# Assessment of the Performance of Light-Emitting Diode Roadway Lighting Technology

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Abstract:

This study, championed by the Virginia Department of Transportation (VDOT) Traffic Engineering Division, involved a thorough investigation of light-emitting diode (LED) roadway lighting technology by testing six types of roadway luminaires (including housing and all components enclosed) in a laboratory environment and on the field over a 2-year period.

The results showed that LED luminaires exhibited superior lighting and related qualities compared to high-pressure sodium luminaires. Different photometric characteristics were found among LED luminaires of different designs, indicating a careful selection considering light distribution and illuminance level is necessary for individual lighting applications. During the first 2 years of operation, the average light loss for the LED luminaires was 6% based on laboratory testing. The study also found that implementing LED technology systematically will result in a return on investment between 3.25 and 5.76 for different scenarios over a 25-year period due to savings in maintenance and energy consumption.

The study resulted in the *VDOT LED Roadway Luminaire Specification* document and developed recommendations relevant to VDOT's implementation of LED technology.

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## ABSTRACT

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## INTRODUCTION

Roadway and street lighting across the nation consumes a large amount of energy and is responsible for significant tonnage of carbon dioxide ($CO_2$). The DOE estimated that the 26.5 million streetlights in the US consumed as much electricity each year as 1.9 million households, and generated greenhouse gas emissions equivalent to that produced by 2.6 million cars.[1] Currently, the majority of the lamps used on American roads are traditional gas-discharge lamps, such as high-pressure sodium (HPS), low-pressure sodium (LPS), mercury vapor (MV), and metal halide (MH). In addition to their high power consumption, the service lives of such lamps are greatly affected by an array of factors.[2]

As the nation continues to make efforts in conserving energy and reducing $CO_2$ emission, and as state and local transportation agencies strive to save operational costs, more efficient roadway lighting technologies are becoming increasingly appealing. Among the various emerging technologies, solid-state lighting (SSL) differs from other lighting technologies in that it is based on light-emitting diodes (LEDs) or organic LEDs (OLEDs) instead of filaments, plasma, or gases.[3] Among various technologies, LED is currently gaining popularity for general illumination applications as many challenges still remain in the adaptation of other SSL technologies. LEDs typically have a much longer service life and provide higher luminaire efficacy than traditional sources. Their light output is also a much broader spectrum than other sources, meaning that the light appears to be white and provides proper color appearance. This feature can result in an improved visual performance for the same design light level of traditional lighting technologies.

Over the past decade, LED lighting has experienced significant growth in roadway lighting applications. However, it is still in its early stages due to reasons related to immaturity of the technology and unfamiliarity with the technology at state and local transportation agencies. Estimates in 2010 suggested that only approximately 3% of the streetlight lamps across the nation were LED. In contrast, HPS technology represents 80% of the streetlight lamps currently used in the United States.[4]

While providing the benefits of energy efficiency and superior light quality, however, LEDs have changed the lighting industry. Traditionally, the lighting industry has been dominated by a very few companies who had extensive experience in providing products that would be able to withstand the exterior environment. Now, small, typically electronics companies have started the development of lighting products. These systems may have issues with the durability of the luminaires and the ease of the installation of the luminaires. Similarly, the luminaires must match the requirements of the application to provide a proper light distribution while reducing glare and uplight. With the advent of all of these less experienced companies and even the production of the new technology by traditional lighting companies, it is important that careful evaluations of the luminaires be made before the full scale implementation of the technology is undertaken.

To develop a comprehensive understanding of this fast evolving technology, stakeholders have launched various studies across the nation. The U.S. Department of Energy (DOE), for example, is performing a large-scale field assessment of SSL performance for general illumination in exterior and interior applications, known as the SSL Technology Demonstration GATEWAY program.[5, 6] Some state DOTs and municipalities also conducted similar studies to understand LED technology.[7, 8, 9, 10] Past experience with LED technology in roadway lighting has suggested the following:

- The light efficacy of LED roadway lighting systems is comparable to that of HPS in roadway lighting applications, but is improving rapidly and is expected to exceed that of other traditional technologies significantly in the near future. Many studies, particularly those conducted in the early 2000s, suggested that LED lighting systems had a comparable efficacy compared to HPS technology on a lumen-per-watt basis. However, some recent studies reported significant increases in efficacy for LED systems. DOE expects that a 200 lm/W efficacy for LED will be achieved in the future - doubling to tripling that of conventional incandescent lighting.[11]

- Replacing traditional luminaires with LED luminaires of comparable wattages is not likely to result in significant cost savings. However, most studies showed that LED systems with much lower wattages were capable of emitting lights meeting minimum design standards, therefore yielding more significant cost savings.[12]

- Most studies concluded that the light quality of LED systems, such as light color, distribution, perception, and ground illuminance, was superior to that of traditional lighting technologies.[6] User surveys also suggested that most roadway users preferred LED lighting to traditional lighting.

- There is a wide range of LED manufacturers and models commercially available for roadway lighting. Some LED lighting products vary considerably in cost and lighting performance (e.g., color rendering, efficacy, life span, and light distribution).

- Many previous LED lighting studies were based on relatively short-term lighting data measurements. As such, few studies have resulted in a thorough understanding of LED lumen maintenance over time based on field measurements.

Recognizing the critical needs for energy conservation and better lighting, the Virginia Department of Transportation (VDOT) Traffic Engineering Division (TED) championed this study to comprehensively assess LED roadway lighting technology and LED performance over time. The results of this research provide valuable insights in key performance differences between standard HPS and LED technologies as well as among LED luminaires of different designs. The findings also fill in a knowledge gap regarding how LED luminaires perform differently in a laboratory environment and in the field. The knowledge developed from this research served as the basis for the development of the *VDOT LED Roadway Luminaire Specification* document and associated implementation recommendations.

## PURPOSE AND SCOPE

The primary objectives of this study were as follows:

- Develop a comprehensive understanding of LED lighting performance for roadway lighting applications based on laboratory and field evaluations.

- Identify performance improvements and cost savings associated with a potential adoption of LED technology for roadway lighting and related purposes.

- Develop a specification document and recommendations relevant to the adoption of LED systems for roadway lighting at VDOT.

During the study, the research team tested and monitored five different LED luminaire designs for 2 years and compared their performance characteristics to those of standard HPS luminaires.

## METHODS

### Overview

Five major tasks were performed to meet the study objectives:

1. Conduct a literature review to summarize previous findings relevant to the performance of LED technology in roadway lighting applications in comparison with traditional roadway lighting systems.

2. Conduct rigorous laboratory evaluations of LED systems to determine their lighting performance metrics.

3. Conduct multi-year field evaluations to determine the lumen maintenance and field lighting performance of LED lighting technology over time.

4. Perform economic analysis to determine potential energy and cost savings associated with LED lighting systems as compared with existing VDOT roadway lighting systems.

5. Develop recommendations and specifications for using LED lighting systems at VDOT-maintained facilities.

A laboratory test was conducted first and focused on key luminaire performance metrics such as power consumption, light output, and spectral performance in a controlled environment. The luminaires were then tested at a VDOT park-and-ride facility for field assessment in an effort to understand LED lighting performance over time. For comparison, the Virginia Tech Transportation Institute (VTTI) team also performed laboratory and field evaluations of VDOT's standard HPS fixtures. During data analysis, all outdoor measurements of the LED systems were corrected based on ambient horizontal and vertical illuminance levels. In addition, all LED illuminance measurements were normalized to a standard temperature (i.e., 25°C) assuming that a reduction of each degree Celsius in ambient temperature coincides to a light output increase by 0.25%.

## LED System Selection

Based on previous research experience and VDOT recommendations, the research team contacted a list of reputable LED lighting vendors to acquire sample systems for evaluation. At the end of the process, interested vendors provided sample LED systems of different designs. For benchmarking purposes, the research team also used three 250 W HPS luminaires of the same design from a single manufacturer. Table 1 lists the LED systems evaluated during this study followed by photographs of the luminaires in Figure 1. Note that Design B had a manufacturer-related Correlated Color Temperature (CCT) of 5000±300, which was much higher than that of other LED luminaires and was in the cool white range.

**Table 1. Luminaires Evaluated During the Study**

| Design | Mfg. Year | Mfr. Rated Watt | Correlated Color Temp. | Mfr. Rated Lumen | Weight (lb) | Qty. | LED Design Feature |
|---|---|---|---|---|---|---|---|
| HPS | 03/2012 | 250 | - | - | - | 3 | N/A |
| Design A | 04/2012 | 195 | 4300 | 4452 | - | 6 | Exposed LED optic array |
| Design B | 2012 | 120 | 5000±300 | 8985 | 25 | 6 | Three-panel folding design with large LED sources |
| Design C | 05/2012 | 148 | 4000 | - | 45 | 6 | Three large LED sources with conventional layout |
| Design D | 2012 | 150 | 4000 | 9285-13890 | 25 | 6 | Exposed, elongated LED optic array |
| Design E | 08/2011 | 200 | 4000 | - | 32 | 6 | Exposed LED optic array |

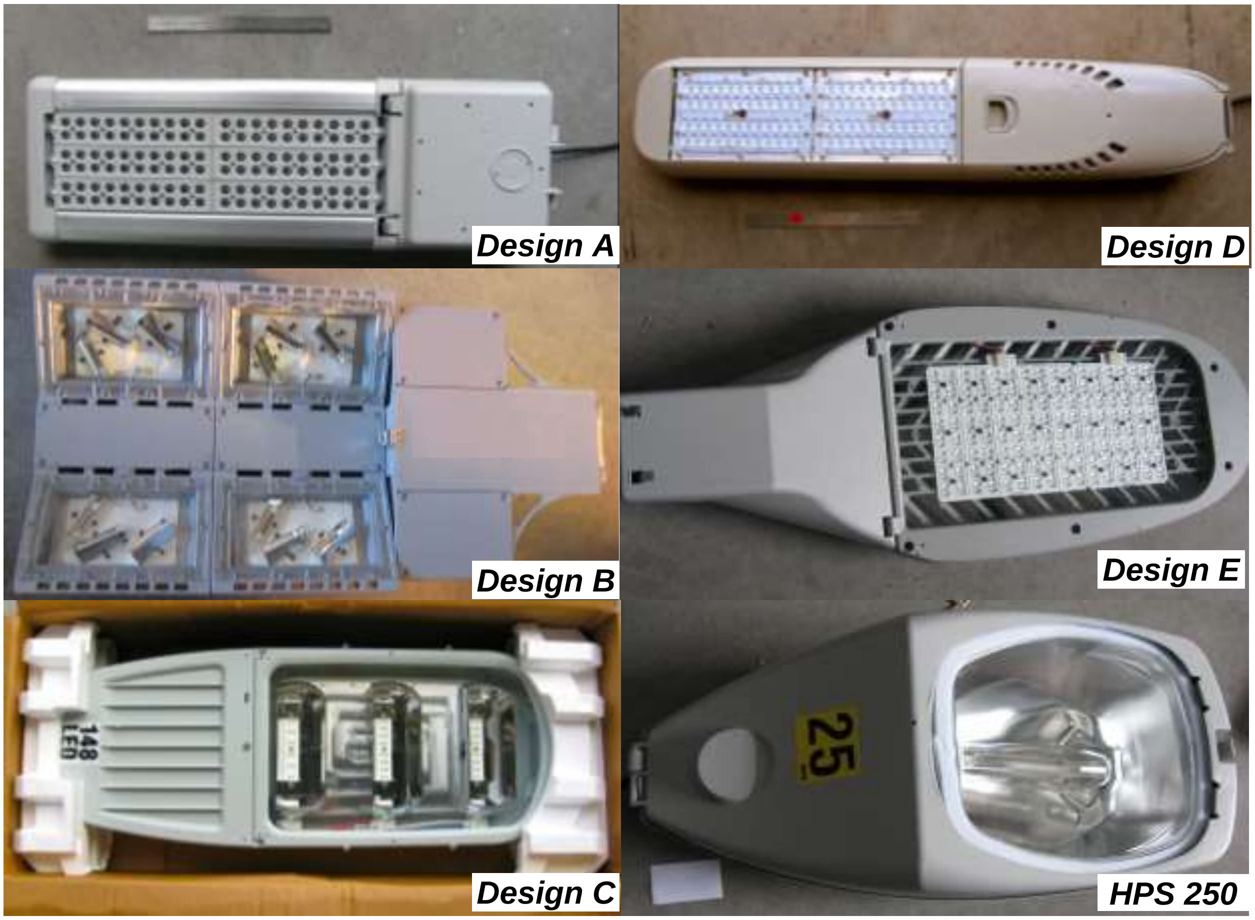


**Figure 1. LED and HPS Systems Used in Study**

## Laboratory Evaluation

VTTI conducted two rounds of laboratory evaluations as part of this study, both following a similar process:

1. *Initial laboratory testing.* After obtaining the luminaires, the VTTI team performed the initial laboratory evaluation of the luminaires to compare the different LED luminaire designs with each other and with HPS. The initial testing entailed mounting two sample luminaires (labeled No. 1 and No. 2) of each manufacturer in a laboratory facility for an initial "burning-in" time of approximately 100 hours and then installing the luminaires individually in an outdoor VTTI test facility for detailed performance assessment.

2. *Second laboratory testing.* After the luminaires were tested in the VDOT test bed for 2 years, the research team retrieved the luminaires and conducted final laboratory testing for comparison with the results of the initial laboratory testing. During the second round of testing, the research team first collected data from each luminaire in the same condition as when it was retrieved from the field installation (i.e., dirty condition) and then cleaned the luminaires and tested them again. The Design C (1)

luminaire was not properly retrieved after the field testing and therefore that luminaire was not included in some of the comparison analyses.  In addition, due to site conditions, only HPS (2) was evaluated on the test bed and in the second round of laboratory testing.

