means to accomplish the project's objectives. LCCA enables the analyst to make sure that the selection of a design alternative is not based solely on the lowest initial costs, but also considers all the future costs (appropriately discounted) over the project's usable life. To ensure that the alternatives can be compared fairly, the analyst specifies a multiyear analysis period over which the life-cycle costs will be measured.

The values of a certain amount of money are different at different points in time. For example, the value of $100 at present will not be $100 in ten years because some values will be added to the money in terms of interest. Through LCCA, the future costs are converted to the present values using an interest rate so that the costs can be compared on a common basis.

In highway related economic analysis, discount rate, rather than interest rate, is often used to convert the future costs and benefits in terms of monetary values to the present value. An appropriate value of real discount rate can be estimated by subtracting the rate of inflation (measured by a general price index like CPI) from a market (nominal) interest rate for government borrowing, which is derived from government bonds. Table 6.1 lists the discount rates that are used by some state

TABLE 6.1
Discount Rate Used by Some State DOTs

DOT	Discount Rate	DOT	Discount Rate
California	4.0	Colorado	3.3
Illinois	3.0	Indiana	4.0
Kentucky	4.0	Missouri	2.3
Ohio	2.8	Pennsylvania	6.0
Virginia	4.0	Wisconsin	5.0

DOTs, including INDOT. The discount rate of 4% is currently used by INDOT in economic analysis of highway projects. In this study, a discount rate of 4% is used in the life cycle cost analysis. In order to examine the effect of discount rate, the discount rates of 3% and 6% are also used in the life cycle cost analysis.

To compare two alternatives with LCCA, it is necessary for the two alternatives to have a service period for the same number of years (*19*). The service life is 25 years for current conventional highway HPS lighting fixtures and 40 years for high mast HPS lighting fixtures in Indiana. The current HPS lamp replacement cycle is three years for both conventional and high mast HPS luminaires. It is expected that the service lives of the lighting fixtures for LED, induction, and plasma should also be 25 years. A service life of 40 years is assumed for high mast lightings. The light emitter replacement cycles for the three new lighting systems are not known. For the purpose of life cycle cost analysis, the warranty periods of the new lighting systems are used as their replacement cycles. In addition, to examine the effects of replacement cycles on life cycle costs, replacement cycles of 8 years and 12 years are also used to calculate life cycle costs for the new lighting systems.

In this study, the initial investment of a lighting device is the total cost of the installed lighting fixture, pole and foundation costs, the annual cost includes the electricity cost and maintenance cost, and the periodical cost is the lamp or emitter replacement cost at the fixed time interval. For one cycle of the service life, the costs for the HPS lights along the time line are shown in Figure 6.1, where the estimated service life is assumed to be 25 years, the initial investment is “I”, the lamp replacement cost is “r”, the annual maintenance cost is “m”, and the annual electricity cost is “e”.

To calculate life cycle cost, the following symbols are used in the formulas that convert monetary values at different points over time:

- i represents an interest rate per year.
- n represents a number of years in the interest period.
- P represents a present value of money, i.e., the value of money at Year 0.
- F represents the value of money at the end of the n^{th} year from the present time (Year 0) that is equivalent to P with interest rate i.
- A represents the end-of-year payment in a uniform series continuing for the coming n years, the entire series equivalent to P at interest rate i.

In this study, the following three formulas that express the relationship between P, F, and A in terms of interest rate i and number of years n are used to convert the lighting costs to the equivalent present values (*52*):

$$\text{Given F, to find P}: \quad P = F\left[\frac{1}{(1+i)^n}\right] \tag{6.1}$$

$$\text{Given A, to find P}: \quad P = A\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] \tag{6.2}$$

$$\text{Given P, to find A}: \quad A = P\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \tag{6.3}$$

The data on costs, rated and measured power values, and estimated service lives of the lighting systems included in this study is presented in Table 6.2. The cost data were provided by the INDOT Crawfordsville District and several members of the Study Advisory Committee (SAC) for this study. The measured power values are used to calculate the electricity usages. To determine if the tested new lighting systems are cost effective, the luminaires installed in Zones 1 through 3 are compared to the existing HPS (250W and 400W, GE) luminaires in terms of life cycle costs. In Zone 5, the six HPS (1000W, GE) luminaires are compared to the six LED (392W, Global Tech) luminaires.

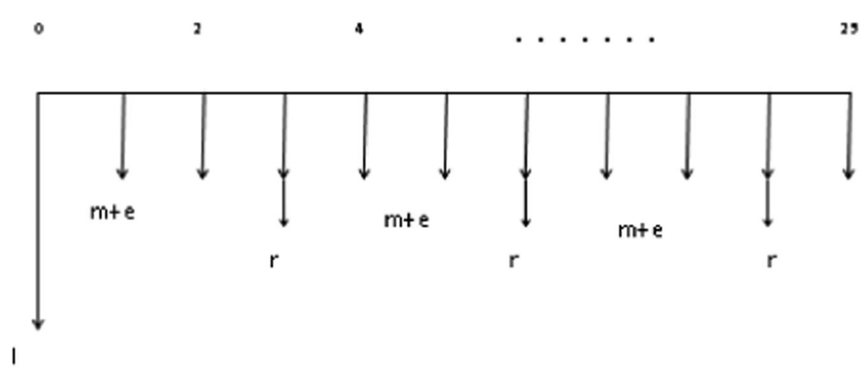


Figure 6.1 Cost flow along service life.

TABLE 6.2
Data Pertinent to Life Cycle Cost Analysis

Luminaire Type	Measured Power (Watts)	Pole & Foundation Cost ($)	Installed Luminaire Cost ($)	Lamp or Emitter Cost ($)	Labor Cost of Lamp or Emitter Replacement ($)	Lamp/Emitter Replacement Cycle (yr)
GE LU250 HPS 250W	**302**	**$2,140**	**$195**	**$21.8**	**$18.2**	**3**
GE LU400 HPS 400W	**473**	**$2,140**	**$210**	**$21.8**	**$18.2**	**3**
EcoReady MH 320W	320	$2,140	$500	$80.1	$75.0	5
GE Evolve ERS4 LED 258W	244	$2,140	$800	$120	$75.0	5
Philips RoadView RVM LED 270W	241	$2,140	$975	$120	$75.0	5
Horner ETG LED 200W	254	$2,140	$850	$120	$75.0	3
Stray Light TESLA II plasma 295W	269	$2,140	$1100	$120	$75.0	5
EcoLuminator induction 200W	227	$2,140	$500	$100	$75.0	5
GE LU1000 HPS 6 × 1000W	**7430**	**N/A**	**$3,780**	**$300**	**$150.0**	**3**
Global Tech SoLtice LED 6 × 392W	2196	N/A	$11,400	$372	$149.0	5

6.2 Life Cycle Costs

Using an annual operating time of 4380 hours estimated by the Traffic Administration Section of INDOT and Indiana electricity price of $0.10/kWh, the annual electricity costs are presented in Table 6.3. Also presented in Table 6.3 are the other cost items necessary for life cycle cost analysis as provided by the INDOT Crawfordsville District and SAC members. Currently, the HPS lamps are commonly replaced every three years by INDOT. The warranty periods provided by the vendors are used as the emitter replacement cycles for the new lighting sources. The costs for the high mast luminaires (1000W HPS and 392W LED) include the costs of six lamps for each type, while those for all other luminaires are single lamp costs.

For the alternative luminaires in Zone 1 through Zone 4, the life cycle cost of each luminaire is compared to those of the 400W HPS and 259W HPS luminaires on a same length of service period. Since the service lives vary from luminaire to luminaire, the least common multiple of two service lives is used in the cost analysis. In Zone 5, the six 392W LED luminaires are compared with the six 1000W HPS luminaires. In order to thoroughly study the cost effectiveness of the new luminaires, the life cycle costs are computed with different discount rates and with different lamp/emitter replacement cycles.

6.2.1 Life Cycle Costs at Discount Rate of 4%

Lamp/emitter replacement cycles of new lighting devices: warranty periods. INDOT replaces the existing HPS lamps every three years. The reasonable lamp/emitter replacement cycles of the new lighting devices under evaluation in this study are not known at this time. In the life cycle analysis, different lamp/emitter replacement cycles are used, including warranty periods given by the manufacturers, 8 years, and 12 years. The warranty periods are all 5 years except for the Horner ETG LED 200W lighting device with a 3 year warranty period. Presented in the following is the life cycle cost analysis at a discount of 4% and using the warranty periods of the new lighting devices as their lamp/emitter replacement cycles.

To illustrate the analysis process, the detailed life cycle cost calculations of the 400W HPS and 320W MH luminaire are presented as follows:

1. The service life is 25 years.

TABLE 6.3
Luminaire Costs and Replacement Cycle

Luminaire Type	Lamp or Emitter Life (Years)	Pole & Foundation Cost	Installed New Luminaire Cost	Lamp or Emitter Replacement Cost	Annual Electricity Cost* (e)	Annual Maintenance Cost (m)	Annual Cost (m+e)
GE LU250 HPS 250W	**3**	**$2,140**	**$195**	**$40**	**$132**	**$60**	**$192**
GE LU400 HPS 400W	**3**	**$2,140**	**$210**	**$40**	**$207**	**$60**	**$267**
EcoReady MH 320W	5	$2,140	$500	$155	$140	$50	$190
GE Evolve ERS4 LED 258W	5	$2,140	$800	$195	$107	$50	$157
Philips RoadView RVM LED 270W	5	$2,140	$975	$195	$106	$50	$156
Horner ETG LED 200W	3	$2,140	$850	$195	$111	$50	$161
Stray Light TESLA II plasma 295W	5	$2,140	$1100	$195	$118	$50	$168
EcoLuminator induction 200W	5	$2,140	$500	$175	$99	$50	$149
GE LU1000 HPS 6 × 1000W	**3**	**N/A**	**$3,780**	**$450**	**$3,254**	**$105**	**$3,359**
Global Tech SoLtice LED 6 × 392W	5	N/A	$11,400	$521	$962	$105	$1,067

*Annual Electricity Cost Calculation: ($0.10/kWh) × [Measured Power (W)] × (4380 hours) ÷ (1000).