The VTTI outdoor testing facility consisted of a light pole fitted with an adjustable bracket that could accommodate most luminaire types.  The research team defined a measurement grid extending 6 m behind, 13 m in front of, and 20 m to each side of the luminaire (Figure 2).  Luminaires were mounted at a height of 30 ft (9.1 m) because a majority of conventional roadway luminaires at VDOT are installed at a height between 30 and 45 ft (9.1 and 13.7 m).

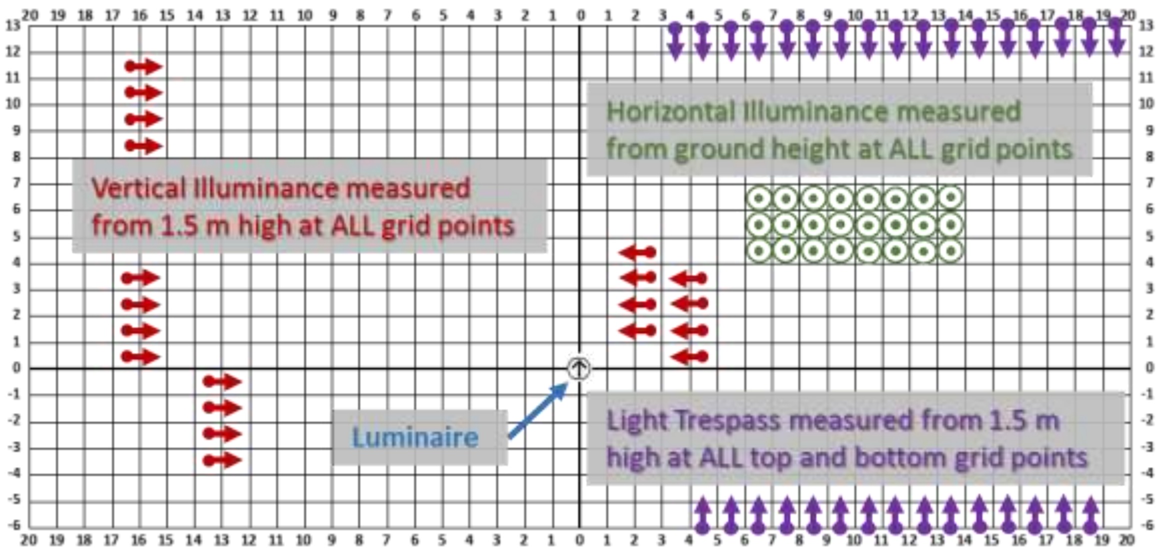



**Figure 2.  Overhead View of Laboratory Evaluation Grid (m) and Measurement Method**

During laboratory testing, the research team collected the following measurements:

- *Horizontal illuminance*, measured with a Minolta T-10 illuminance meter on the pavement, facing up, at the center of each cell in the 20 x 40 m grid, as shown in green in Figure 3.

- *Vertical illuminance*, measured using a Minolta T-10 illuminance meter affixed to a mobile cart, mounted 1.5 m from ground level, as shown in red in Figure 3.  During the data collection, the meter was aimed along the roadway in the direction of the luminaire; in the left half of the grid, the illuminance meter was aimed parallel to the grid facing the right, and in the right half of the grid, the meter was aimed parallel to the grid facing the left.

- *Light trespass*, measured as vertical illuminance along the front and back edges of the grid with the meter mounted at 1.5 meters from the ground level and facing the luminaire side, as shown in violet in Figure 3.

- *Electrical power usage*, measured with a Yokogowa WT 110 power meter. The research team waited at least 15 min after the LED luminaire was powered on before taking this measurement to avoid the potential effects of in-rush current. For each HPS measurement, the research team waited at least 30 min after the HPS luminaire stabilized.

- *Spectral power distribution (SPD)*, which was measured using an Ocean Optics S4000 spectroradiometer with a Teflon integrating sphere acceptance optic. The research team measured only the relative irradiance as the research team's interest was the relative power concentration by wavelength. *Irradiance* is defined as the amount of radiant flux hitting or passing through a unit area of a surface. Relative irradiance measures the shape of the light spectrum but not the absolute magnitude, which allows a user to determine whether there is more light at one wavelength than another. To facilitate comparisons, the SPD results for different luminaires were normalized to the same scale.

The initial laboratory testing was conducted at night, between 9 P.M. and 1 A.M. in May 2012, and the second laboratory testing was conducted between February and March 2015, also at night.

**Figure 3. Horizontal and Vertical Illuminance Measurement Systems**

Collecting horizontal and vertical illuminance measurements over the 20 x 40 m grid required 800 readings for each luminaire, which was time-consuming. To improve efficiency and accuracy, the research team developed an automated data acquisition application in the National Instruments® LabVIEW software environment. During the data collection, the automated application collected continuous illuminance readings from the Minolta T-10 illuminance meter for 2 s at each location and then wrote the mean illuminance into a comma-separated values (CSV) file. To enable real-time data validation, the application interface included measurement visualization windows as well as buttons that allowed values to be redone or deleted upon faulty measurements (Figure 4).

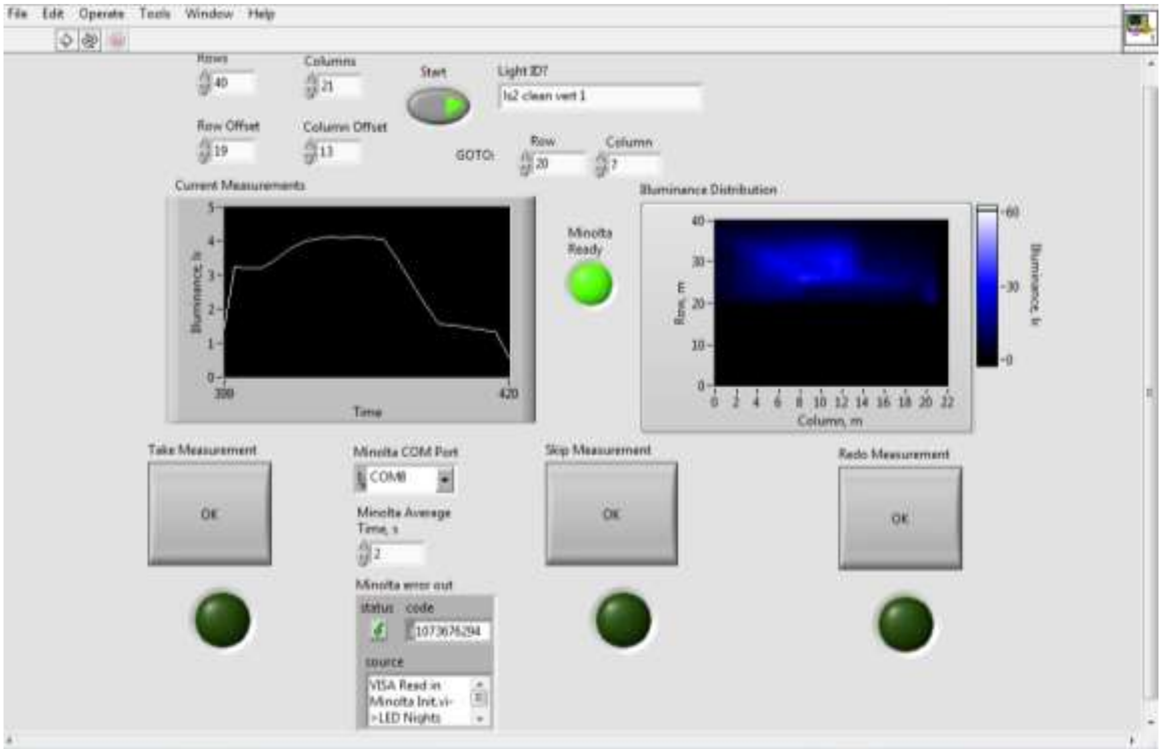



**Figure 4. Illuminance Data Acquisition Application**

## Field Evaluation

### Test Site Settings

During the field evaluation, all sample luminaires, including both LED and HPS systems, were installed in a park-and-ride facility that VDOT designated as a lighting test bed between September 2012 and September 2014. The test bed is in Woodbridge, Virginia, on the north side of Telegraph Road, approximately 600 ft (183 m) northeast of Caton Hill Road or 2,000 ft (610 m) northwest of I-95. The facility is in the middle of a large wooded area with minimum interference of environmental lighting from adjacent roadways and commercial and residential developments.

Before the official opening of the parking facility in September 2012, 26 of the 33 luminaires acquired (five LED systems of each type and one HPS system limited by parking lot lighting needs) were installed at a standard height of approximately 35 ft (10.6 m) for testing. The performance of six of the installed luminaires, one of each type and all lab tested, was monitored for 24 months. Figure 5 shows the locations of the luminaires installed in the test facility. The circled luminaires are those for which manual measurements were collected. The luminaires were operating every night from dusk to dawn, equivalent to a total operational period of approximately 8,800 hours. Among the six tested luminaires, one Design D and one Design E luminaires were installed directly above a bus station and subjected to different dirt/dust condition than other luminaires in the parking lot.


**Figure 5. Telegraph Road Evaluation Area Luminaires**

## Field Data Collection

During the field evaluation period, from September 2012 to September 2014, the research team conducted field measurements at 3-month intervals, for a total of nine rounds of data collection. During each visit, the research team collected measurements both manually and with the automated data collection system. Before each data collection, the research team took multiple ambient horizontal and vertical illuminance measurements for controlling ambient factors during data analysis. The hourly temperatures during each data collection were later obtained for the nearest weather station from the National Oceanic and Atmospheric Administration (NOAA).

During each site visit, the research team manually collected the following data:

- *Horizontal illuminance*, with the same equipment as used for laboratory data collection, but on a smaller version of the laboratory grid. The field measurement grid was 12 m x 36 m, with slight variations made to accommodate site conditions such as curbs and sidewalks. For efficiency, the research team took measurements at 3-m increments.

- *Vertical illuminance,* with the same equipment as used for laboratory data collection at a height of 1.5 meters above the ground. The vertical illuminance measurements were taken using the same field grid as the horizontal illuminance measurements.

- *CCT,* with a Minolta CL-500 Illuminance Spectrophotometer measured directly beneath each luminaire.

Beginning with the second round of data collection, VDOT supplied the research team with a bucket truck, allowing the team to visually inspect and record the physical condition of the luminaires. Each inspection included a general visual inspection for dirt buildup and wildlife intrusions, luminaire temperature recording (ballast and LED components), and an observation of the luminaires' installation condition.

Due to construction at the Telegraph Road Park & Ride, data were not collected for the high-pressure sodium luminaire during the September 2013 visit.

During this study, the research team also made an attempt to collect lighting measurement data at a finer spatial resolution using the VTTI Roadway Lighting Mobile Measurement System (RLMMS). RLMMS synchronizes several key lighting measurement devices including four illuminance meters designed for horizontal illuminance measurement. However, due to the parking lot settings and luminaire installation locations, it was difficult to collect measurements at the exact same locations for all luminaires. As such, the RLMMS data analysis yielded bias that was relatively significant and therefore the results were not included.

## LED Life Cycle Cost Analysis

### Relevant Lighting Inventory Data at VDOT

Interviews with VDOT engineers suggested that VDOT does not currently maintain an accurate inventory of luminaires in the state. They indicated that the vast majority (> 95%) of the luminaires used at VDOT are HPS systems. Figure 6 summarizes the information obtained from VDOT staff during interviews relevant to the roadway luminaire composition at VDOT. Table 2 and Table 3 further list VDOT-estimated lighting inventory and relevant maintenance costs based on the most recent VDOT's highway lighting needs assessment. The VDOT *Methods for Calculating Maintenance and Operations Needs: Highway Lighting – Asset 380* document[13] details the procedures and assumptions used to obtain these estimates. Note that the values in Table 2 and Table 3 are provided separately by VDOT officials and are more up-to-date compared with those in the needs assessment document. Several pieces of critical information needed for this cost analysis were derived based on these data.

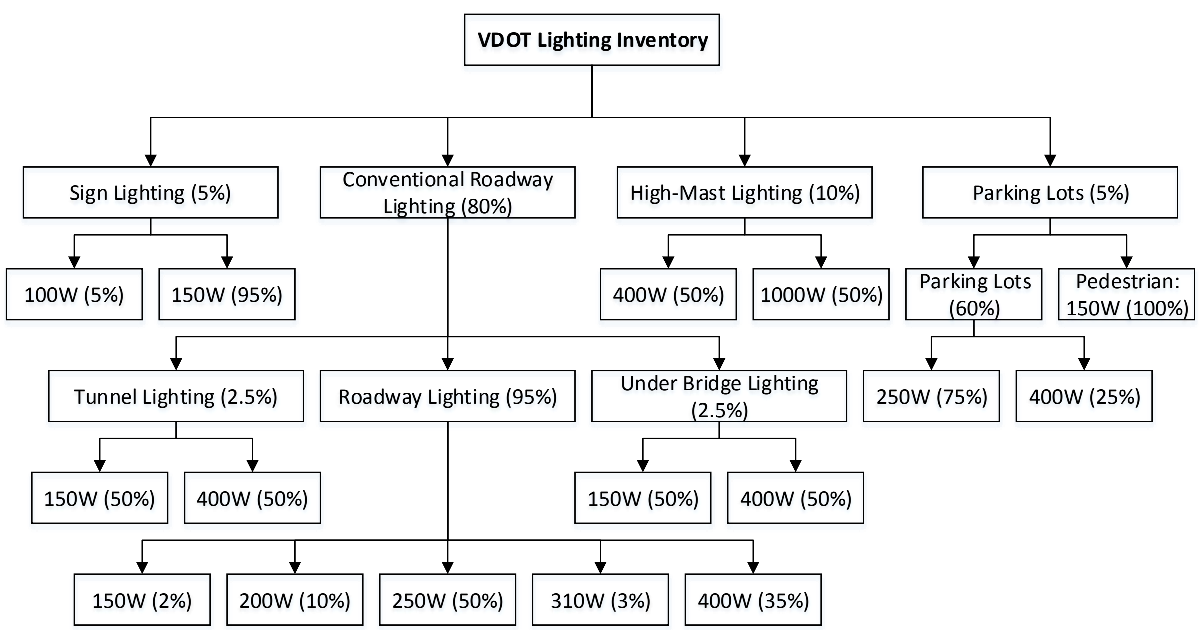



**Figure 6. VDOT-Maintained Luminaires by Wattage**

**Table 2. Estimates of VDOT Light Inventory (2014 Data)**

| Light Type | VDOT District | Interstate | Primary | Secondary | Total |
|---|---|---|---|---|---|
| Conventional light (each pole is counted as 1) | Bristol | 44 | 0 | 0 | 44 |
| | Salem | 688 | 753 | 0 | 1,441 |
| | Lynchburg | 0 | 324 | 0 | 324 |
| | Richmond | 660 | 624 | 0 | 1,284 |
| | Hampton Roads | 5,526 | 1,474 | 92 | 7,092 |
| | Fredericksburg | 1,500 | 420 | 0 | 1,920 |
| | Culpeper | 0 | 50 | 0 | 50 |
| | Staunton | 0 | 45 | 0 | 45 |
| | Northern Virginia | 10,044 | 4,937 | 2,890 | 17,871 |
| | Conventional light subtotal | 18,462 | 8,627 | 2,982 | 30,071 |
| High mast light (each pole is counted as 1) | Bristol | 87 | 0 | 0 | 87 |
| | Salem | 13 | 0 | 0 | 13 |
| | Lynchburg | 0 | 0 | 0 | 0 |
| | Richmond | 60 | 0 | 0 | 60 |
| | Hampton Roads | 100 | 13 | 0 | 113 |
| | Fredericksburg | 300 | 0 | 0 | 300 |
| | Culpeper | 0 | 0 | 0 | 0 |
| | Staunton | 13 | 0 | 0 | 13 |
| | Northern Virginia | 345 | 205 | 144 | 694 |
| | High mast light subtotal | 918 | 218 | 144 | 1,280 |
| Sign light (each luminaire is counted as 1) | Bristol | 36 | 0 | 0 | 36 |
| | Salem | 27 | 5 | 10 | 42 |
| | Lynchburg | 0 | 21 | 0 | 21 |
| | Richmond | 881 | 479 | 0 | 1,360 |
| | Hampton Roads | 1,007 | 196 | 0 | 1,203 |
| | Fredericksburg | 695 | 90 | 10 | 795 |
| | Culpeper | 0 | 27 | 0 | 27 |
| | Staunton | 60 | 65 | 0 | 125 |
| | Northern Virginia | 10,025 | 4,480 | 503 | 15,008 |
| | Sign light subtotal | 12,731 | 5,363 | 523 | 18,617 |
| Grand Total | | 32,111 | 14,208 | 3,649 | 49,968 |

**Table 3. FY16 Lighting Maintenance & Operational Needs**

| Lights | $27,253,178 |
|---|---|
| Ancillary Structure Maintenance - Lighting | $5,826,494 |
| Ancillary Structure Replacement - Conventional Lights | $5,793,155 |
| Ancillary Structure Replacement - High Mast Lights | $2,950,556 |
| Conventional Lighting Re-lamp/Elect Repair | $1,324,206 |
| High Mast Lighting Re-lamp/Elect Repair | $41,444 |
| Highway Lighting Power Bills | $3,498,667 |
| Sign Lighting Lifecycle Replacement | $750,417 |
| Sign Lighting Re-lamp/Elect Repair | $668,535 |
| Turnkey Asset Maintenance Services (TAMS)* | $538,721 |
| Underground Utilities Replacement | $5,860,982 |

*TAMS refer to a specific type of contacts at VDOT performing routine, ordinary and preventive maintenance of highway system and its assets.

## Cost-Benefit Analysis Period and Scenarios

During this study, the research team used an analysis period of 25 years as suggested by VDOT officials and according to manufacturer warranted LED luminaire operational life required by VDOT. The research team examined a number of potential scenarios pertaining to how VDOT would acquire and implement LED technology.

Currently, the two most common scenarios for State DOTs to obtain LED luminaires are through leasing or purchasing:

- *Leasing.* Many manufacturers offer LED luminaire leasing services. In general, there can be two different options for leasing LED luminaires:

  — Provide LED luminaires at a lower or no cost to state DOTs but harvest a portion of or entire energy cost savings for a certain period of time.

  — Provide LED luminaires at a lower or no cost to state DOTs but charges a predetermined fee for each luminaire for a certain period of time.

  Discussions with VDOT officials suggested that VDOT intends to fully acquire LED luminaires instead of operating rented luminaires when starts concerting HPS roadway lighting to LED. As such, this cost-benefit analysis did not consider the leasing scenario.

- *Purchasing.* This analysis only considered the scenario where VDOT purchases all LED luminaires.

The researchers examined the following luminaire replacement scenarios:

- *Retrofitting.* Many manufacturers offer LED luminaires that can be readily retrofitted into existing luminaire housings. However, studies suggested that retrofitting existing housings with LED luminaires did not necessarily result in more significant cost savings over time.[14] In addition, retrofitting luminaires does not enable full utilization of the state-of-the-art LED roadway lighting technologies considering that LED luminaires have very different optical control and thermal performance. Retrofitting could also void manufacturers' warrantees on the existing lighting systems and result in liability issues.[14] Furthermore, due to foreseeable technology improvements, it is reasonably certain that the LED products on the market in the near future will be considerably more efficient, physically different, and not mechanically compatible with current luminaires. As such, the discussions with VDOT officials suggested that VDOT would not be interested in the retrofitting scenario as well.

- *Replacing.* This scenario assumes that VDOT will replace the existing fixtures with new LED luminaires, using the existing poles/structural supports. It is the goal of VDOT to ultimately convert all existing roadway luminaires to LED systems. The most likely process for the conversion would be project by project. However, to accurately account for this process in the cost analysis, it is necessary to obtain information regarding future lighting projects on VDOT roadways. Such information is extremely difficult to obtain due to data availability, reliability of planned project schedules, and funding availability at VDOT. For simplicity, the research team assumed the following replacement scenarios during the cost-benefit analysis:

— *Scenario 1 (S1):* replacing all luminaires with LED luminaires at once. This scenario can be considered as a baseline for comparison and better understanding of the cost-benefits.

— *Scenario 2 (S2):* phasing out within 5 years. This scenario assumes that traditional luminaires will be phased out within a 5-year period and replaced with an equal number of LED luminaires. Old luminaires approaching their designed service lives will be replaced first.

— *Scenario 3 (S3):* phasing out within 10 years. This scenario assumes that traditional luminaires will be phased out within a 10-year period and replaced with an equal number of LED luminaires. Old luminaires approaching their designed service lives will be replaced first.

In summary, the research team considered the following scenarios during this cost-benefit analysis:

- *Luminaire acquisition method:* purchasing

- *Luminaire replacing method:* replacing entire fixtures. The luminaires will be replaced in the following three scenarios:

  — Replace all luminaires at year 1.
  — Replace all luminaires within a 5-year period.
  — Replace all luminaires within a 10-year period.

## Cost-Benefit Analysis Factors and Formulae

The following is a list of the energy-related factors included in the cost-benefit analysis:

- *Current electricity cost ($/kWh) for DOT (CEC).* Conversations with VDOT officials suggested that it would be difficult to obtain an accurate estimate of a unit electricity cost for roadway lighting at VDOT for a number of reasons. VDOT uses several different billing mechanisms depending on the agreements with power companies, location, and the service provider. Lighting fixtures installed recently tend to use power meters while many older fixtures are covered by fixed flat-rate bills per service (a number of luminaires within an agreed area). Based on the total estimated power bills (Table 3) and roadway lighting wattage (see the following section) obtained from VDOT, the research team estimated a power cost of $0.043 per kWh, which is slightly lower than the rate at other state DOTs (e.g., 0.046 at MnDOT[14]).

- *Future energy cost increase factor (ECI).* The U.S. Energy Information Administration (EIA) projects that the electricity price will continuously grow following the previous growth trends.[15] Currently, EIA projects that the U.S. retail residential price for electricity will increase by 1.1% in 2015 and by 1.8% in 2016. In addition, EIA data show that the residential electricity price increased annually by 3.6 % over the past decade on average (Figure 7). Based on the above information, the research team estimated a 2% annual *ECI* taking inflation into consideration.

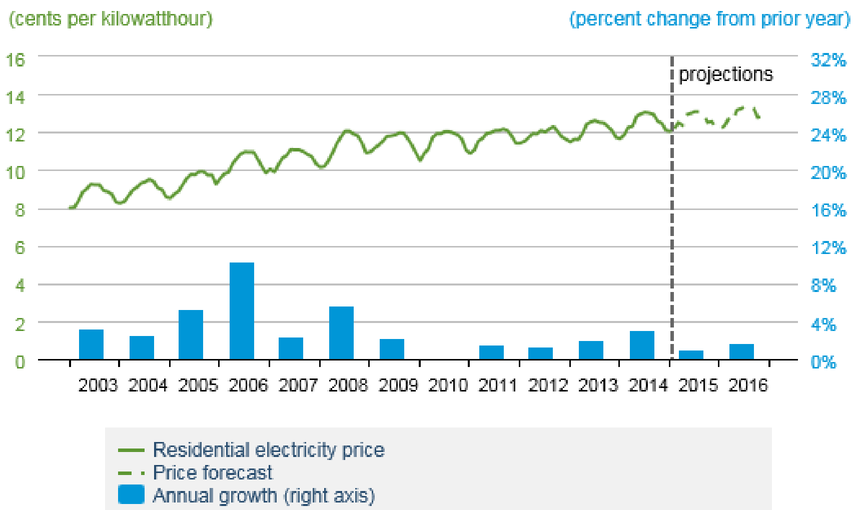



**Figure 7. U.S. Residential Electricity Price[15]**

- *Rebates/incentives for LED lighting.* To accelerate the use of energy-efficient lighting technologies, many federal and state agencies offer incentives for implementing LED roadway lighting.[16] In addition, some utility companies also offer rebates to customers for the use of LED luminaires.[17] However, such incentive and rebate programs usually change over time and will be typically phased out as LED luminaires gain more popularity. Therefore, such incentives are difficult to quantify for a long-term cost-benefit analysis and the research team did not include this factor in the study.

The following is a list of the luminaire-related cost factors:

- *Number of existing luminaires (NEL) on VDOT roadways by type.* Based on the information obtained from VDOT, the research team estimated the number of luminaires on VDOT roadways by wattage as listed in Table 4. To develop the estimates, the research team assumed that 10% of the conventional light poles included dual heads and an average of 6 luminaires are installed on each high-mast light pole. Further, the research team assumed a 15% moderate wattage variation of HPS luminaires according to the laboratory testing results and available studies.[18, 19]

Table 4. Estimated Luminaires by Wattage on VDOT Facilities (2014 Data)

| Type/Wattage | Conventional Light | High-Mast Light | Sign Light | Total | Total Watt (Nominal) | Total Watt (15% Variation) |
|---|---|---|---|---|---|---|
| 100 W | | | 931 | 931 | 93,100 | 107,065 |
| 150 W | 2,343 | | 17,686 | 20,029 | 3,004,350 | 3,455,003 |
| 200 W | 3,227 | | | 3,227 | 645,400 | 742,210 |
| 250 W | 17,088 | | | 17,088 | 4,272,000 | 4,912,800 |
| 310 W | 968 | | | 968 | 300,080 | 345,092 |
| 400 W | 12,460 | 3,840 | | 16,300 | 6,520,000 | 7,498,000 |
| 1000 W | | 3,840 | | 3,840 | 3,840,000 | 4,416,000 |
| Total | 36,086 | 7,680 | 18,617 | 62,383 | - | - |
| Total Watt (Nominal) | 10,552,930 | 5,376,000 | 2,746,000 | - | 18,674,930 | 21,476,170 |
| Total Watt (15% Variation) | 12,135,870 | 6,182,400 | 3,157,900 | - | 21,476,170 | - |

- *Number of additional luminaires that VDOT plans to install during the analysis period.* Conversations with VDOT officials suggested that they have no plans in the foreseeable future to add large numbers of lighting fixtures.

- *Current and future annual luminaire operating hours (LOH).* VDOT operates luminaires from dusk to dawn every day without light curfews. Based on the sunrise and sunset time in 2014, the total annual lighting hours are estimated as 4,324 hours. For simplicity, this study used 4,000 hours as the annual lighting hours. Conversations with VDOT officials suggested that VDOT currently does not have plans on increasing or reducing this operation time in the near future.

- *Current LED luminaire cost (LEDC).* Based on the luminaire price obtained from the vendors, the unit costs of the tested LED luminaires ranged from \$1.8/W to \$5.7/W when ordering in large quantities (e.g., 100 luminaires). This analysis used the average unit cost of the evaluated luminaires which was \$3.45/W.

- *Current HPS lamp cost.* This cost is included in the annual HPS re-lamping and electric repair costs (see Table 3). Note that this analysis only considered existing HPS fixtures assuming no new roadway lighting fixtures are planned based on conversations with VDOT officials.

- *Future LED luminaire price reduction factor (LPRF).* Currently, the LED technology is still in its early maturing stage and it is expected that the price of LED luminaires will continue dropping rapidly in the near future. A recent study showed that the average LED luminaire price is expected to drop by about 30% between 2014 and 2017, with an average annual reduction factor of 10%.[20] Knowing that the price drop factor is not linear, the research team assumed a conservative LPRF:

$$LPRF = (9\% - 9/25*t)$$

where $t$ is the number of years into the 25-year analysis period from the base year (i.e., 2015). With this factor, it is assumed that the average LED luminaire price in 10 years will be just over one-half of the current price, and the price in 25 years will be about one-third of the current price. Note that DOE projected a more than 50% price drop between 2013 and 2015, much higher than the value used for this analysis.[11]

- *Initial LED luminaire replacement wattage factor (LRWF).* The research team did not find third-party studies recommending an equivalent wattage for LED luminaires when replacing HPS systems. Several LED luminaire manufacturers suggested a replacement factor of 0.4 to 0.6 (e.g., a 100 W HPS luminaire can be replaced with a 40 to 60 W LED luminaire). Sample case studies showed examples where 250 W HPS luminaires were replaced with LED luminaires ranging from 104 W (0.42) to 210 W (0.84) based on different design requirements and LED products.[21] Users should note that because different LED luminaires can have very different photometric performances, it is not feasible to develop a universal wattage replacement rate between HPS and LED luminaires. During this study, the wattage of the LED luminaires used for comparison against the 250 W HPS systems ranged from 120 W (0.48) to 200 W (0.8). Based on this information, the research team assumed an *LRWF* of 0.6.