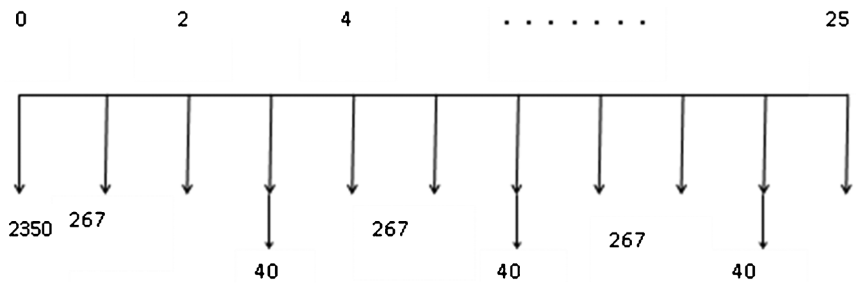


Figure 6.2 Cost flow of 400W HPS.

2. Choose interest rate: 4%.
3. The lamps are replaced every 3 years. The cost flow over a 25-year period is shown in Figure 6.2.
4. Convert all costs to the present worth of the monetary values (interest rate: 4%):

   a. Present worth of the 400W HPS luminaire:
   Present worth of installed luminaire cost and pole and foundation cost:
   P_{HPS1} = \$2350(cost in year 0, it is already present worth)
   Present worth of annual maintenance and electricity costs:

$$P_{HPS2} = A\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] = \$267\left[\frac{(1+0.04)^{25} - 1}{0.04(1+0.04)^{25}}\right] = \$4174.2$$

Present worth of lamp replacement (every 3 years) costs:

$$P_{HPS3} = F\left[\frac{1}{(1+i)^n}\right] = \$40\left\{\left[\frac{1}{(1+0.04)^3}\right] + \left[\frac{1}{(1+0.04)^6}\right] + \cdots + \left[\frac{1}{(1+0.04)^{24}}\right]\right\} = \$195.0$$

Total present worth:

$$P_{HPS} = P_{HPS1} + P_{HPS2} + P_{HPS3} = \$6719.2$$

Equivalent uniform annual cost:

$$A = P_{HPS}\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] = \$6719.2\left[\frac{0.04(1+0.04)^{25}}{(1+0.04)^{25} - 1}\right] = \$430$$

   b. Present worth of the 320W MH luminaire:
   Present worth of lamp and labor cost and pole and foundation cost (cost in year 0, it is already present worth):

$$P_{MH1} = \$2640$$

Present worth of annual maintenance and electricity costs:

$$P_{MH2} = A\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] = \$190.2\left[\frac{(1+0.04)^{25} - 1}{0.04(1+0.04)^{25}}\right] = \$2973.5$$

Present worth of lamp replacement (replaced every 5 years) costs:

$$P_{MH3} = F\left[\frac{1}{(1+i)^n}\right] = \$155\left\{\left[\frac{1}{(1+0.04)^5}\right] + \left[\frac{1}{(1+0.04)^{10}}\right] + \cdots + \left[\frac{1}{(1+0.04)^{25}}\right]\right\} = \$444.3$$

Total present worth:

$$P_{MH} = P_{MH1} + P_{MH2} + P_{MH3} = \$6057.8$$

Equivalent uniform annual cost:

$$A = P_{HPS}\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] = \$6057.8\left[\frac{0.04(1+0.04)^{25}}{(1+0.04)^{25} - 1}\right] = \$388$$

Thus, the life cycle costs of the two luminaires are as follows:

1. The 400W HPS luminaire: Total present worth of costs: P_{HPS} = \$6719.2
2. The 320W MH luminaire: Total present worth of costs: P_{MH} = \$6057.8

In terms of life cycle cost, the 320W MH luminaire is more cost effective than the 400W HPS luminaire. Over a period of 25 years, the total savings for using the 320W MH instead of the 400W HPS will be:

$$\Delta P = P_{HPS} - P_{MH} = \$6719.2 - \$6057.8 = \$661.4$$

The reason for the savings is that the 320W MH luminaire has a lower annual cost of electricity and maintenance, which will eventually compensate its

TABLE 6.4
Results of Life Cycle Cost Analysis

Luminaire Type	Lamp or Emitter Life (Years)	Pole & Foundation Cost	Installed New Luminaire Cost	Lamp or Emitter Replacement Cost	Annual Maintenance & Electricity Cost	Present Worth of Life Cycle Cost	Equivalent Uniform Annual Cost
GE LU250 HPS 250W	**3**	**$2,140**	**$195**	**$40**	**$192**	**$5,534**	**$354**
GE LU400 HPS 400W	**3**	**$2,140**	**$210**	**$40**	**$267**	**$6,719**	**$430**
EcoReady MH 320W	5	$2,140	$500	$155	$190	$6,058	$388
GE Evolve ERS4 LED 258W	5	$2,140	$800	$195	$157	$5,953	$381
Philips RoadView RVM LED 270W	5	$2,140	$975	$195	$156	$6,108	$391
Horner ETG LED 200W	3	$2,140	$850	$195	$161	$6,462	$414
Stray Light TESLA II plasma 295W	5	$2,140	$1100	$195	$168	$6,424	$411
EcoLuminator induction 200W	5	$2,140	$500	$175	$149	$5,479	$351
GE LU1000 HPS 6 × 1000W	**3**	**N/A**	**$3,780**	**$450**	**$3,359**	**$73,094**	**$3,693**
Global Tech SoLtice LED 6 × 392W	5	N/A	$11,400	$521	$962	$34,311	$1,734

relatively higher new lighting fixture costs over a certain period of time. In addition, the replacements of the MH lamp are less frequent (every 5 years) than those of the HPS (every 3 years), which saves money over the service life. Following the same steps as described above, the life cycle costs for other types of luminaries can be computed. The results of life cycle costs are shown in Table 6.4. In the life cycle cost analysis, the pole and foundation costs are included as part of the initial cost for all types of luminaires except for the high mast luminaires. It is assumed that the number of poles of high mast luminaires will remain the same with different types of luminaires.

The life cycle costs of the alternative lighting fixtures are compared to that of the 250W HPS as presented in Table 6.5. The differences between the life cycle cost of the 250W HPS fixture and the individual life cycle costs are listed in the last column in Table 6.5. For a given lighting fixture, if the difference value is positive, it means that the lighting fixture is more cost effective that the 250W HPS. Otherwise, the lighting fixture is not cost effective as compared to the 250W HPS. As indicated in Table 6.5, the 250W HPS is more cost effective than all of the new lighting luminaires except for the 200W induction luminaire. This is clearly illustrated in Figure 6.3. In the figure, all of the individual life cycle costs are represented by the bars. In addition, the life cycle cost of the 250W HPS fixture is plotted as a reference horizontal line. The life cycle cost bars below the reference line represent the more cost effective lighting fixtures and the bars above the reference line represent the less cost effective lighting fixtures as compared to the 250W HPS light.

In a similar manner, the life cycle costs of the alternative lighting fixtures are compared to that of the 400W HPS fixture as shown in Table 6.6 and Figure 6.4. The differences between the life cycle costs of the 400W HPS light and those of other types of lights are all positive. That is, all the alternative lighting devices are more cost effective than that of the 400W HPS device.

Finally, the 392W LED fixtures installed on the tower are compared with the existing 1000W HPS lights in terms of life cycle costs as shown in Table 6.7 and Figure 6.5. The LED tower lights are more cost effective than the HPS tower lights. It should be noted that the pole and foundation costs are not included in the life cycle costs. However, the relative difference between the two life cycle costs should be the same with or without the pole and foundation costs. That is, the fact that the LED tower lights are more cost effective will not be changed with or without the pole and foundation costs.

In addition to the life cycle cost comparisons, the return period is also computed for each new lighting device to provide the information on the time needed for a new lighting device to have a break-even life cycle cost as compared to the conventional lighting device. The return period of a lighting device would be useful for INDOT to identify how soon the device can became cost effective within its service life and to determine the minimum warranty time period of the device. A return period is determined by comparing the present worth values of two lighting devices and identifying the point in time after which the cost of the new lighting device becomes less than that of the conventional lighting device. Figures 6.6 through 6.9 illustrate some examples of return period identifications. For instance, as can be seen in Figure 6.6, the two curves intersect between Year 5 and Year 6 and thus the return period for the 320W MH luminaire is 6 years as compared to the 400W HPS luminaire. If a new luminaire is not more cost effective than the conventional one, the two cost curves will not intersect within the service life and, therefore, no return period can be identified, as demonstrated in Figures 6.10 and 6.11. The return periods are listed in Tables 6.8, 6.9, and 6.10 for different lighting luminaires.

In summary, with a discount rate of 4% and using the warranty periods as the lamp/emitter replacement cycles, the life cycle cost analysis indicates that all the alternative new types of lighting devices (LED, plasma,

TABLE 6.5
Comparison of Life Cycle Costs with 250W HPS

Luminaire Type	Present Worth of Life Cycle Cost	Life Cycle Cost Difference ($5,534-LCC)	Equivalent Uniform Annual Cost (EUAC)	Equivalent Uniform Annual Savings ($354-EUAC)
GE LU250 HPS 250W	**$5,534**	—	**$354**	—
EcoReady MH 320W	$6,058	−$524	$388	−$34
GE Evolve ERS4 LED 258W	$5,953	−$419	$381	−$27
Philips RoadView RVM LED 270W	$6,108	−$574	$391	−$37
Horner ETG LED 200W	$6,462	−$928	$414	−$60
Stray Light TESLA II plasma 295W	$6,424	−$890	$411	−$57
EcoLuminator induction 200W	$5,479	$55	$351	$4

and induction) are more cost effective than the existing 400W HPS lights. The 392W LED luminaires are more cost effective than the existing 100W HPS luminaires as the tower lights. In comparison with the existing 250W HPS lights, only the 200W induction luminaire is more cost effective and the rest are less cost effective.