- *Luminaire operational life (LOL).* The following are manufacturer-rated operational lives for the studied luminaires:

    — *HPS 250 W:* the research team did not obtain a manufacturer-rated operational life for the specific HPS luminaires evaluated, but the average service life for HPS lamps was found to be 24,000 hours.22 Discussions with VDOT officials suggested that VDOT re-lamps HPS luminaires every 1 to 2 years on normal conditions and every 2 to 6 months for HPS luminaires installed on bridges

    — *Design A LED luminaires:* L70 (time required when the lumen output reaches 70% of the initial output) of 149,000 hours at 25°C

    — *Design B LED luminaires:* manufacturer calculated L70 of 914,000 hours and reported L70 of 60,500 hours

    — *Design C LED luminaires:* L85 (time required when the lumen output reaches 85% of the initial output) of 50,000 hours

    — *Design D LED luminaires:* L70 of 100,000 hours at 25°C or 85,000 hours at 40°C

    — *Design E LED luminaires:* L70 of 80,000 hours at 25°C.

    During this study, the research team used 100,000 hours for the *LOL* of LED luminaires (*LLOL*) as this value is used in most state LED roadway luminaire specifications and can be met by a majority of modern LED luminaires. The *LOL* for HPS luminaires (*HLOL*) used in this study was 2 years based on VDOT feedback, knowing that HPS luminaires on bridges are replaced much more frequently. In addition, since most HPS lamps are replaced after complete lamp failures, salvage values were not considered during this cost analysis.

- *LED luminaire efficacy increase factor (LEF).* U.S. Department of Energy projections suggested an increase in LED luminaire efficacy by 89% between 2013 and 2020.[11] More conservative projections suggested efficacy increase factors between 38% and 46% during the next decade from 2015 to 2025.[19] Realizing this factor is non-linear over time (i.e., the efficacy increase slows over time), the research team used a simplified formula:

$$LEF = (6\% - 6/25*t)$$

  where $t$ is the number of years into the analysis period. This *LEF* would result in a 50% efficacy increase in 10 years or a 100% increase in 25 years.

The following is a list of the installation- and maintenance-related cost factors:

- *Annual luminaire and ancillary structure maintenance cost.* The annual maintenance cost for HPS (*HAMC*; including costs of lamp replacement) is estimated as $0.96/W (i.e., total lighting maintenance and operational costs with the exceptions of power bills and underground utility replacement in Table 3 divided by total nominal wattage in Table 4). The research team estimated an annual luminaire and ancillary structure maintenance cost of $1.30/W for LED luminaires (*LAMC*) without luminaire costs (i.e., total ancillary lighting structure maintenance and replacement costs in Table 3 divided by total nominal wattage in Table 4 and then by *LRWF*). Note that VDOT currently does not conduct routine roadway luminaire cleaning and inspection. When functioning properly, therefore, LED luminaires themselves (excluding ancillary structures) are considered "maintenance free" since they do not require lamp replacement.

- *Disposal cost per luminaire.* Conversations with VDOT officials suggested that this cost is typically included in the annual maintenance costs and cannot be separately accounted for in a straightforward manner. As such, the research team did not separate this cost from the maintenance costs.

- *Installation-related labor and traffic control costs.* This study did not consider additional costs associated with the labor and traffic control required for installing LED luminaires. The researchers assumed that, regardless of luminaire types, new lighting projects require the same installation costs. Replacing existing HPS luminaires when they are functioning, however, results in additional installation-related costs (particularly in the case of S1). However, conversations with VDOT officials suggested that the installation related costs such as traffic control costs could change significantly based on installation scenarios and whether it was done in-house. Therefore, these costs were not considered in this study.

The following are factors and assumptions that are not included in the categories above:

- Crash reduction savings and environmental benefits are not considered.

- All costs are in 2015 dollars with an annual inflation rate of 2%.

- *Year* is the basic time unit in this analysis for all scenarios and all LED luminaire purchases are assumed at the beginning of each year. The timing of luminaire replacement within individual years was not considered due to the complications associated with potential changes of variables such as inflation, interest rate, luminaire price, electricity price, and LED luminaire efficacy within a single year.

- This study did not consider utilities-related costs including utilities maintenance, relocation, and upgrades, with the assumption that the conversion to LED luminaires would not result in significant increase in such costs.

Table 5 summarizes the factors used for this cost-benefit analysis.

**Table 5. Summary of Cost Analysis Factors**

| Factor | Variable | Value |
|---|---|---|
| **General Factors and Assumption** | | |
| Analysis period (year) | - | 25 |
| Analysis base year | - | 2015 |
| Inflation rate | *r* | 2% |
| **Energy-Related Costs** | | |
| Current energy cost ($/kWh) | *CEC* | 0.043 |
| Future energy cost increase factor | *ECI* | 2% |
| Total nominal wattage (W) | *TNW* | 18,674,930 |
| Total HPS power consumption wattage (W) | *TCW* | 21,476,170 |
| Current and future annual luminaire operating hours | *LOH* | 4,000 |
| **Luminaire-Related Factors** | | |
| Current LED luminaire cost ($/W) | *LEDC* | 3.45 |
| Future LED luminaire price reduction factor | *LPRF* | 9% - 9/25*$t$ |
| Initial LED luminaire replacing wattage factor | *LRWF* | 0.6 |
| LED luminaire operational life (hours) | *LLOL* | 100,000 |
| HPS luminaire operational life (hours) | *HLOL* | 8,000 |
| LED luminaire efficacy increase factor | *LEF* | 6% - 6/25*$t$ |
| **Luminaire and Ancillary Structure Maintenance Costs** | | |
| Current annual maintenance cost for HPS luminaires ($/W/year) | *HAMC* | 0.96 |
| Current annual maintenance cost for LED luminaires ($/W/year) | *LAMC* | 1.3 |

The research team used the following equations for the calculations:

- Base scenario (without conversion to LED) annual energy cost for $t^{th}$ year:

Eq. 1: $$\text{Cost}_{t,\text{base,energy}} = CEC \times (1 + ECI)^t \times TCW \times LOH$$

- Base scenario annual maintenance cost for $t^{th}$ year:

Eq. 2: $$\text{Cost}_{\text{t,base,maint}} = HAMC \times TNW \times (1 + r)^t$$

- Base scenario annual total lighting maintenance and operational cost for $t^{th}$ year:

Eq. 3: $$\text{Cost}_{t,\text{base,total}} = \text{Cost}_{t,\text{base,energy}} + \text{Cost}_{t,\text{base,maint}}$$

- S1 (converting all HPS luminaires to LED in year 1) initial investment cost:

Eq. 4: $$\text{Cost}_{\text{S1,initial}} = TNW \times LRWF \times LEDC$$

- S1 annual energy cost after LED conversion for $t^{th}$ year:

Eq. 5: $$\text{Cost}_{t,\text{S1,energy}} = CEC \times (1 + ECI)^t \times TNW \times LRWF \times LOH$$

- S1 annual maintenance cost after LED conversion for $t^{th}$ year:

Eq. 6: $$\text{Cost}_{t,\text{S1,maint}} = LAMC \times TNW \times (1 + r)^t$$

- S1 annual total lighting maintenance and operational cost after LED conversion for $t^{th}$ year:

Eq. 7: $$\text{Cost}_{t,\text{S1,total}} = \text{Cost}_{t,\text{S1,energy}} + \text{Cost}_{t,\text{S1,maint}}$$

- S2 (converting all HPS luminaires in a 5-year period) annual LED luminaire cost for $t^{th}$ year ($t$ <=5):

Eq. 8: $$\text{Cost}_{t,\text{S2,LED}} = \frac{TNW}{5} \times LRWF \times LEDC \times \prod_1^t (1 - LPRF)$$

- S2 annual energy cost for $t^{th}$ year:

Eq. 9: $$\text{Cost}_{t,\text{S2,energy}} = \left(\sum_1^t \left(\frac{t}{5} \times TNW \times LRWF \times \prod_1^t (1 - LEF)\right) + \frac{5-t}{5} \times TCW\right) \times CEC \times (1 + ECI)^t \text{ if } t <=5;$$
$$\text{Cost}_{t,\text{S2,energy}} = \sum_1^t \left(\frac{t}{5} TNW/5 \times LRWF \times \prod_1^t (1 - LEF) \times CEC \times (1 + ECI)^t \text{ if } t >5;$$

- S2 annual maintenance cost for $t^{th}$ year:

Eq. 10: $$\text{Cost}_{t,\text{S2,maint}} = \frac{t}{5} \times TNW \times LRWF \times LAMC \times (1 + r)^t + \frac{5-t}{5} \times TNW \times HAMC \times (1 + r)^t \text{ if } t <=5;$$
$$\text{Cost}_{t,\text{S2,maint}} = TNW \times LAMC \times (1 + r)^t \text{ if } t >5;$$

- S2 annual total lighting maintenance and operational cost for $t^{th}$ year:

Eq. 11: $$\text{Cost}_{t,\text{S2,total}} = \text{Cost}_{t,\text{S2,LED}} + \text{Cost}_{t,\text{S2,energy}} + \text{Cost}_{t,\text{S2,maint}}$$

- S3 (converting all HPS luminaires in a 10-year period) annual LED luminaire cost for $t^{\text{th}}$ year ($t$ <=10):

Eq. 12: $$\text{Cost}_{t,\text{S3,LED}} = \frac{TNW}{10} \times LRWF \times LEDC \times \prod_1^t (1 - LPRF)$$

- S3 annual energy cost for $t^{\text{th}}$ year:

Eq. 13: $$\text{Cost}_{t,\text{S3,energy}} = \left(\sum_1^t \left(\frac{t}{10} \times TNW \times LRWF \times \prod_1^t (1 - LEF)\right) + \frac{10-t}{10} \times TCW\right) \times CEC \times (1 + ECI)^t \text{ if } t \text{ <=10;}$$
$$\text{Cost}_{t,\text{S3,energy}} = \sum_1^t \left(\frac{t}{10} TNW \times LRWF \times \prod_1^t (1 - LEF) \times CEC \times (1 + ECI)^t\right) \text{ if } t \text{ >10}$$

- S3 annual maintenance cost for $t^{\text{th}}$ year:

Eq. 14: $$\text{Cost}_{t,\text{S3,maint}} = \frac{t}{10} \times TNW \times LRWF \times LAMC(1 + r)^t + \frac{10-t}{10} \times TNW \times HAMC \times (1 + r)^t \text{ if } t \text{ <=10;}$$
$$\text{Cost}_{t,\text{S3,maint}} = TNW \times LAMC \times (1 + r)^t \text{ if } t \text{ >10.}$$

- S3 annual total lighting maintenance and operational cost for $t^{\text{th}}$ year:

Eq. 15: $$\text{Cost}_{t,\text{S3,total}} = \text{Cost}_{t,\text{S3,LED}} + \text{Cost}_{t,\text{S3,energy}} + \text{Cost}_{t,\text{S3,maint}}$$

## Development of VDOT Specification for Roadway LED Luminaires

As part of this study, the research team developed draft specifications of LED luminaires for use on the VDOT-maintained roadways. The development was based on the LED evaluation results of this study, a comprehensive understanding of existing standards and guidelines relevant to the LED industry, interviews with VDOT officials, manufacturer and consultant input, and a review of LED luminaire specifications of several sample state transportation agencies.

In accordance with VDOT recommendations, the specification document was developed as a special provision for quick implementation, with the intent of incorporation into the VDOT *Road and Bridge Specifications*. The specification was intended to address requirements relevant to the selection, testing, and installation of LED luminaires for use on VDOT facilities. The document applies to conventional pole-mounted and wall-mounted luminaires with the exception of high-mast luminaires and luminaires to be used for tunnel applications. The target audience of the document is contractors performing VDOT lighting projects.

The developed specification (*Virginia Department of Transportation Special Provision for Light Emitting Diode [LED] Roadway Luminaires*) was delivered to the Virginia Transportation Research Council separately as a stand-alone product of this study.

## RESULTS

### Initial Laboratory Horizontal Illuminance

Horizontal illuminance is an indication of the distribution of light reaching the ground. It also shows the level of uniformity of the luminaire's output. Measurements were conducted for two luminaires of each type, and the results for two luminaires of the same type were mostly consistent. Readers should understand that higher absolute illuminance values may not necessarily indicate good luminaire performance. The goodness of a luminaire's photometric performance is determined by multiple variables, such as horizontal/vertical illuminance, uniformity, light distribution, CCT, and light loss over time.

Figure 8 through Figure 13 show the recorded horizontal illuminance values over the laboratory measurement grid (40 x 20 m) for the six luminaire types evaluated, respectively. The figures clearly suggest that the HPS system provided much higher horizontal illuminance values at the focal center than the LED systems did. However, the horizontal illuminance relatively concentrated beneath the luminaire and quickly decreased across the laboratory grid. Among the LED systems, the Designs C and E systems exhibited the highest horizontal illuminance values, with the Design E system showing more widespread light shed across the entire laboratory grid.

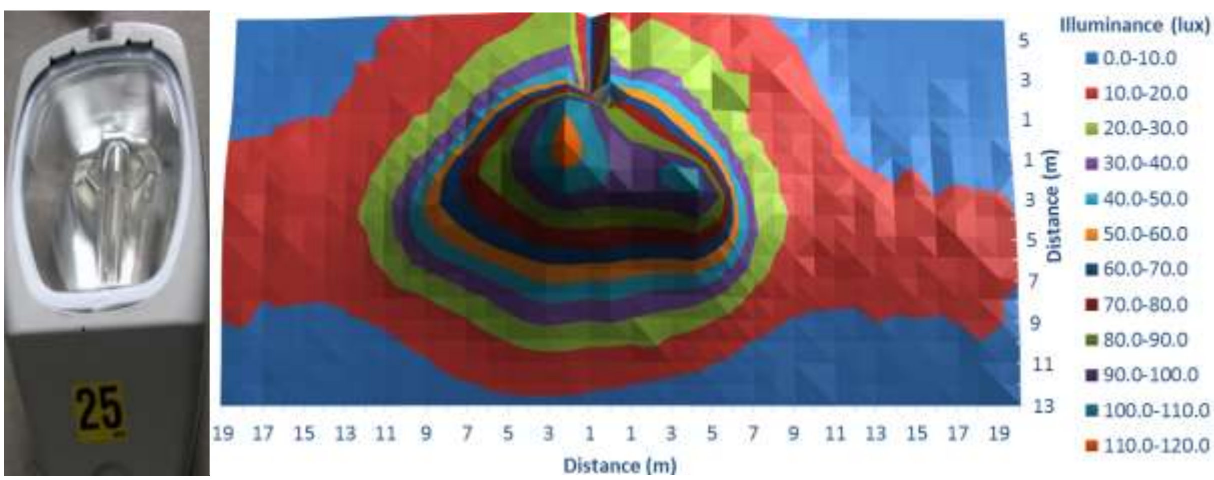



**Figure 8. Laboratory Horizontal Illuminance – HPS 250W**

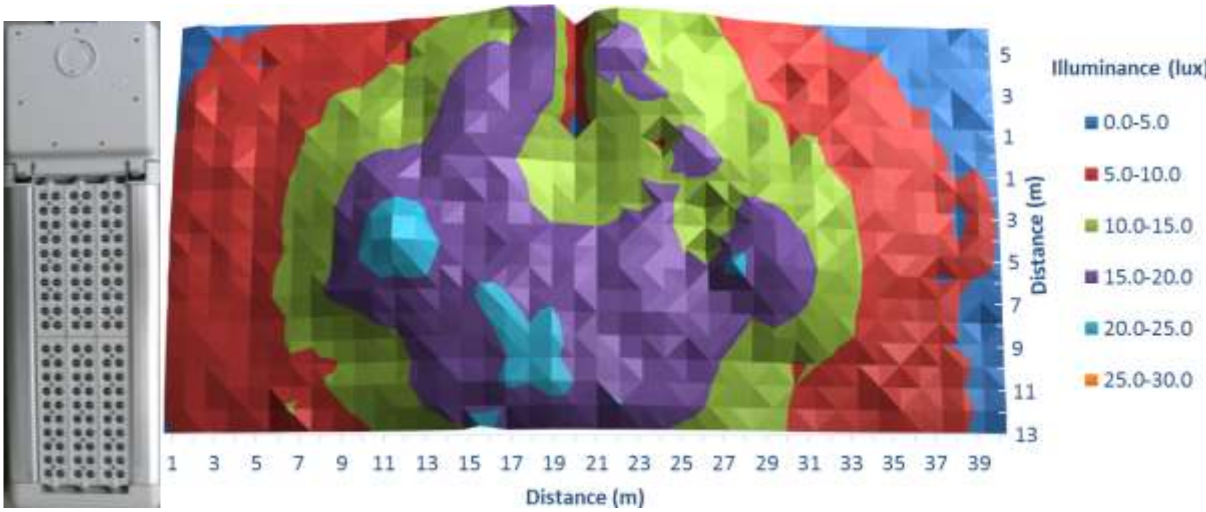



**Figure 9. Laboratory Horizontal Illuminance – Design A**

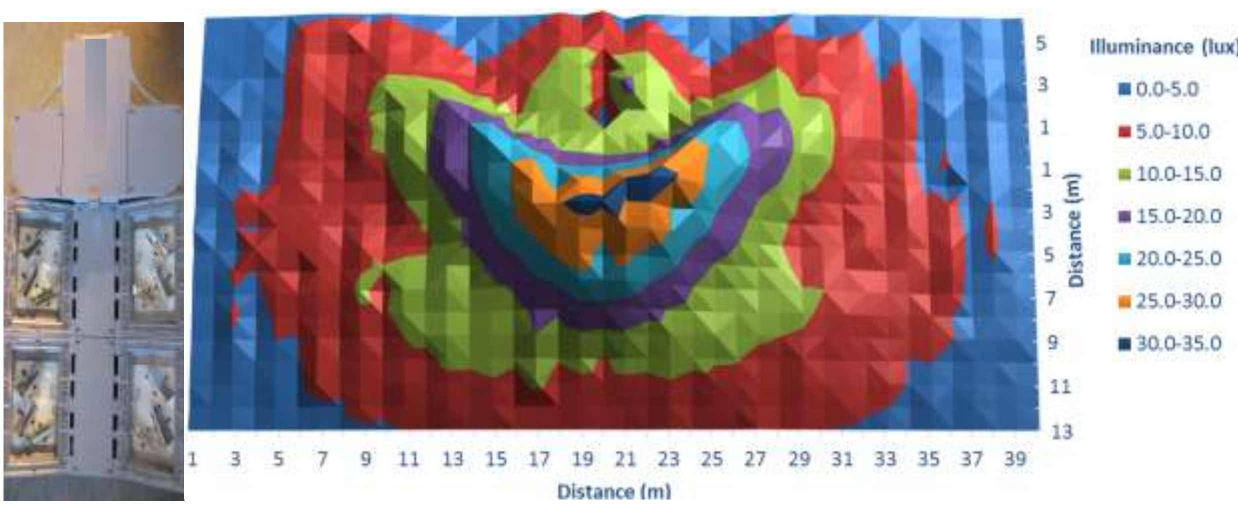



**Figure 10. Laboratory Horizontal Illuminance – Design B**

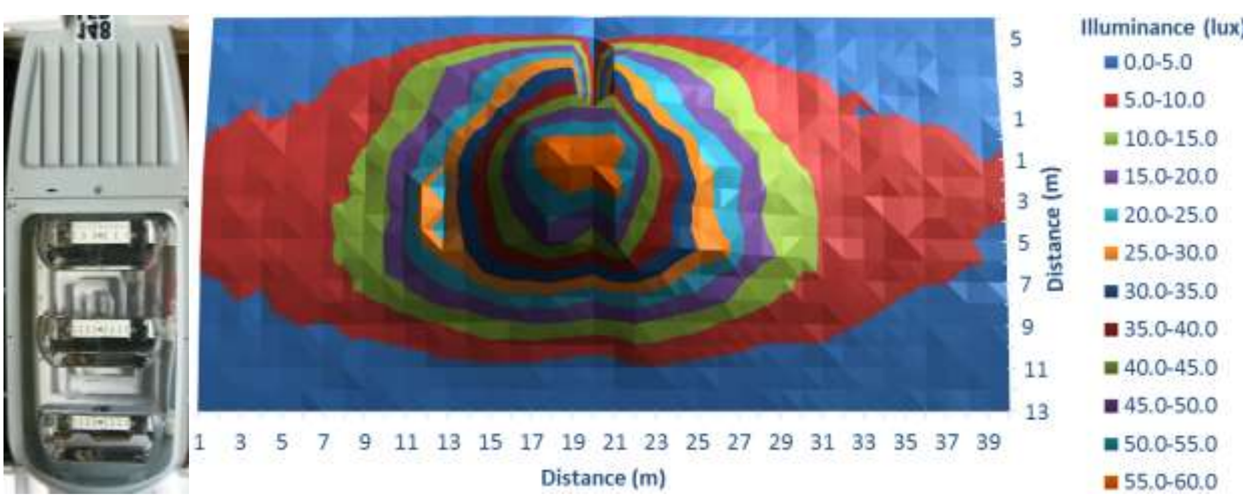



**Figure 11. Laboratory Horizontal Illuminance – Design C**

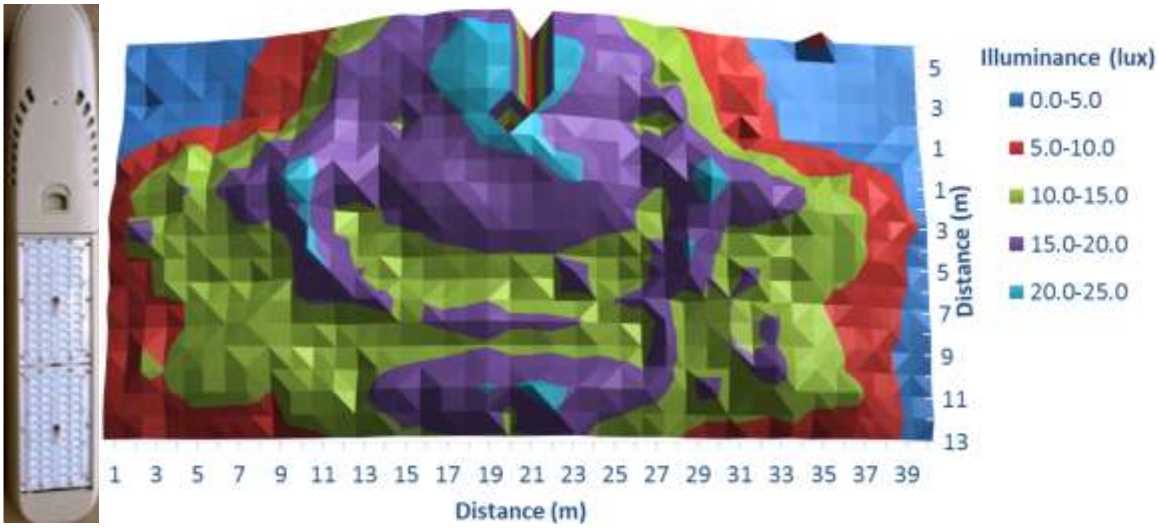



**Figure 12. Laboratory Horizontal Illuminance – Design D**

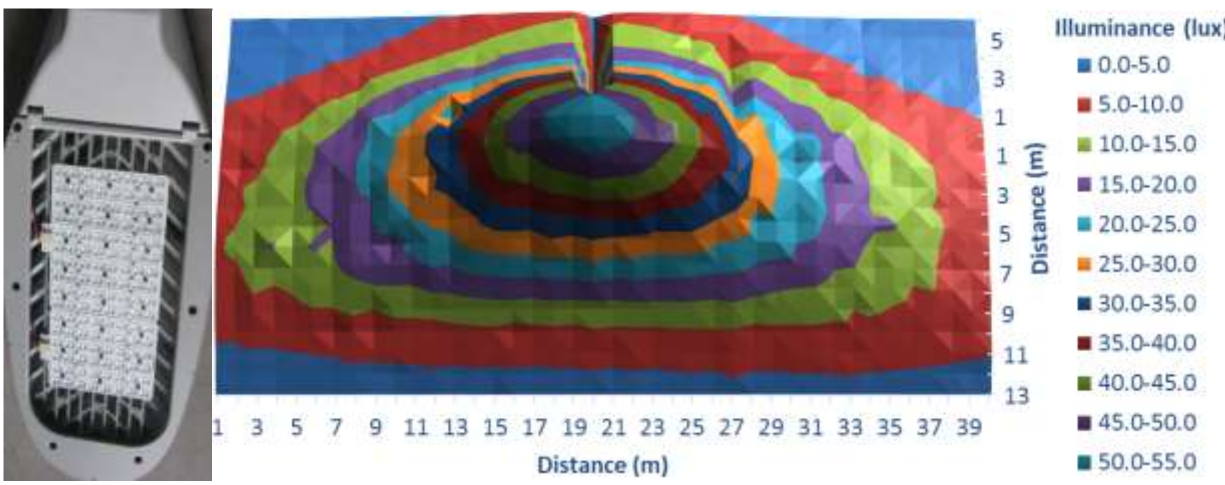



**Figure 13. Laboratory Horizontal Illuminance – Design E**

Figure 14 shows the average horizontal illuminance over the laboratory grid for all evaluated luminaire systems. Notice that although the Design A and D systems exhibited relatively lower maximum horizontal illuminance, the horizontal illuminance values across the entire measurement grid were much more uniform, resulting in average horizontal illuminance levels similar to those of the Design C and E systems.

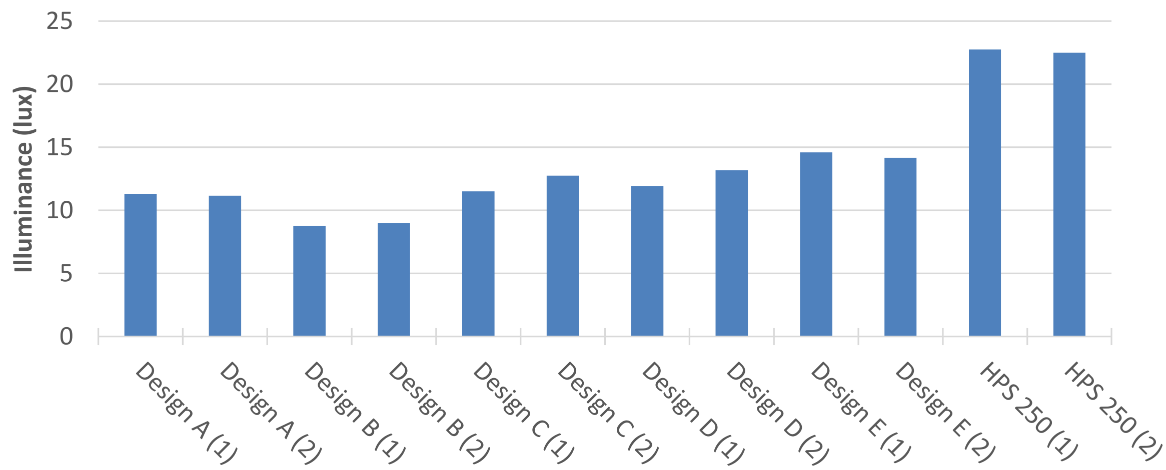



**Figure 14. Average Laboratory Horizontal Illuminance**

To better understand and compare the horizontal illuminance uniformity between the LED and HPS systems and among the different LED designs, the research team selected the illuminance readings along the 3-meter, 6-meter, and 9-meter grid lines in front of the luminaire, as shown in Figure 15. If a roadway light were located directly above the edge line of the rightmost lane, illuminance values along these three grid lines would roughly correspond to the amount of light falling on the lane-marking lines for three adjacent traffic lanes.