The return periods of the new luminaires provide a new point of view for examining the cost effectiveness of individual luminaires, which would be useful for selecting appropriate lighting devices and determining the minimum warranty periods of the products. The lower life cycle costs of the alternative lighting devices are attributed to their relatively lower electricity usages and longer lamp/emitter replacement cycles. It is necessary to emphasize that the results of the life cycle costs should not be used as a sole basis for choosing appropriate roadway lighting devices. The performance of a lighting device described in previous chapters should be first considered when determining the lighting device's appropriateness for roadway lighting.

Lamp/emitter replacement cycles of new lighting devices: 8 years. In the life cycle cost analysis discussed above, the warranty periods of the new lighting devices were used as the lamp/emitter replacement cycles. It is likely that the lamps or emitters would work satisfactorily for a longer time than their warranty periods. With a discount rate of 4%, a replacement cycle of 8 years is used for the new lighting devices for the life cycle cost analysis. The life cycle costs and the return periods for 8-year replacement cycles are presented in Tables 6.11, 6.12, and 6.13. The values in Table 6.11 and Table 6.12 are the life cycle costs, life cycle cost differences, and return periods of the new lighting devices as compared to the existing 250W HPS and 400W HPS. Table 6.13 shows the result for the high mast luminaires, the existing 1000W HPS versus the 392W LED. As can be seen, the life cycles costs of the new lighting devices decreased as the replacement cycles increased from the warranty periods to 8 years.

Lamp/emitter replacement cycles of new lighting devices: 12 years. In a similar manner, the life cycle costs and return periods are computed for a 12-year lamp/emitter replacement cycle as shown in Tables 6.14, 6.15, and 6.16. As expected, the life cycle costs are further reduced as the replacement cycles changed from 8 years to 12 years.

6.2.2 Life Cycle Costs at Discount Rate of 3%

Since discount rate is an important factor in the life cycle cost analysis for transportation projects, extreme

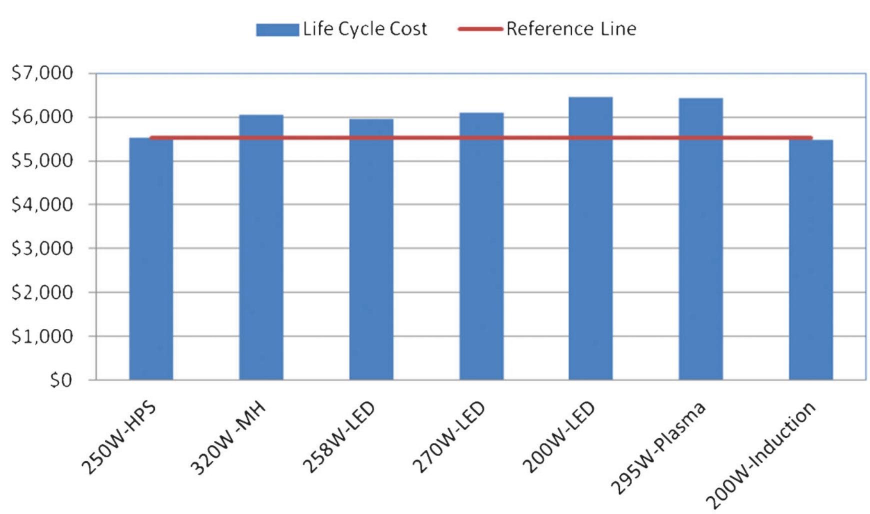


Figure 6.3 Comparison of life cycle costs with 250W HPS.

TABLE 6.6
Comparison of Life Cycle Costs with 400W HPS

Luminaire Type	Present Worth of Life Cycle Cost	Life Cycle Cost Difference ($6,719-LCC)	Equivalent Uniform Annual Cost (EUAC)	Equivalent Uniform Annual Savings ($430-EUAC)
GE LU400 HPS 400W	**$6,719**	—	**$430**	
EcoReady MH 320W	$6,058	$661	$388	$42
GE Evolve ERS4 LED 258W	$5,953	$766	$381	$49
Philips RoadView RVM LED 270W	$6,108	$611	$391	$39
Horner ETG LED 200W	$6,462	$257	$414	$16
Stray Light TESLA II plasma 295W	$6,424	$295	$411	$19
EcoLuminator induction 200W	$5,479	$1,240	$351	$79

care should be taken to determine an appropriate discount rate that reflects the agency's actual time value of resources. In general, the discount rate is positive whether or not there is inflation in the economy due to the difficulty to predict inflation in economy. As shown in Table 6.1, the discount rate used in economic analysis of highway projects varies from state to state. A higher discount rate results in a smaller present value. As a rule of best practice, States commonly a discount rate ranging from 3% to 5% for discounting highway investments (*53*). In order to assess the effects of discount rates on the life cycle costs of the lighting devices, the discount rates of 3% and 6% are also used to calculate the life cycle costs. The life cycle costs at discount rate of 3% are shown in the following tables (Tables 6.17 through 6.25) with respect to the replacement cycles of warranty periods, 8 years, and 12 years.

Lamp/emitter replacement cycles of new lighting devices: warranty periods. Tables 6.17, 6.18, and 6.19 show life cycle costs at the discount rate of 3% with respect to the warranty period replacement cycle.

Lamp/emitter replacement cycles of new lighting devices: 8 years. Tables 6.20, 6.21, and 6.22 show life cycle costs at the discount rate of 3% with respect to the 8-year replacement cycle.

Lamp/emitter replacement cycles of new lighting devices: 12 years. Tables 6.23, 6.24, and 6.25 show life cycle costs at the discount rate of 3% with respect to the 12-year replacement cycle.

6.2.3 Life Cycle Costs at Discount Rate of 6%

The life cycle cost results at the discount rate of 6% with different lamp/emitter replacement cycles are presented in Tables 6.26 through 6.34.

Lamp/emitter replacement cycles of new lighting devices: warranty periods. Tables 6.26, 6.27, and 6.28 show life cycle costs at the discount rate of 6% with respect to the warranty period replacement cycle.

Lamp/emitter replacement cycles of new lighting devices: 8 years. Tables 6.29, 6.30, and 6.31 show life

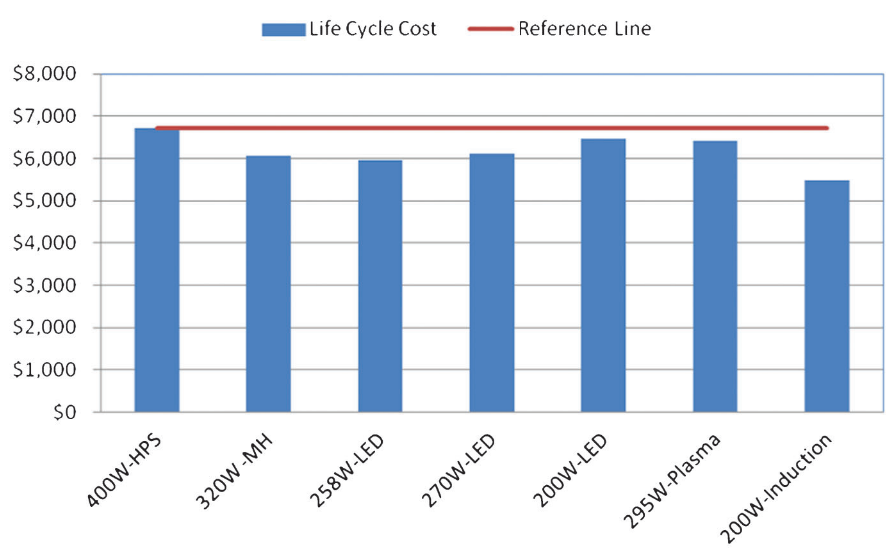


Figure 6.4 Comparison of life cycle costs with 400W HPS.

TABLE 6.7
Comparison of Life Cycle Costs of High Mast Lights

Luminaire Type	Present Worth of Life Cycle Cost	Equivalent Uniform Annual Cost (Present Dollar)
GE LU1000 HPS 6 × 1000W	**$73,094**	**$3,693**
Global Tech SoLtice LED 6 × 392W	$34,311	$1,734
Savings	$38,783	$1,959

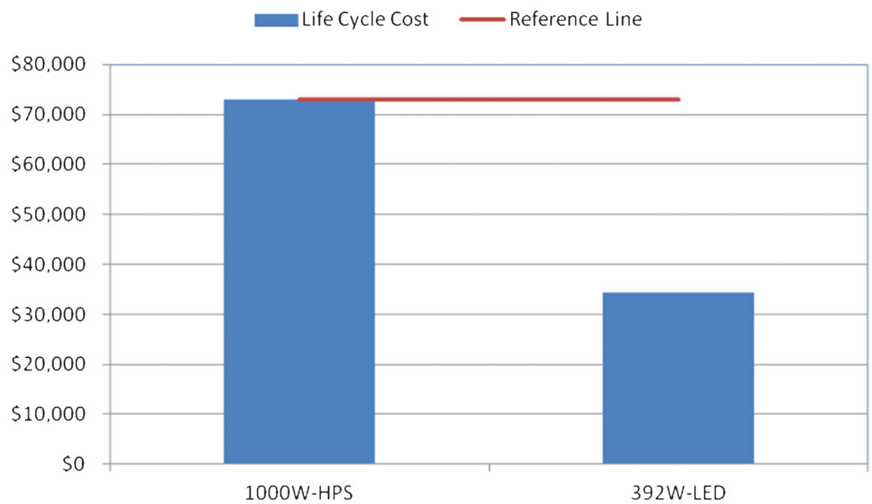


Figure 6.5 Comparison of life cycle costs of tower lights.