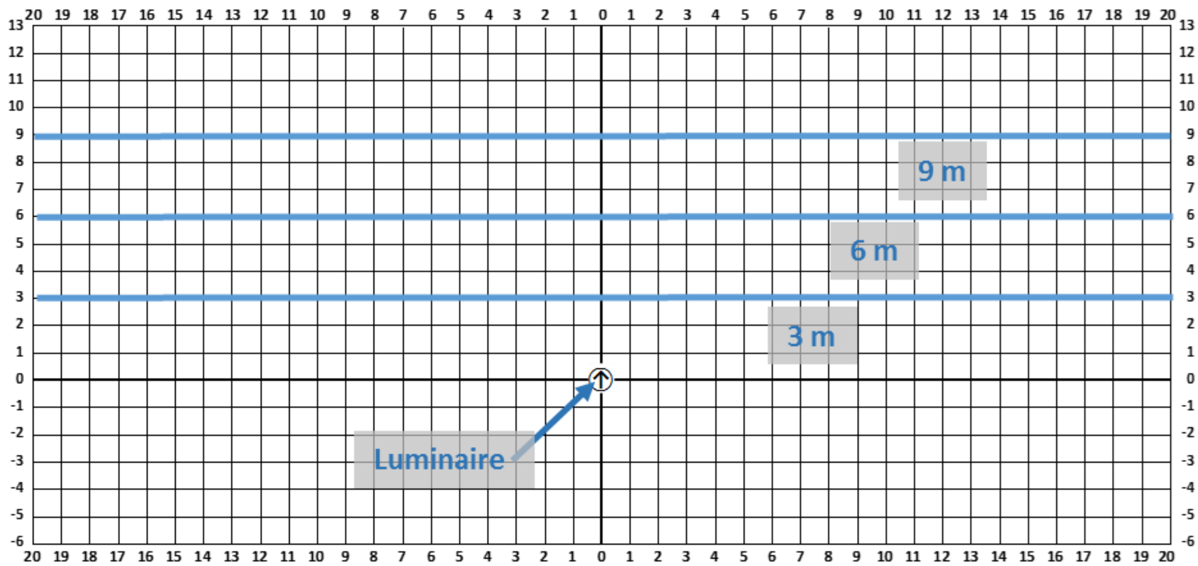



**Figure 15. Horizontal Illuminance at 3, 6, and 9 m Grid Lines**

Figure 16 through Figure 18 compare the measured horizontal illuminance levels at the 3-meter, 6-meter, and 9-meter laboratory grid lines, respectively. As the figures show, the horizontal illuminance values of the HPS luminaire are much higher in the center of the 3-meter grid but quickly approach the levels of other LED systems at approximately 9 m laterally away from the luminaire. This is also shown in Figure 8 where much of the HPS light output concentrates within a roughly 9-m circular area beneath the luminaire. When comparing across the three grid lines, the horizontal illuminance values of the HPS system decrease significantly as the distance increases transversely, with the peak values closely approaching those of the LED systems.

Among the various LED designs, the Design C luminaire exhibited a relatively similar horizontal illuminance distribution as that of the HPS systems.  LED luminaires with LED optic arrays in general had a much more spread-out light distribution.

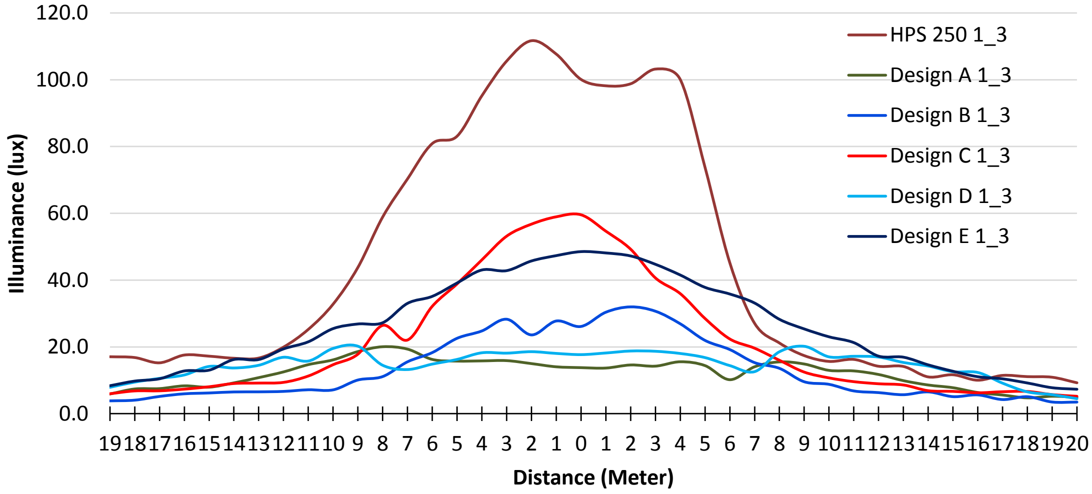



**Figure 16.  Horizontal Illuminance at 3-Meter Grid Line**

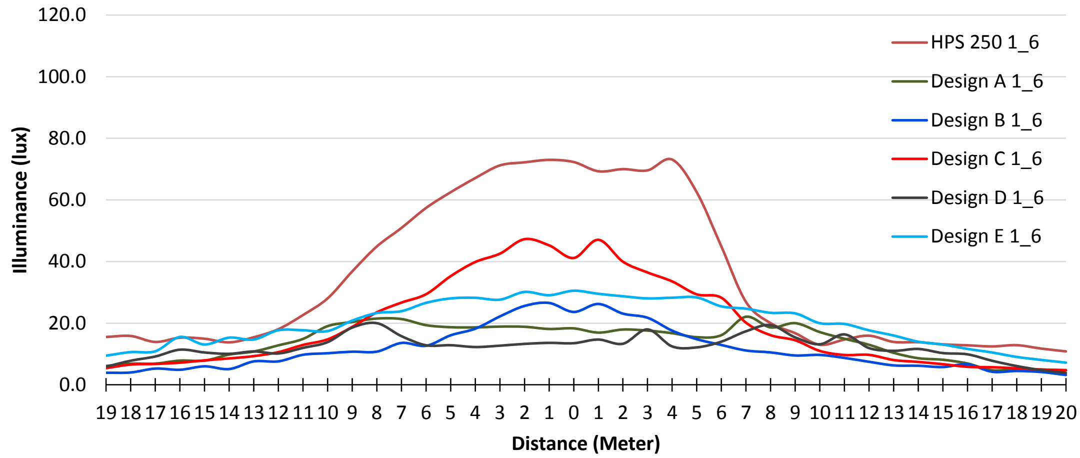



**Figure 17.  Horizontal Illuminance at 6-Meter Grid Line**

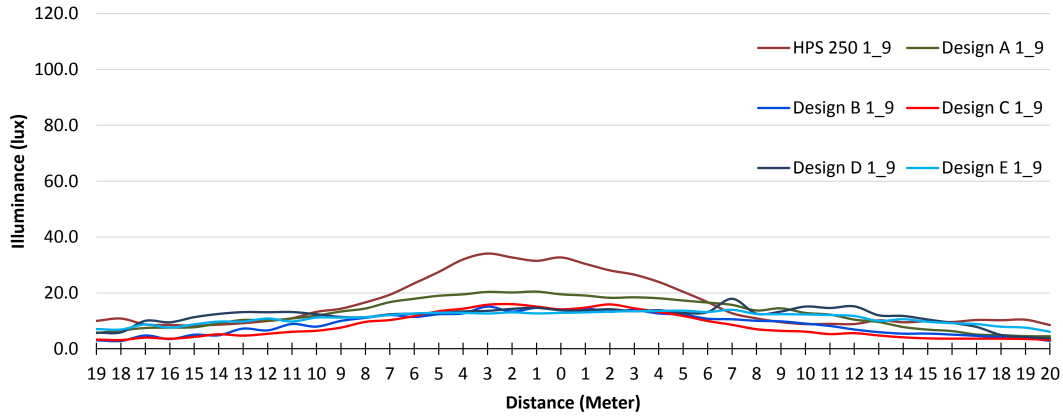



**Figure 18. Horizontal Illuminance at 9-Meter Grid Line**

To understand the horizontal illuminance uniformity in a quantitative manner, the research team calculated maximum and average uniformity ratios for the three grid lines based on illuminance using a method similar to the concepts described in IES RP-8-14.[23] In this context, the ratios were calculated as:

$$Maximum\ Uniformity\ Ratio = E_{max}/E_{min}$$

and

$$Average\ Uniformity\ Ratio = E_{avg}/E_{min}$$

where $E_{max}$ is the average of three continuous maximum horizontal illuminance readings; $E_{min}$ is the average of three continuous minimum horizontal illuminance readings; and $E_{avg}$ is the average of the horizontal illuminance readings along the entire grid line.

Figure 19 through Figure 21 illustrate the ratios for the three grid lines. Comparing the figures, it is clear that the maximum uniformity ratio of the HPS system was much higher than most LED systems at the 3-meter grid line. In addition, the Design C LED system (with three large LED optics) exhibited a maximum uniformity ratio much higher than that of other LED designs. In contrast, LED systems, such as Designs A, D, and E to a certain extent, showed a better horizontal illuminance uniformity along all three grid lines and transversely between the three grid lines.

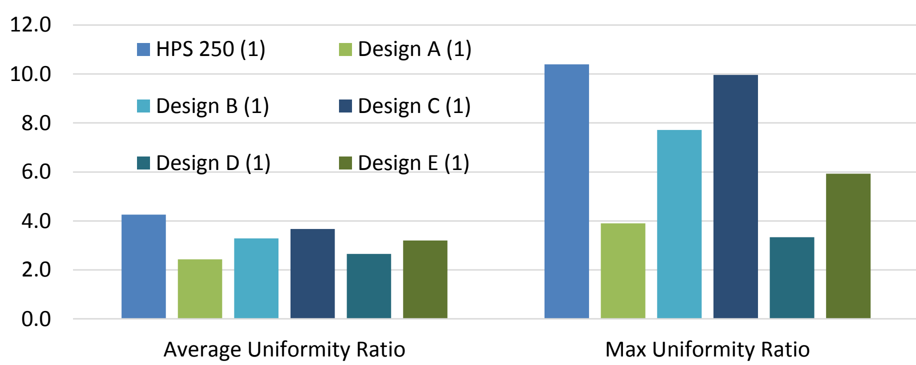



**Figure 19. Average and Max Uniformity Ratio at 3-Meter Grid Line**

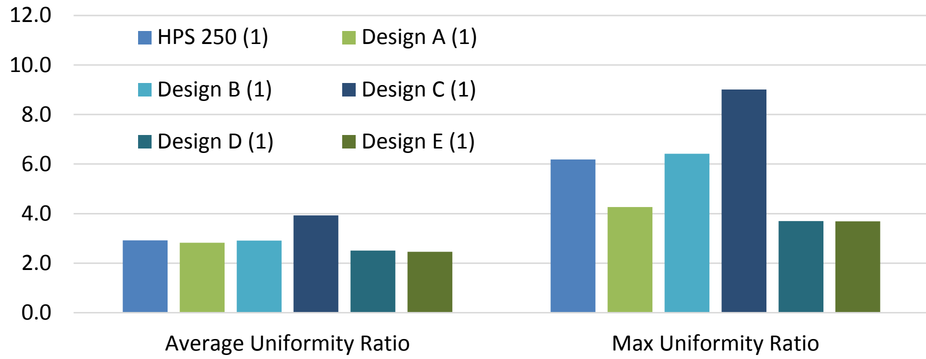



**Figure 20. Average and Max Uniformity Ratio at 6-Meter Grid Line**

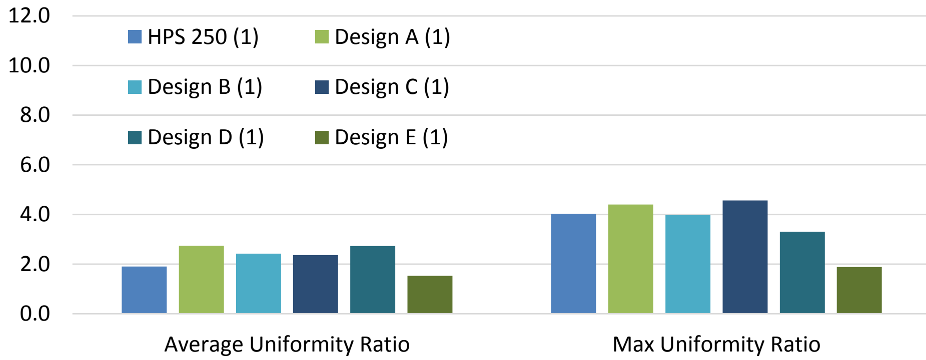



**Figure 21. Average and Max Uniformity Ratio at 9-Meter Grid Line**

## Initial Laboratory Vertical Illuminance and Lighting Quality

### Vertical Illuminance and Uniformity

Vertical illuminance is the amount of illuminance that lands on a vertical surface. Vertical illuminance is an important roadway lighting metric as it is a reasonable criterion for determining the amount of light landing on pedestrians. At 1.5 m from the ground, vertical illuminance measurements also give an indication of the light that would adversely affect an observer's eyes creating glare. Similarly, the two luminaires of each design evaluated during this study performed similarly, thus this section only discusses the results for one system for each type.