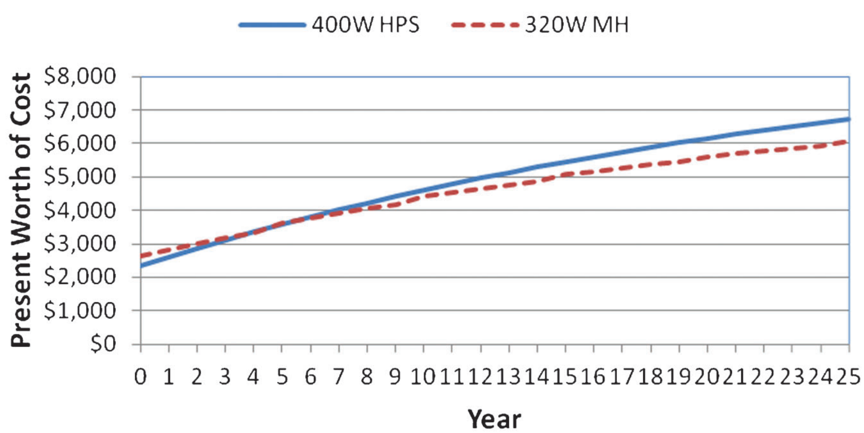


Figure 6.6 Return period identification (400W HPS vs. 320W MH).

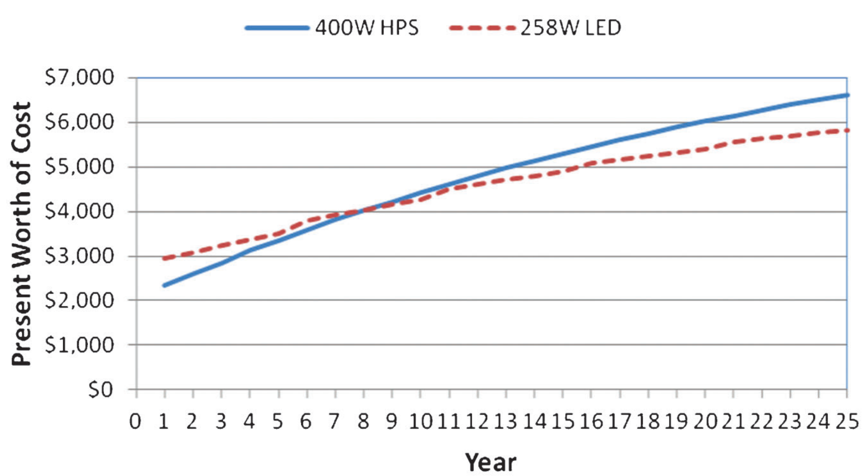


Figure 6.7 Return period identification (400W HPS vs. 258W LED).

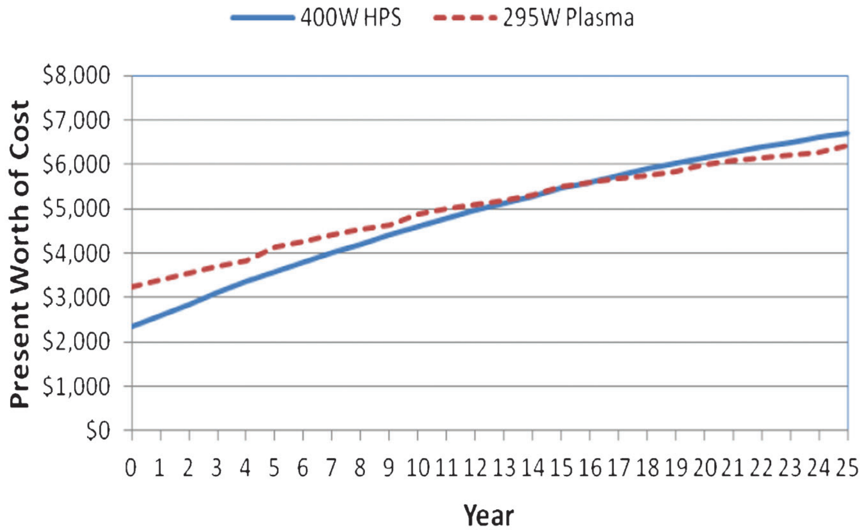


Figure 6.8 Return period identification (400W HPS vs. 295W plasma).

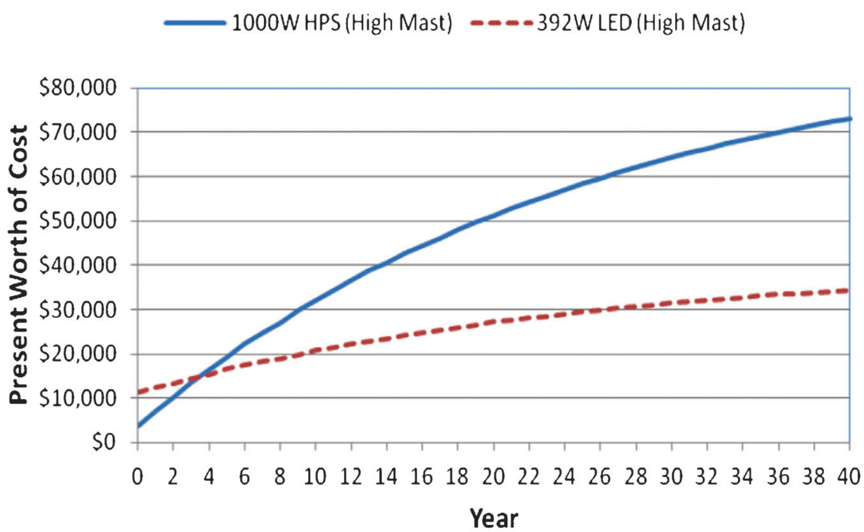


Figure 6.9 Return period identification (400W HPS High Mast vs. 292W LED High Mast).

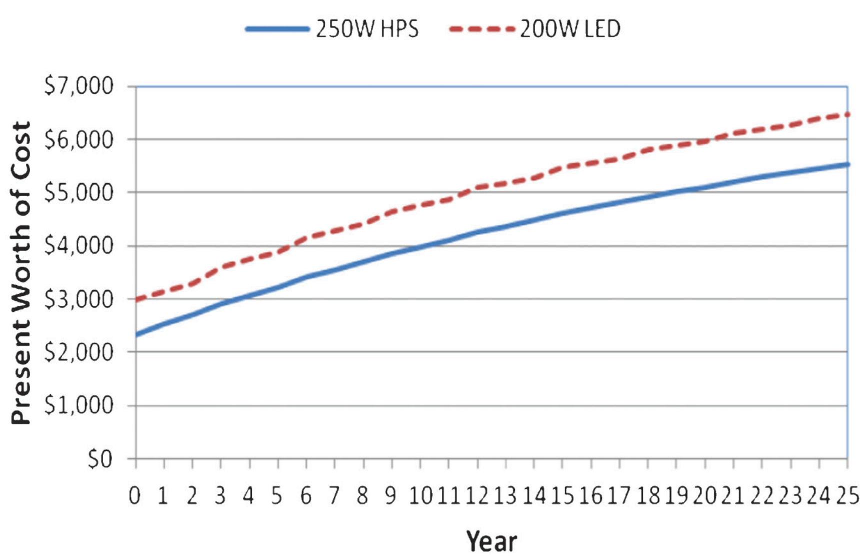


Figure 6.10 Case of no return period (250W HPS vs. 200W LED).

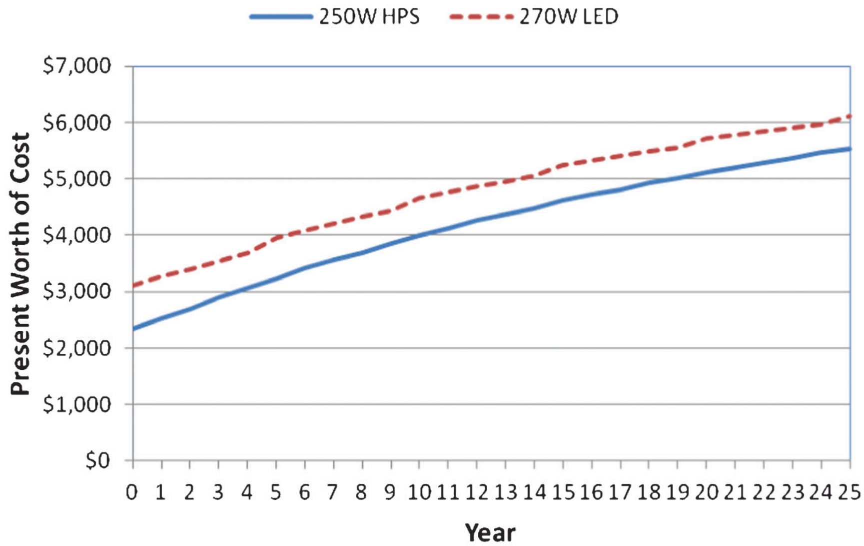


Figure 6.11 Case of no return period (250W HPS vs. 270W LED).

TABLE 6.8
Return Periods of Luminaires in Comparison with 250W HPS

Luminaire Type	Return Period (Year)
GE LU250 HPS 250W	—
EcoReady MH 320W	N/A
GE Evolve ERS4 LED 258W	N/A
Philips RoadView RVM LED 270W	N/A
Horner ETG LED 200W	N/A
Stray Light TESLA II plasma 295W	N/A
EcoLuminator induction 200W	18

TABLE 6.9
Return Periods of Luminaires in Comparison with 400W HPS

Luminaire Type	Return Period (Year)
GE LU400 HPS 400W	—
EcoReady MH 320W	6
GE Evolve ERS4 LED 258W	8
Philips RoadView RVM LED 270W	11
Horner ETG LED 200W	16
Stray Light TESLA II plasma 295W	16
EcoLuminator induction 200W	3

TABLE 6.10
Return Period of 392W LED Luminaire as High Mast Lighting

Luminaire Type	Return Period (Year)
GE LU1000 HPS 6 × 1000W	—
Global Tech SoLtice LED 6 × 392W	4

cycle costs at the discount rate of 3% with respect to the 8-year replacement cycle.