Figure 22 through Figure 27 illustrate the vertical illuminance values of each different luminaire system over the laboratory grid. As the figures suggest, the HPS system had much higher peak values than the LED systems. However, the values decreased quickly across the grid from the focal points. In general, the vertical illuminance values of the LED systems were much more widespread on the grid, with the exception of the Design C Luminaires. These results suggest that most LED systems outperform the HPS system in terms of reducing glare for travelers.

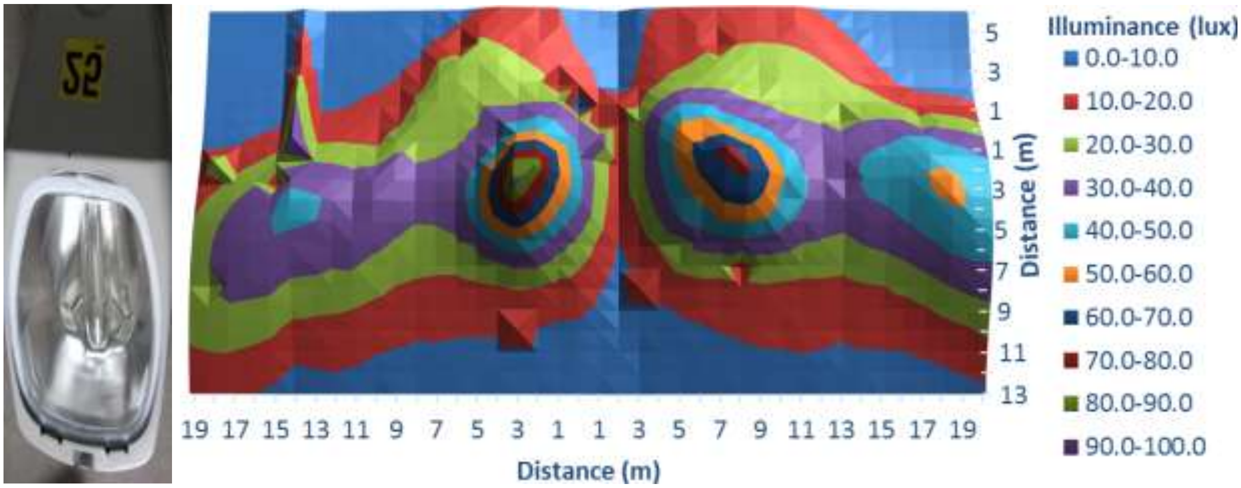


**Figure 22. Laboratory Vertical Illuminance – HPS 250 W**

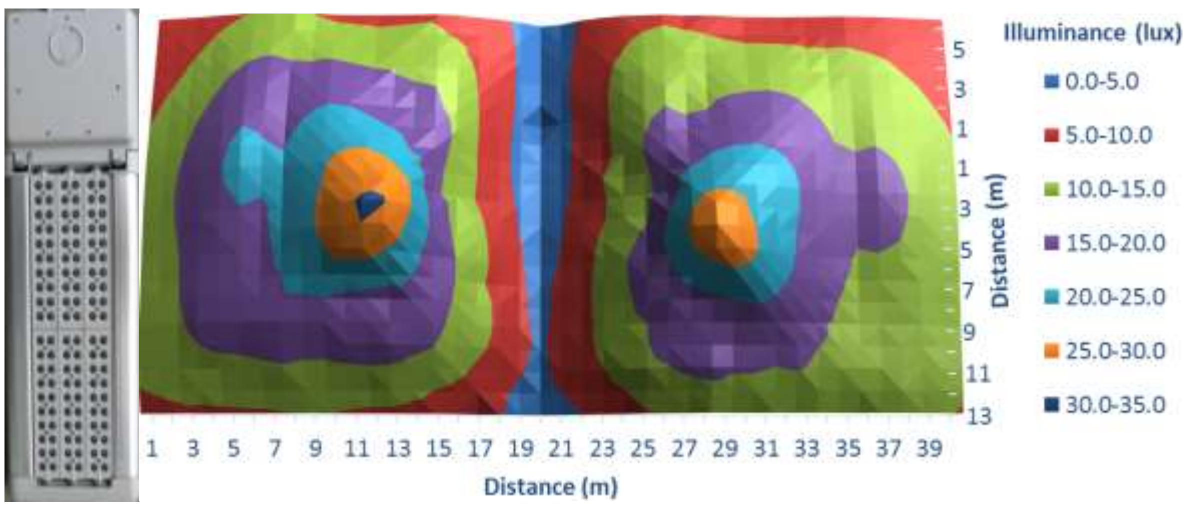


**Figure 23. Laboratory Vertical Illuminance – LED Design A**

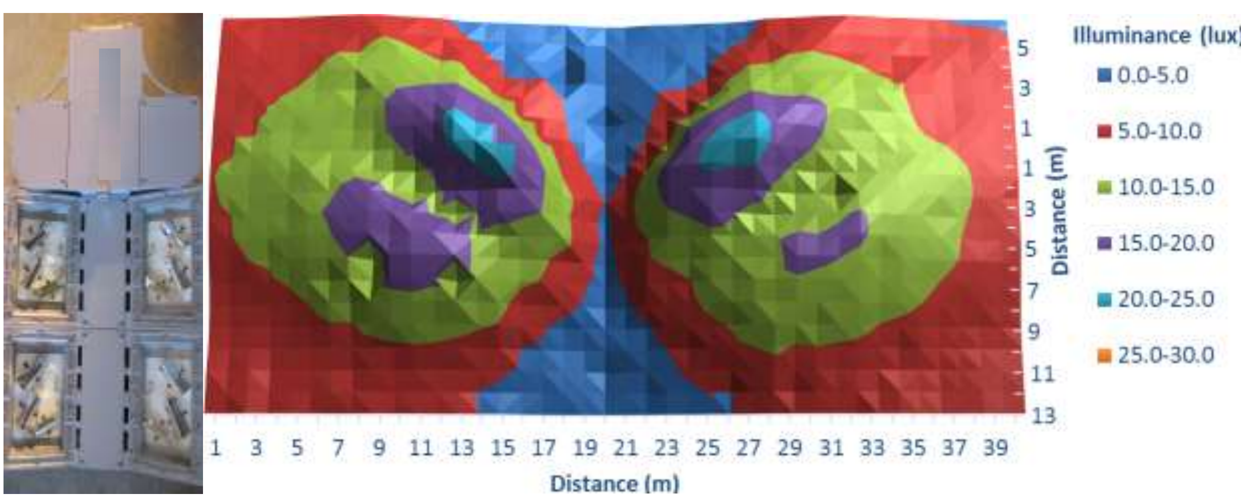


**Figure 24. Laboratory Vertical Illuminance – LED Design B**

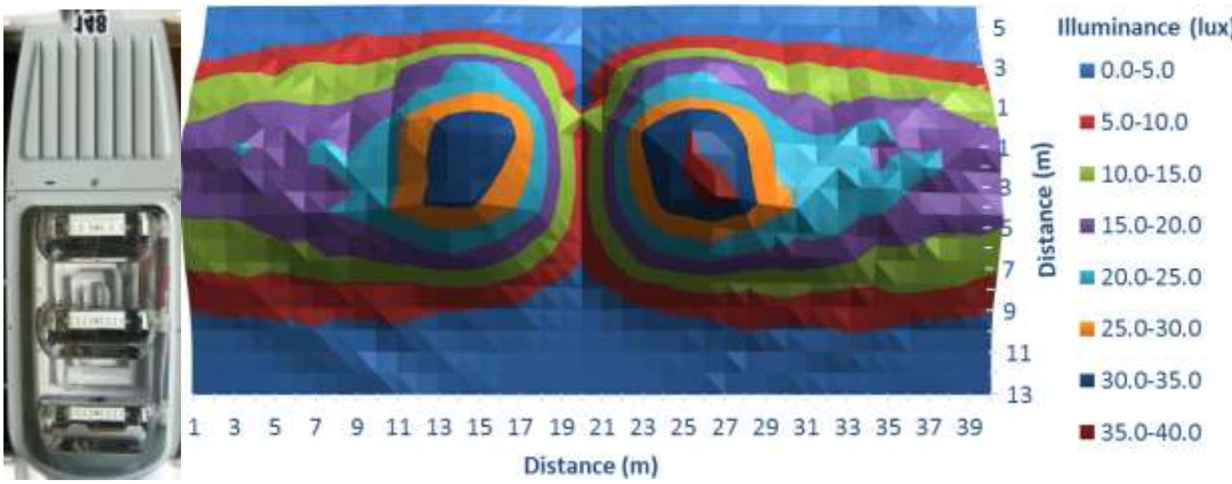



**Figure 25. Laboratory Vertical Illuminance – LED Design C**


**Figure 26. Laboratory Vertical Illuminance – LED Design D**

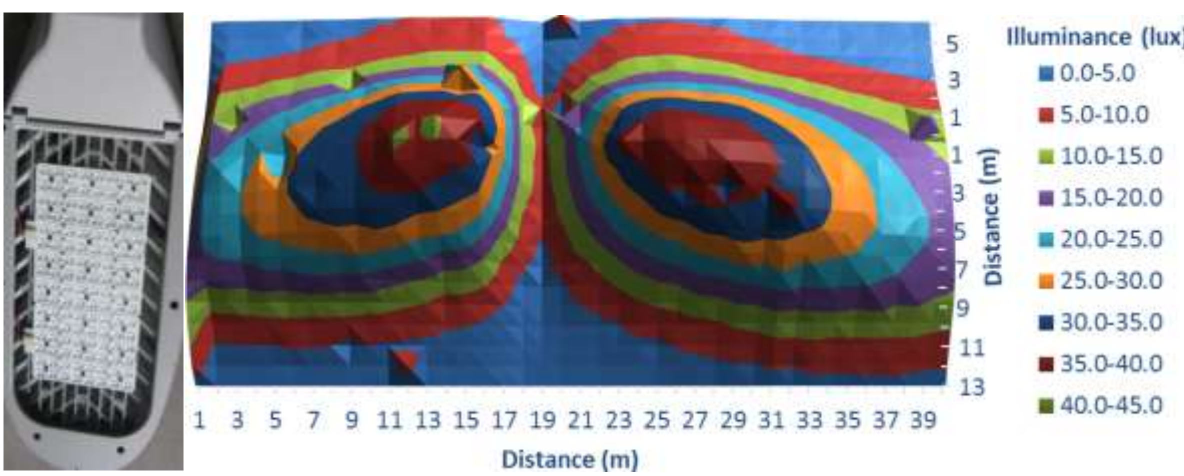



**Figure 27. Laboratory Vertical Illuminance – LED Design E**

Figure 28 shows the average vertical illuminance values of all evaluated luminaire systems across the entire laboratory grid. The figure shows that the HPS systems generated higher vertical illuminance on average, partly attributable to the high peak illuminance values. Among the LED designs, Design E luminaires had the highest average vertical illuminance. The Design A and D systems also emitted relatively high average vertical illuminance across the evaluation grid, especially compared to their lower maximum vertical illuminance readings.

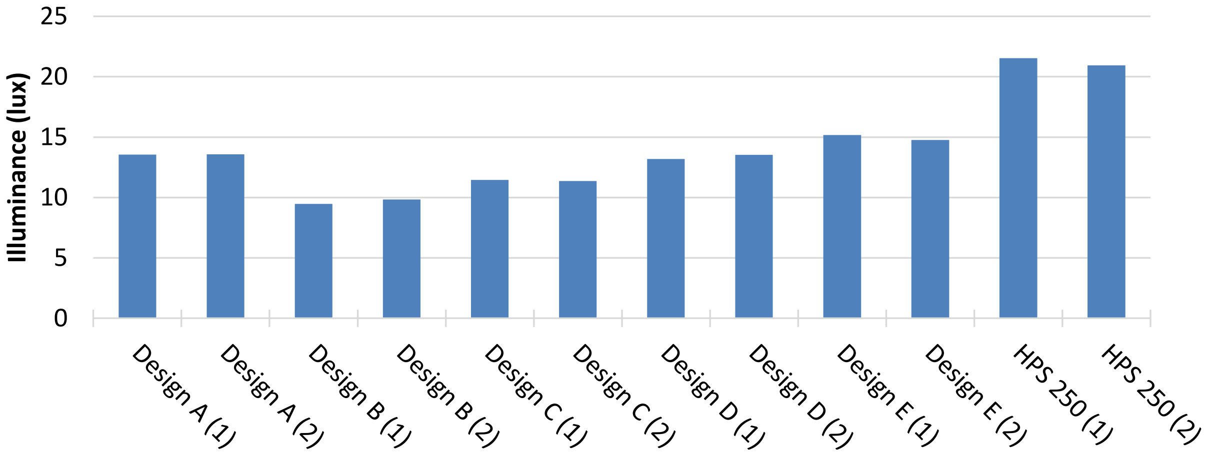



**Figure 28. Average Laboratory Vertical Illuminance**

The researchers also compared the vertical illuminance readings of the systems along the three-, six-, and nine- meter grid lines, and the vertical illuminance uniformity ratios were calculated along these grid lines using the same method described previously for horizontal illuminance uniformity ratios. Figure 29 through Figure 31 show the laboratory vertical illuminance profiles along the three grid lines. Clearly, the HPS system had a much more concentrated vertical illuminance level in the close vicinity of the luminaire. As the distance increases both longitudinally and transversely, the peak vertical illuminance readings for the HPS system decreased quickly to a level similar to that of most LED systems.