Lamp/emitter replacement cycles of new lighting devices: 12 years. Tables 6.32, 6.33, and 6.34 show life cycle costs at the discount rate of 3% with respect to the 12-year replacement cycle.

6.2.4 Life Cycle Costs and Return Periods at Different Discount Rates and Lamp/Emitter Replacement Cycles

With the calculated life cycle costs and return periods, the effects of discount rates and lamp replacement cycles can be examined. The life cycle costs with different discount rates and lamp replacement cycles are listed in Table 6.35. As noted in the table, the lamp replacement cycles of the existing luminaires remain 3 years under different discount rates. The warranty period for the Horner 200W LED device is 3 years, so a 3-year emitter replacement cycle is used for this device when 5-year replacement cycles are used for other tested devices. Table 6.35 indicates that when the discount rate increases, the life cycle cost decreases; and that when the replacement cycle increases, the life cycle cost decreases.

Tables 6.36, 6.37, and 6.38 show the return periods of the test lighting devices as compared to the conventional 250W, 400W, and 1000W HPS lightings, respectively. As shown in Table 6.36, only the 200W induction is more cost effective than the 250W HPS under different discount rates and lamp replacement cycles. The return period of the 200W induction changes as the discount rate and the replacement cycle change.

Table 6.37 illustrates that all the tested new lighting devices are more cost effective than the conventional 400W HPS lighting device. However, the return periods

TABLE 6.11
Life Cycle Costs and Return Periods Compared to 250W HPS

Luminaire Type	Lamp/Emitter Replacement Cycle (Years)	Present Worth of Life Cycle Cost	Life Cycle Cost Difference ($5,534-LCC)	Return Period (Years)
GE LU250 HPS 250W	**3**	**$5,534**	—	—
EcoReady MH 320W	8	$5,867	−$333	N/A
GE Evolve ERS4 LED 258W	8	$5,713	−$179	N/A
Philips RoadView RVM LED 270W	8	$5,868	−$334	N/A
Horner ETG LED 200W	8	$5,832	−$298	N/A
Stray Light TESLA II plasma 295W	8	$6,184	−$650	N/A
EcoLuminator induction 200W	8	$5,264	$270	10

TABLE 6.12
Life Cycle Costs and Return Periods Compared to 400W HPS

Luminaire Type	Lamp/Emitter Replacement Cycle (Years)	Present Worth of Life Cycle Cost	Life Cycle Cost Difference ($6,719-LCC)	Return Period (Years)
GE LU400 HPS 400W	**3**	**$6,719**	—	—
EcoReady MH 320W	8	$5,867	$852	4
GE Evolve ERS4 LED 258W	8	$5,713	$1,006	6
Philips RoadView RVM LED 270W	8	$5,868	$851	9
Horner ETG LED 200W	8	$5,832	$887	9
Stray Light TESLA II plasma 295W	8	$6,184	$535	12
EcoLuminator induction 200W	8	$5,264	$1,455	3

TABLE 6.13
Life Cycle Cost and Return Period of High Mast LED Lights

Luminaire Type	Lamp/Emitter Replacement Cycle (Years)	Present Worth of Life Cycle Cost	Life Cycle Cost Difference ($73,094-LCC)	Return Period (Years)
GE LU1000 HPS 6 × 1000W	**3**	**$73,094**	—	—
Global Tech SoLtice LED 6 × 392W	8	$33,527	$39,567	4

TABLE 6.14
Life Cycle Costs and Return Periods Compared to 250W HPS

Luminaire Type	Lamp/Emitter Replacement Cycle (Years)	Present Worth of Life Cycle Cost	Life Cycle Cost Difference ($5,534-LCC)	Return Period (Years)
GE LU250 HPS 250W	**3**	**$5,534**	—	—
EcoReady MH 320W	12	$5,768	−$234	N/A
GE Evolve ERS4 LED 258W	12	$5,588	−$54	N/A
Philips RoadView RVM LED 270W	12	$5,8743	−$208	N/A
Horner ETG LED 200W	12	$5,707	−$173	N/A
Stray Light TESLA II plasma 295W	12	$6,060	−$526	N/A
EcoLuminator induction 200W	12	$5,152	$382	7

TABLE 6.15
Life Cycle Costs and Return Periods Compared to 400W HPS

Luminaire Type	Lamp/Emitter Replacement Cycle (Years)	Present Worth of Life Cycle Cost	Life Cycle Cost Difference ($6,719-LCC)	Return Period (Years)
GE LU400 HPS 400W	**3**	**$6,719**	—	—
EcoReady MH 320W	12	$5,768	$951	4
GE Evolve ERS4 LED 258W	12	$5,588	$1,131	6
Philips RoadView RVM LED 270W	12	$5,743	$976	8
Horner ETG LED 200W	12	$5,707	$1012	7
Stray Light TESLA II plasma 295W	12	$6,060	$660	10
EcoLuminator induction 200W	12	$5,152	$1,567	3

TABLE 6.16
Life Cycle Cost and Return Period of High Mast LED Lights

Luminaire Type	Lamp/Emitter Replacement Cycle (Years)	Present Worth of Life Cycle Cost	Life Cycle Cost Difference ($73,094-LCC)	Return Period (Years)
GE LU1000 HPS 6 × 1000W	**3**	**$73,094**	—	—
Global Tech SoLtice LED 6 × 392W	12	$33,172	$39,922	4

TABLE 6.17
Life Cycle Costs and Return Periods Compared to 250W HPS

Luminaire Type	Lamp/Emitter Replacement Cycle (Years)	Present Worth of Life Cycle Cost	Life Cycle Cost Difference ($5,902-LCC)	Return Period (Years)
GE LU250 HPS 250W	**3**	**$5,902**	—	—
EcoReady MH 320W	5	$6,460	−$557	N/A
GE Evolve ERS4 LED 258W	5	$6,311	−$409	N/A
Philips RoadView RVM LED 270W	5	$6,463	−$561	N/A
Horner ETG LED 200W	3	$6,866	−$964	N/A
Stray Light TESLA II plasma 295W	5	$6,802	−$900	N/A
EcoLuminator induction 200W	5	$5,816	$86	17

TABLE 6.18
Life Cycle Costs and Return Periods Compared to 400W HPS

Luminaire Type	Lamp/Emitter Replacement Cycle (Years)	Present Worth of Life Cycle Cost	Life Cycle Cost Difference ($7,222-LCC)	Return Period (Years)
GE LU400 HPS 400W	**3**	**$7,222**	—	—
EcoReady MH 320W	5	$6,460	$762	6
GE Evolve ERS4 LED 258W	5	$6,311	$910	8
Philips RoadView RVM LED 270W	5	$6,463	$758	11
Horner ETG LED 200W	3	$6,866	$355	14
Stray Light TESLA II plasma 295W	5	$6,802	$420	14
EcoLuminator induction 200W	5	$5,816	$1,406	3

TABLE 6.19
Life Cycle Cost and Return Period of High Mast LED Lights

Luminaire Type	Lamp/Emitter Replacement Cycle (Years)	Present Worth of Life Cycle Cost	Life Cycle Cost Difference ($84,751-LCC)	Return Period (Years)
GE LU1000 HPS 6 × 1000W	**3**	**$84,751**	—	—
Global Tech SoLtice LED 6 × 392W	5	$38,169	$46,582	4

TABLE 6.20
Life Cycle Costs and Return Periods Compared to 250W HPS

Luminaire Type	Lamp/Emitter Replacement Cycle (Years)	Present Worth of Life Cycle Cost	Life Cycle Cost Difference ($5,902-LCC)	Return Period (Years)
GE LU250 HPS 250W	**3**	**$5,902**	—	—
EcoReady MH 320W	8	$6,247	−$345	N/A
GE Evolve ERS4 LED 258W	8	$6,043	−$141	N/A
Philips RoadView RVM LED 270W	8	$6,195	−$293	N/A
Horner ETG LED 200W	8	$6,169	−$267	N/A
Stray Light TESLA II plasma 295W	8	$6,534	−$631	N/A
EcoLuminator induction 200W	8	$5,575	$327	10

TABLE 6.21
Life Cycle Costs and Return Periods Compared to 400W HPS

Luminaire Type	Lamp/Emitter Replacement Cycle (Years)	Present Worth of Life Cycle Cost	Life Cycle Cost Difference ($7,222-LCC)	Return Period (Years)
GE LU400 HPS 400W	**3**	**$7,222**	—	—
EcoReady MH 320W	8	$6,247	$975	4
GE Evolve ERS4 LED 258W	8	$6,043	$1,179	6
Philips RoadView RVM LED 270W	8	$6,195	$1,027	9
Horner ETG LED 200W	8	$6,169	$1,052	6
Stray Light TESLA II plasma 295W	8	$6,534	$689	12
EcoLuminator induction 200W	8	$5,575	$1,646	3

TABLE 6.22
Life Cycle Cost and Return Period of High Mast LED Lights

Luminaire Type	Lamp/Emitter Replacement Cycle (Years)	Present Worth of Life Cycle Cost	Life Cycle Cost Difference ($84,751-LCC)	Return Period (Years)
GE LU1000 HPS 6 × 1000W	**3**	**$84,751**	—	—
Global Tech SoLtice LED 6 × 392W	8	$37,255	$47,496	4

TABLE 6.23
Life Cycle Costs and Return Periods Compared to 250W HPS

Luminaire Type	Lamp/Emitter Replacement Cycle (Years)	Present Worth of Life Cycle Cost	Life Cycle Cost Difference ($5,902-LCC)	Return Period (Years)
GE LU250 HPS 250W	**3**	**$5,902**	—	—
EcoReady MH 320W	12	$6,136	−$234	N/A
GE Evolve ERS4 LED 258W	12	$5,904	−$2	N/A
Philips RoadView RVM LED 270W	12	$6,056	−$154	N/A
Horner ETG LED 200W	12	$6,031	−$128	N/A
Stray Light TESLA II plasma 295W	12	$6,395	−$493	N/A
EcoLuminator induction 200W	12	$5,450	$452	7

TABLE 6.24
Life Cycle Costs and Return Periods Compared to 400W HPS

Luminaire Type	Lamp/Emitter Replacement Cycle (Years)	Present Worth of Life Cycle Cost	Life Cycle Cost Difference ($7,222-LCC)	Return Period (Years)
GE LU400 HPS 400W	**3**	**$7,222**	—	—
EcoReady MH 320W	12	$6,136	$1,085	4
GE Evolve ERS4 LED 258W	12	$5,904	$1,317	6
Philips RoadView RVM LED 270W	12	$6,057	$1,165	7
Horner ETG LED 200W	12	$6,031	$1,191	6
Stray Light TESLA II plasma 295W	12	$6,395	$827	10
EcoLuminator induction 200W	12	$5,451	$1,171	3

TABLE 6.25
Life Cycle Cost and Return Period of High Mast LED Lights

Luminaire Type	Lamp/Emitter Replacement Cycle (Years)	Present Worth of Life Cycle Cost	Life Cycle Cost Difference ($84,751-LCC)	Return Period (Years)
GE LU1000 HPS 6 × 1000W	**3**	**$84,751**	—	—
Global Tech SoLtice LED 6 × 392W	12	$36,861	$47,890	4

TABLE 6.26
Life Cycle Costs and Return Periods Compared to 250W HPS

Luminaire Type	Lamp/Emitter Replacement Cycle (Years)	Present Worth of Life Cycle Cost	Life Cycle Cost Difference ($4,951-LCC)	Return Period (Years)
GE LU250 HPS 250W	**3**	**$4,951**	—	—
EcoReady MH 320W	5	$5,422	−$472	N/A
GE Evolve ERS4 LED 258W	5	$5,388	−$437	N/A
Philips RoadView RVM LED 270W	5	$5,546	−$595	N/A
Horner ETG LED 200W	3	$5,820	−$869	N/A
Stray Light TESLA II plasma 295W	5	$5,828	−$877	N/A
EcoLuminator induction 200W	5	$4,947	$4	22

TABLE 6.27
Life Cycle Costs and Return Periods Compared to 400W HPS

Luminaire Type	Lamp/Emitter Replacement Cycle (Years)	Present Worth of Life Cycle Cost	Life Cycle Cost Difference ($5,923-LCC)	Return Period (Years)
GE LU400 HPS 400W	**3**	**$5,923**	—	—
EcoReady MH 320W	5	$5,422	$501	6
GE Evolve ERS4 LED 258W	5	$5,388	$536	8
Philips RoadView RVM LED 270W	5	$5,546	$377	12
Horner ETG LED 200W	3	$5,820	$103	19
Stray Light TESLA II plasma 295W	5	$5,827	$95	21
EcoLuminator induction 200W	5	$4,947	$976	3

TABLE 6.28
Life Cycle Cost and Return Period of High Mast LED Lights

Luminaire Type	Lamp/Emitter Replacement Cycle (Years)	Present Worth of Life Cycle Cost	Life Cycle Cost Difference ($56,439-LCC)	Return Period (Years)
GE LU1000 HPS 6 × 1000W	**3**	**$56,439**	—	—
Global Tech SoLtice LED 6 × 392W	5	$28,792	$27,647	4

TABLE 6.29
Life Cycle Costs and Return Periods Compared to 250W HPS

Luminaire Type	Lamp/Emitter Replacement Cycle (Years)	Present Worth of Life Cycle Cost	Life Cycle Cost Difference ($4,951-LCC)	Return Period (Years)
GE LU250 HPS 250W	**3**	**$4,951**	—	—
EcoReady MH 320W	8	$5,267	−$317	N/A
GE Evolve ERS4 LED 258W	8	$5,193	−$242	N/A
Philips RoadView RVM LED 270W	8	$5,350	−$400	N/A
Horner ETG LED 200W	8	$5,299	−$348	N/A
Stray Light TESLA II plasma 295W	8	$5,633	−$682	N/A
EcoLuminator induction 200W	8	$4,772	$179	11

TABLE 6.30
Life Cycle Costs and Return Periods Compared to 400W HPS

Luminaire Type	Lamp/Emitter Replacement Cycle (Years)	Present Worth of Life Cycle Cost	Life Cycle Cost Difference ($5,923-LCC)	Return Period (Years)
GE LU400 HPS 400W	**3**	**$5,923**	—	—
EcoReady MH 320W	8	$5,267	$656	4
GE Evolve ERS4 LED 258W	8	$5,193	$731	6
Philips RoadView RVM LED 270W	8	$5,350	$572	10
Horner ETG LED 200W	8	$5,299	625	9
Stray Light TESLA II plasma 295W	8	$5,633	$291	14
EcoLuminator induction 200W	8	$4,772	$1,151	3

TABLE 6.31
Life Cycle Cost and Return Period of High Mast LED Lights

Luminaire Type	Lamp/Emitter Replacement Cycle (Years)	Present Worth of Life Cycle Cost	Life Cycle Cost Difference ($56,439-LCC)	Return Period (Years)
GE LU1000 HPS 6 × 1000W	**3**	**$56,439**	—	—
Global Tech SoLtice LED 6 × 392W	8	$28,194	$28,245	4

TABLE 6.32
Life Cycle Costs and Return Periods Compared to 250W HPS

Luminaire Type	Lamp/Emitter Replacement Cycle (Years)	Present Worth of Life Cycle Cost	Life Cycle Cost Difference ($4,951-LCC)	Return Period (Years)
GE LU250 HPS 250W	**3**	**$4,951**	—	—
EcoReady MH 320W	12	$5,186	−$236	N/A
GE Evolve ERS4 LED 258W	12	$5,900	−$140	N/A
Philips RoadView RVM LED 270W	12	$5,249	−$298	N/A
Horner ETG LED 200W	12	$5,196	−$246	N/A
Stray Light TESLA II plasma 295W	12	$5,530	−$580	N/A
EcoLuminator induction 200W	12	$4,680	$270	8

TABLE 6.33
Life Cycle Costs and Return Periods Compared to 400W HPS

Luminaire Type	Lamp/Emitter Replacement Cycle (Years)	Present Worth of Life Cycle Cost	Life Cycle Cost Difference ($5,923-LCC)	Return Period (Years)
GE LU400 HPS 400W	**3**	**$5,923**	—	—
EcoReady MH 320W	12	$5,186	$737	4
GE Evolve ERS4 LED 258W	12	$5,900	$833	6
Philips RoadView RVM LED 270W	12	$5,923	$677	9
Horner ETG LED 200W	12	$5,196	$727	7
Stray Light TESLA II plasma 295W	12	$65,530	$393	14
EcoLuminator induction 200W	12	$4,680	$1,243	3

TABLE 6.34
Life Cycle Cost and Return Period of High Mast LED Lights

Luminaire Type	Lamp/Emitter Replacement Cycle (Years)	Present Worth of Life Cycle Cost	Life Cycle Cost Difference ($56,439-LCC)	Return Period (Years)
GE LU1000 HPS 6 × 1000W	**3**	**$56,439**	—	—
Global Tech SoLtice LED 6 × 392W	12	$27,904	$28,535	4

TABLE 6.35
Life Cycle Costs at Various Discount Rates and Replacement Cycles

	3%			4%			6%		
Luminaire Type	**5 Yrs**	**8 Yrs**	**12 Yrs**	**5 Yrs**	**8 Yrs**	**12 Yrs**	**5 Yrs**	**8 Yrs**	**12 Yrs**
GE LU250 HPS 250W	**$5,902**	**$5,902**	**$5,902**	**$5,534**	**$5,534**	**$5,534**	**$4,951**	**$4,951**	**$4,951**
GE LU400 HPS 400W	**$7,222**	**$7,222**	**$7,222**	**$6,719**	**$6,719**	**$6,719**	**$5,923**	**$5,923**	**$5,923**
EcoReady MH 320W	$6,460	$6,247	$6,136	$6,058	$5,867	$5,768	$5,422	$5,267	$5,186
GE Evolve ERS4 LED 258W	$6,311	$6,043	$5,904	$5,953	$5,713	$5,588	$5,388	$5,193	$5,900
Philips RoadView RVM LED 270W	$6,463	$6,195	$6,057	$6,108	$5,868	$5,743	$5,546	$5,350	$5,923
Horner ETG LED 200W	**$6,866**	$6,169	$6,031	**$6,462**	$5,832	$5,707	**$5,820**	$5,299	$5,196
Stray Light TESLA II plasma 295W	$6,802	$6,534	$6,395	$6,424	$6,184	$6,060	$5,827	$5,633	$65,530
EcoLuminator induction 200W	$5,816	$5,575	$5,451	$5,479	$5,264	$5,152	$4,947	$4,772	$4,680
GE LU1000 HPS 6 × 1000W	**$84,751**	**$84,751**	**$84,751**	**$73,094**	**$73,094**	**$73,094**	**$56,439**	**$56,439**	**$56,439**
Global Tech SoLtice LED 6 × 392W	$38,167	$37,255	$36,861	$34,311	$33,527	$33,172	$28,792	$28,194	$27,904

NOTE: **Boldfaced values** are from 3-year replacement cycles.

TABLE 6.36
Return Periods at Discount Rates and Replacement Cycles (vs. 250W HPS)

	3%			4%			6%			
Luminaire Type	**5 Yrs**	**8 Yrs**	**12 Yrs**	**5 Yrs**	**8 Yrs**	**12 Yrs**	**5 Yrs**	**8 Yrs**	**12 Yrs**	**Avg.**
GE LU250 HPS 250W	—	—	—	—	—	—	—	—	—	—
GE MH 320W	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	—
GE Evolve ERS4 LED 258W	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	—
Philips RoadView RVM LED 270W	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	—
Horner ETG LED 200W	**N/A**	N/A	N/A	**N/A**	N/A	N/A	**N/A**	N/A	N/A	—
Stray Light TESLA II plasma 295W	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	—
EcoLuminator induction 200W	17	10	7	18	10	7	22	11	8	12

NOTE: **Boldfaced values** are from 3-year replacement cycles.

TABLE 6.37
Return Periods at Discount Rates and Replacement Cycles (vs. 400W HPS)

	3%			4%			6%		
Luminaire Type	**5 Yrs**	**8 Yrs**	**12 Yrs**	**5 Yrs**	**8 Yrs**	**12 Yrs**	**5 Yrs**	**8 Yrs**	**12 Yrs**
GE LU400 HPS 400W	—	—	—	—	—	—	—	—	—
EcoReady MH 320W	6	4	4	6	4	4	6	4	4
GE Evolve ERS4 LED 258W	8	6	6	8	6	6	8	6	6
Philips RoadView RVM LED 270W	11	9	7	11	9	8	12	10	9
Horner ETG LED 200W	**14**	6	6	**14**	6	7	**19**	9	7
Stray Light TESLA II plasma 295W	14	12	10	14	12	10	21	14	14
EcoLuminator induction 200W	3	3	3	3	3	3	3	3	3

NOTE: **Boldfaced values** are from 3-year replacement cycles.

TABLE 6.38
Return Periods at Discount Rates and Replacement Cycles (vs. 1000W HPS)

	3%			4%			6%		
Luminaire Type	**5 Yrs**	**8 Yrs**	**12 Yrs**	**5 Yrs**	**8 Yrs**	**12 Yrs**	**5 Yrs**	**8 Yrs**	**12 Yrs**
GE LU1000 HPS 6 × 1000W	—	—	—	—	—	—	—	—	—
Global Tech SoLtice LED 6 × 392W	4	4	4	4	4	4	4	4	4

NOTE: **Boldfaced values** are from 3-year replacement cycles.

are different under different discount rates and lamp replacement cycles.

Table 6.38 indicates that the 392W LED is more cost effective than the 1000W HPS when used as high mast lighting luminaire under any of the given discount rates and lamp replacement cycles. Because of the great difference between the two life cycle costs, the 392W LED will break-even within 4 years as compared with the 1000W HPS when used as the high mast lighting device.

7. FINDINGS AND RECOMMENDATIONS

7.1 Main Findings

7.1.1 State Highway Agency and Local City Surveys

LED lighting technology has demonstrated higher market penetration than other new lighting technologies in both roadway lighting by SHAs and street lighting by local cities.

Both SHAs and local cities have adopted new lighting technologies for these very same reasons, including maintenance saving, energy saving, and better light performance. In the Midwest, Michigan adopted new lighting technologies mainly for energy savings, and Ohio adopted LED lighting for both maintenance savings and longer lamp life. No SHA intends to pursue savings by sacrificing lighting performance. Federal grants have also played a role in adopting new lighting technologies by local cities.

The main barriers for SHAs to adopt the new lighting technologies are the concerns about light level and luminous efficacy and savings unconvincing. In the Midwest, some SHAs indicated the need for specifications to adopt new lighting technologies and also raised concerns about the performance of induction lighting.

Induction lighting has been used by some SHAs much earlier than LED and plasma lightings. The adoption of LED lighting by SHAs commenced circa 2009. Plasma lighting is relatively new and its use by SHAs started approximately in 2011. Local cities started to use LED lighting at approximately the same time as SHAs. Induction and plasma lightings have recently started to find a way into street lighting.

For SHAS, LED lighting has been used for conventional, high mast and decorative lightings on roadways with different functional classifications in both rural and urban areas. LED lighting has also been used at interchange, intersection and parking lot. Induction lighting has been used for interstate lighting and tunnel and underpass lighting by several SHAs. Florida has uses induction lighting as the primary light source for sign lighting. Plasma lighting has been used for parking lot lighting so far. In the Midwest, LED lighting has been used for interstate, US highway and off-highway lighting, and induction lighting for interstate lighting. LED lighting has recently received increasing use in roadway lighting. For local cities, LED lighting has been used on urban roadways of different classifications at different locations. Use of the induction or plasma lighting is still limited in urban street lighting.

The average service life expected by SHAs is approximately 13, 15, and 10 years for LED, induction, and plasma lighting, respectively. The average LCC is approximately $80, $70, and $122 for LED, induction, and plasma lighting, respectively. Induction lighting was perceived to have the longest service life and the plasma lighting to have the greatest LCC. The expected average service life expected by local cities is about 16 years for LED lighting, longer than induction or plasma lighting. The service life of induction lighting has not lived up to the expectation so far.

In use of the new lighting technologies by SHAS, the top issue is the light performance. Issues also arose with electronic driver and surge protection. Early failures were observed for induction luminaires. For local cities, the major issues in use of new lighting technologies are surge protection and electronic driver failure. Issues also arose with the installation, particularly with use of the existing pole infrastructure.

Both SHAs and local cities are commonly using specifications from the manufacturers or vendors currently. Several SHAs are in the process of developing LED lighting specifications.

New lighting technologies, particularly LED lighting, have made great progress in roadway lighting for highway and urban street lightings. However, many SHAs are looking forward to some kind of national guidance from AASHTO or FHWA.

7.1.2 Field Installation

For Phillips RVM LED, basically, every aspect was user friendly. The fixtures are lighter and easier to hold and level. For GE ERS4 LED, the fixtures are a little heavier and a little difficult to level. However, they were a solid unit and the internal access was user friendly. For Stray Light Tesla II plasma, the fixtures were easy to install and level. The electrical connections are also very user friendly and easy to access. For EcoLuminator induction, the fixtures were the most time consuming and difficult to install. They were heavier than the other three types of fixtures. The terminal block is more difficult to access and has a small screw termination. No issues were identified in installation with other fixtures.

7.1.3 Light Distribution

In conventional lighting, HPS, GE LED and Philips LED luminaires produced oval-shaped lighted areas and the Horner LED and EcoLuminator induction luminaires produced circular lighted areas. The illuminance measurements demonstrated a double-hump distribution for the GE LED luminaires and a single hump distribution for all other new luminaires. Compared to HPS 250W luminaires, the GE LED 258W luminaires were capable of producing a larger lighted area and the Philips LED 270W luminaires were capable of producing an equivalent lighted area in terms of the area size. The areas lighted by the Horner LED 200W and EcoLuminator induction 200W luminaires were both less than the areas lighted by the HPS 250W luminaire. However, the areas lighted by the HPS 400W luminaires are greater than those lighted by all LED luminaires and the plasma 295W luminaires, particularly the Horner LED and plasma luminaires.

All LED, plasma and induction luminaires produced measureable illuminance, i.e., 0.05 foot-candles or greater between the lighting poles. The percentages of grid points with illuminance of greater than 0.2 foot-candles are 71%~98% for HPS 400W, 73%~98% for HPS 250W, 88%~96% for GE LED, 68%~94% for Philips LED, 52%–60% for Horner LED, 49% for Stray Light plasma and 45% for EcoLuminator induction.

In high mast lighting, both HPS 1000W and SoLtice 392W LED luminaires produced a symmetrically lighted, circular area covered with illuminance measurements 100% greater than 0.20 foot-candles. The light illuminance produced by the 1000W HPS luminaires was greater than that by the SoLtice 392W luminaires.

7.1.4 Illuminance Metrics

Compared to HPS 250W luminaires, both the GE 258W and Philips 270W LED luminaires produced similar minimum illuminance and the Horner LED and EcoLuminator induction 200W luminaires produced smaller minimum illuminance. The maximum illuminance values produced by all LED and induction luminaires are all greater than the corresponding maximum illuminance value by the HPS 250W luminaires. The GE LED produced the greatest average illuminance and the Horner LED produced the smallest average illuminance. The average illuminance produced the Philips LED is close to the by the HPS luminaires. The illuminance uniformity ratio produced by Philips LED is slightly better than that by the HPS 250W. The illuminance uniformity ratio produced by the GE LED luminaires is slightly greater than that by the HPS 250W. The illuminance uniformity ratios produced by both the Horner LED and EcoLuminator induction luminaires are much greater than those produced by the GE LED, Philips LED and HPS luminaires.

Compared to HPS 400W luminaires, both LED and plasma luminaires produced smaller minimum, maximum and average illuminance values. The illuminance uniformity ratios produced by the LED and plasma luminaires are greater than those by the HPS luminaires. In addition, both GE and Philips LED luminaires produced greater average illuminance and smaller illuminance ratio values than the Horner LED and Stray Light plasma luminaires.

It was demonstrated that in the urban street lightings, both LED and plasma luminaires are capable of providing better light performance, including illuminance level and uniformity ratio, with appropriate lighting layout.

For high mast lighting, the SoLtice 392 E LED luminaires produced smaller illuminance levels but better uniformity than the HPS 1000W luminaires.

The rankings through field observations by the SAC members agreed well with the field illuminance measurements and indicated that the new lighting sources produced sufficient light levels and GE and Philips provided better light performance in terms of light level and uniformity.

7.1.5 Power Metrics

The measured electric currents for LED, plasma and induction luminaires varied around 1.0 A, regardless of the lamp watts, and are less than the electric currents for not only the HPS 400W luminaires, but the HPS 250W luminaires as well. For high mast lighting, the electric currents for the LED 392W luminaires are much less than those for the HPS 1000W luminaires.

Compared to the HPS 250W luminaires, the calculated energy saving is 12% to 20% for LED luminaires, 12% for the 295W plasma luminaire, and up to 25% for the 200W induction luminaire. Notice that the GE LED, Philips and Stray Light plasma luminaire sizes are all greater the HPS 250W luminaire. Compared to the HPS 400W luminaires, the energy savings produced by the new luminaires varied between 44% and 52%. For high mast lighting, the energy consumed by the SoLtice LED 392W luminaires is 70% less than that by the HPS 1000W luminaires.

7.1.6 Life Cycle Costs

The lower life cycle costs of the alternative lighting devices are attributed to their relatively lower electricity usages and longer lamp/emitter replacement cycles. All of the alternative new luminaires, including LED, plasma, and induction, are more cost effective than the existing 400W HPS lights under various discount rates and lamp replacement cycles. In comparison with the existing 250W HPS lights, only the 200W induction luminaire among the six alternative lighting devices is more cost effective. For high mast lighting, the 392W LED luminaires are more cost effective than the 1000W HPS luminaires. With the huge difference in electricity usages between the 392W LED and 1000W HPS luminaires, the LED luminaires will break even within 4 years.

The discount rate and the lamp/emitter replacement cycle affect the life cycle costs as well as the return periods as demonstrated in this study. An MS Excel based worksheet, INDOT Lighting LCCA, has been developed in this study. The software makes it easy for INDOT engineers to perform life cycle cost analysis. The software can be used beyond this study by INDOT to conduct life cycle cost analysis for new lighting systems. It is recommended that the software be used to conduct thorough cost evaluations for possible new lighting systems in addition to other types of field evaluation.

7.2 Recommendations

It is recommended that the INDOT design manual should consider the new lighting technologies, particularly LED and plasma lights as an option in roadway lighting applications, including lighting replacement and new installation, and conventional lighting and high mast lighting.

To ensure successful use of the new lighting technologies, an approved materials list should be used. However, there is no urgent need to change the current lighting design values in the design manual, such as average maintained illuminance, minimum illuminance and illuminance uniformity ratio. The new lighting technologies have just started to find a way into roadway lighting applications and are not yet fully mature. Field application data on the long term performance and reliability is still needed for future revision of the lighting design values for the new lighting technologies.

The GE 258W, Philips 270W and Horner 200W LED luminaires are capable of producing light levels equivalent to the HPS 250W luminaires with existing lighting poles. The light levels produced by these three types of LED luminaires may be lower than those by the HPS 400W luminaires, but all meet the light level requirements for most roadway lighting applications. The GE 258W and Philips 270W LED luminaires are capable of producing an illuminance uniformity ratio equivalent to that by the HPS 250W luminaires. While the illuminance uniformity ratios produced by the GE 258W and Philips 270W LED luminaires are greater than those by the HPS 400W luminaires, neither the HPS nor the new alternative luminaires could meet the illuminance uniformity requirements. In reality, the Cooper 232W LED luminaires on an urban street demonstrated satisfactory light performance in terms of both light level and uniformity. No failures arose with any of the LED luminaires over the study period. The energy savings ranged between 16-49% with these LED luminaires. The GE 258W, Philips 270W, and Horner 200W LED luminaires may be used to replace the HPS 250W luminaires with the existing lighting poles. The GE 258W and Philips 270W LED luminaires may also be used to replace the HPS 400W luminaires.

The Stray Light plasma 295W luminaires are also capable of producing light levels close to that by the HPS 250W with existing lighting poles. However, this type of plasma luminaire may be unable to provide light performance, particularly light uniformity, equivalent to that by the HPS 400W luminaires. Early failures, as indicated in the local city survey, also arose with the plasma luminaires in this study after around 24 months in service. However, the test results on the plasma street lighting in a local city indicated that plasma technologies are capable of producing satisfactory light performance with appropriate lighting layout and eliminating early failure with appropriate integration. It is recommended that plasma may be used in lighting applications for minor streets, residential areas, and parks. However, special care should be exercised about the quality of luminaire products due to the manufacturing variations.

Failures with induction luminaires were not only indicated in the state highway agency and local city surveys, but observed with the induction luminaires in this study as well. While the induction light sources have the potential to achieve great energy savings, the technologies with the induction lighting may not mature at this time.

The SoLtice LED 392W luminaires for high mast lighting not only produced satisfactory light performance, but also produced up to 70% energy savings. It is recommended that the SoLtice LED 392W luminaires may be used to replace the HPS 1000W luminaires in high mast lightings with the existing lighting poles.

The potential concern associated with use of the new lighting is the light uniformity. While was demonstrated that both LED and plasma lighting technologies are capable of producing satisfactory illuminance uniformity ratio with appropriate lighting layout on urban street, it is recommended that the further efforts should be made by manufacturers to enhance the light uniformity for roadway lighting applications with the existing lighting poles.

The light performance data was collected over a 12-month period and it may be too early to evaluate the new lighting technologies thoroughly. However, early indications are that the new lighting sources are inherently energy-saving, particularly for high mast or area lightings.

Based on the life cycle cost analysis, the return or payback period is 13 years or more for replacing HPS 250W luminaires, between 6 and 9 years for replacing HPS 400W luminaires, and 4 years for replacing HPS 1000W luminaires. Currently, the warranty provided by most of the manufactures is five years, which does not match the above return periods. It is recommended that the manufacturers shall warrant the LED and plasma luminaires to be free from defects in materials and workmanship for a period of at least 8 years for conventional roadway lighting. For high mast lighting, the current warranty of 5 years provided by most of the manufacturers should be sufficient to protect the investment.

To select a cost-effective solution to roadway lighting design, the Excel based life cycle cost analysis software developed in this study, should be adopted as a standard procedure for performing life cycle cost analysis by the agency.

Technical specifications for the new lighting products are necessary for their successful applications. Appropriate technical specification should include but are not limited to the following aspects:

- Lamp/luminaire
  - Photometric properties: lamp watts, initial lumen, CRI, CCT, light distribution type
  - Performance: lumen maintenance, service life
  - Safety: UL1029, UL1598
  - LM-79, LM-80 and ANSI C78.377 tests and reports
  - IP rating: IP65 or better (ANSI C136.25)
- Electrical
  - Voltage
  - Power factor
  - Surge protection: UL 1449 or IEEE/ANSI C62.41
  - Ballast sound rating: A
  - Electromagnetic Interference (EMI): Class A (Title 47 CFR Part 15)
  - Photo electric sensor
- Housing
  - Vibration resistance: 2G or better (ANSI C136.31)
  - Material: Die cast aluminum housing A360 (ANSI/AA A360.0)
  - Slipfitter mount: Adjustable ($\pm 5^\circ$) for leveling
  - Wildlife instruction protection
- Others
  - Materials: RoHS compliant
  - Upward light output ratio (ULOR) rating: 0
  - Temperature rating: -40°F$\sim$122°F
  - Warranty: 8 years for conventional lighting, and 5 years for high mast lighting

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APPENDIX. SURVEY QUESTIONNAIRE ON ROADWAY LIGHTING

1. Has your agency adopted any type(s) of the following roadway lighting technologies? Please check the appropriate boxes (you may double click the boxes to select):

Light emitting diode (LED) lighting:	☐ Yes	☐ No
Induction lighting:	☐ Yes	☐ No
Plasma lighting:	☐ Yes	☐ No

2. If you selected all "No" boxes, what are the main barriers for your agency to use the new lighting technologies?
3. How many years has your agency adopted the new roadway lighting technologies?

   Light emitting diode (LED):

   Induction:

   Plasma:
4. What are the main reasons, such as cost saving and better performance, for your agency to use the new lighting technologies?
5. On what types of roadways (interstate, US routes, state roads, local roads, etc.) and locations (urban, rural, intersection, rest area, etc.) your agency has utilized the new lighting systems?

   Light emitting diode (LED):

   Induction:

   Plasma:
6. Please tell us the specifics of the new roadway lightings that your agency has adopted.

   Light emitting diode (LED) lighting (manufacturer, vendor, model, cost, etc.):

   Induction lighting (manufacturer, vendor, model, cost, etc.):

   Plasma lighting (manufacturer, vendor, model, cost, etc.):
7. Please tell us the expected service life and life cycle cost of the new roadway lightings:

   Light emitting diode (LED) lighting:

   Expected service life (years):

   Life cycle cost ($/year):

   Induction lighting:

   Expected service life (years):

   Life cycle cost ($/year):

   Plasma lighting:

   Expected service life (years):

   Life cycle cost ($/year):

Survey continued next page.

8. Have you had any issues about the installation of new lighting systems?
9. Have you had any safety issues about the new lighting systems?
10. Have you had any issues about the performance of the new lighting systems?
11. Have you had any issues about the maintenance of new lighting systems?
12. Please indicate the performance of the new roadway lighting systems (you may double click the boxes to select):

    Light emitting diode (LED) lighting: ☐ Excellent
    ☐ Satisfactory
    ☐ Unsatisfactory
    ☐ N/A

    Your specific comments: ______________________________

    Induction lighting: ☐ Excellent
    ☐ Satisfactory
    ☐ Unsatisfactory
    ☐ N/A

    Your specific comments: ______________________________

    Plasma lighting: ☐ Excellent
    ☐ Satisfactory
    ☐ Unsatisfactory
    ☐ N/A

    Your specific comments: ______________________________

13. Could you share with us your approval procedures or evaluation methodologies for the new roadway lighting systems?
14. Could you please provide us a copy of your agency's specifications, drawings, and guidelines for the new lighting systems?

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,500 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

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