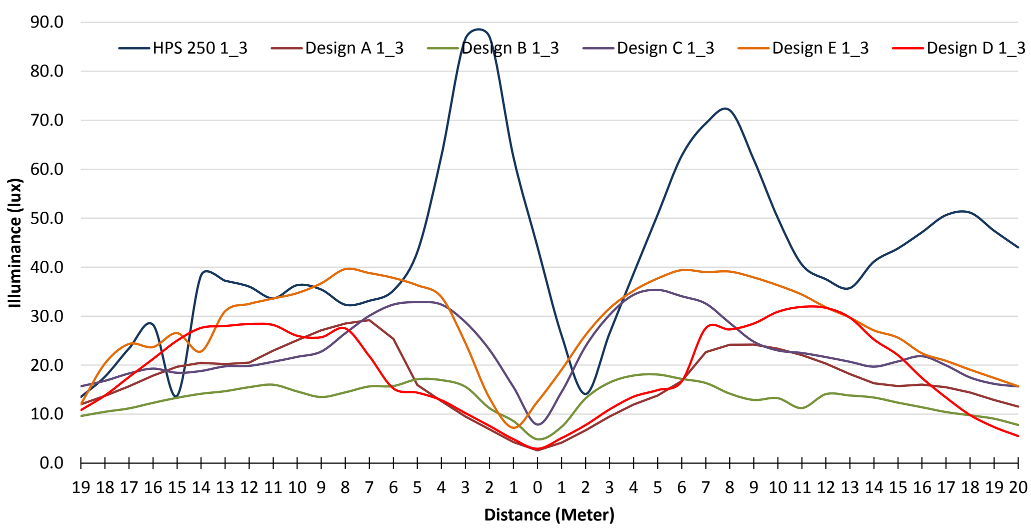



**Figure 29. Vertical Illuminance Along 3-Meter Grid Line**

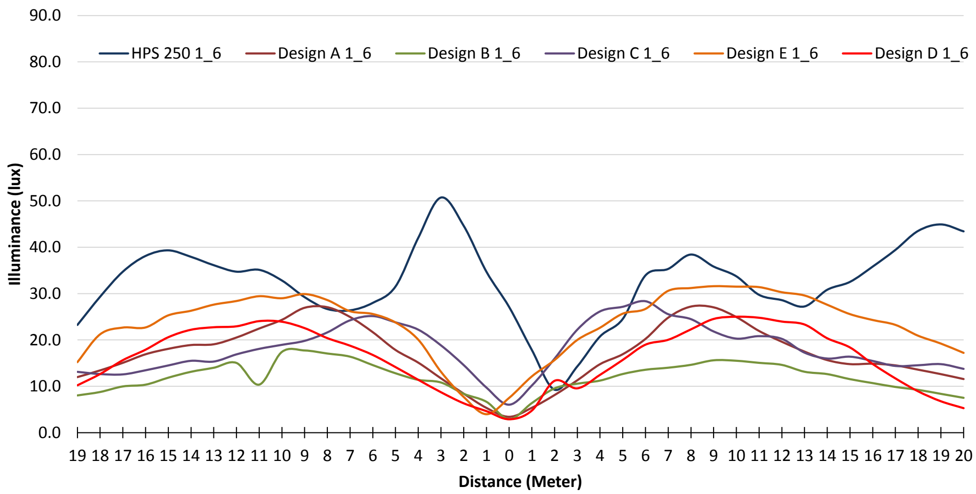



**Figure 30. Vertical Illuminance Along 6-Meter Grid Line**

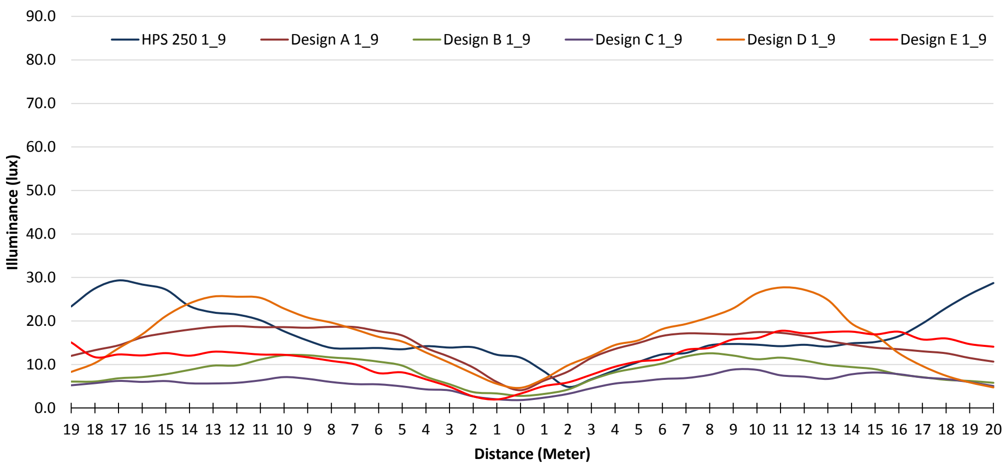



**Figure 31. Vertical Illuminance Along 9-Meter Grid Line**

Figure 32 through Figure 34 further illustrate the vertical illuminance uniformity at the 3-, 6-, and 9-meter laboratory grid lines. From the illustrations, the uniformity ratios of the HPS system did not seem to be particularly higher than the LED systems, which suggested that the vertical illuminance performance of the HPS system was comparable to some LED systems. On the other hand, the LED Design A and D (with LED optical arrays) had relatively higher uniformity ratios.

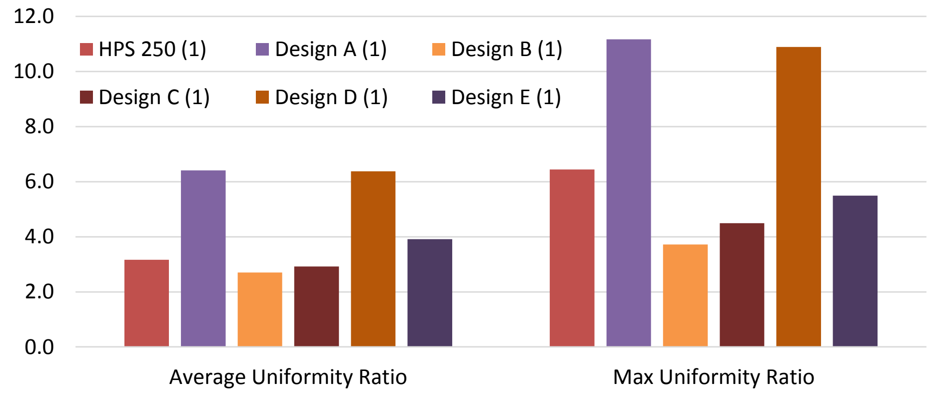



**Figure 32. Vertical Illuminance Uniformity at 3-Meter Grid Line**

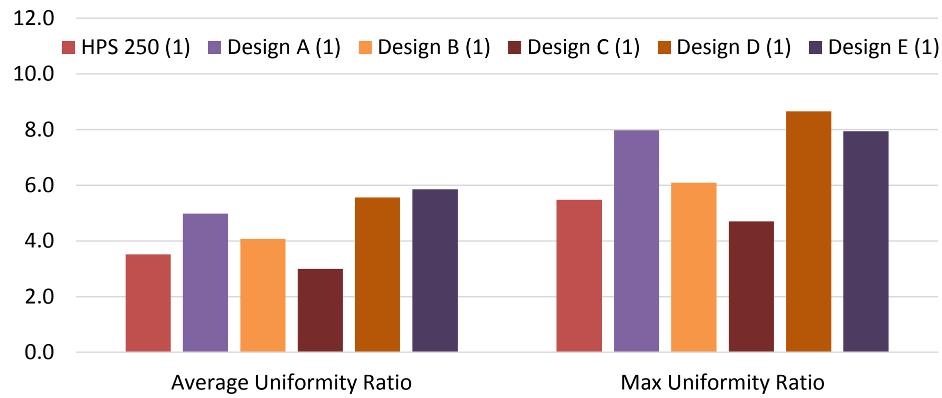



**Figure 33. Vertical Illuminance Uniformity at 6-Meter Grid Line**

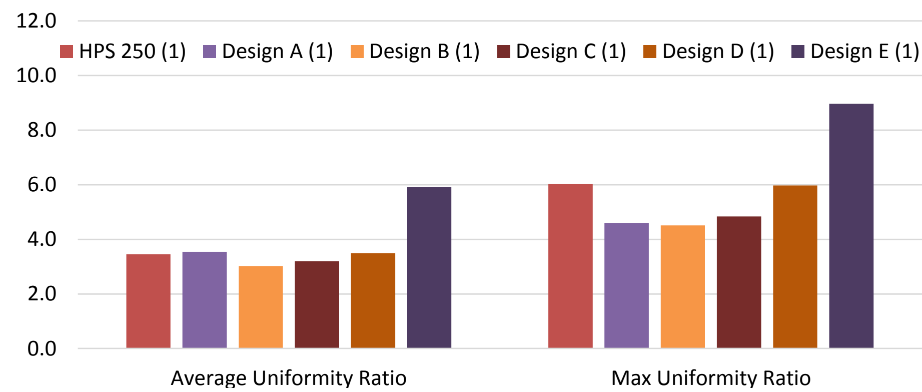



**Figure 34. Vertical Illuminance Uniformity at 9-Meter Grid Line**

## Light Trespass

Light trespass describes that portion of light falling out of the lighting design area, causing light pollution. During this study, the research team measured the vertical illuminance along the front most grid line (i.e., 13 m away from luminaire) and the rear most grid line (i.e., 6 m away from luminaire), both facing the luminaire. Figure 35 and Figure 36 illustrate the front and rear trespass measurements for the HPS and LED systems, respectively. The figures seem to suggest that the HPS and LED Design A and D luminaires had relatively high front and rear trespass levels.  In particular, the rear trespass readings of the HPS systems were the highest among all evaluated luminaires.

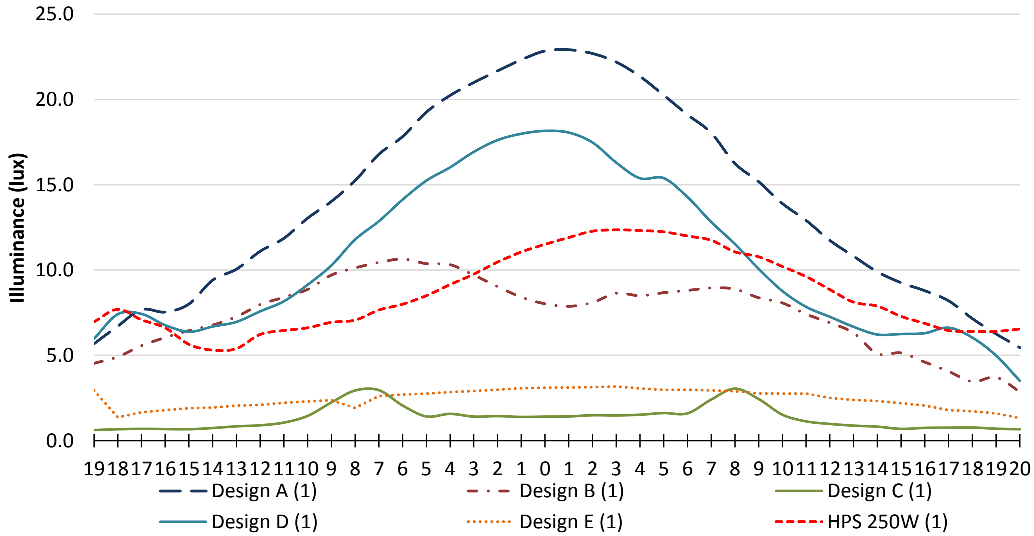



**Figure 35.  Front Trespass Measured Based on VTTI Laboratory Grid**

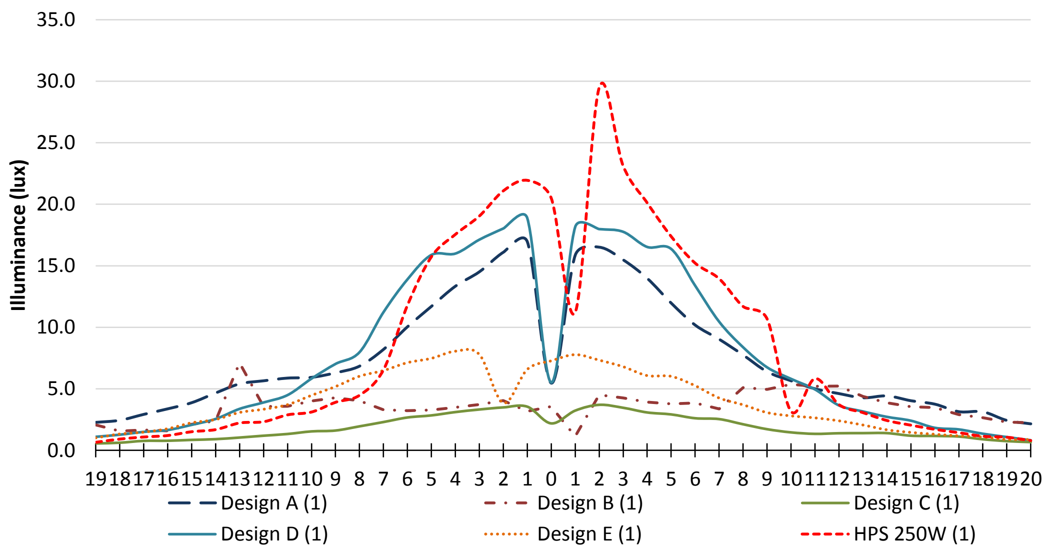



**Figure 36.  Rear Trespass Measured Based on VTTI Laboratory Grid**

## Initial Laboratory Spectral Power Distribution

An SPD measurement describes the power per unit area per unit wavelength of an illuminating body. In practice, SPD frequently refers to the graphic representation of the relative power at each wavelength. SPD curves provide users with a visual profile of the color characteristics of a light source and are one of the most powerful tools for determining the spectral content of a light source. The CCT of a light source gives a good indication of its general appearance, but does not give information on its specific spectral power distribution. Therefore, two luminaires with similar CCTs may appear to be the same color, but their effects on object colors can be quite different if their SPDs are significantly different.

Figure 37 shows the SPD curves for the evaluated LED and HPS systems. Note that the visible range of light wavelengths for typical human eyes is from 390 to 750 nanometers (nm). Within this range, the visible indigo light has a wavelength of about 445 nm, the visible yellow light has a wavelength of about 570 nm, and the visible red light has a wavelength of about 650 nm.

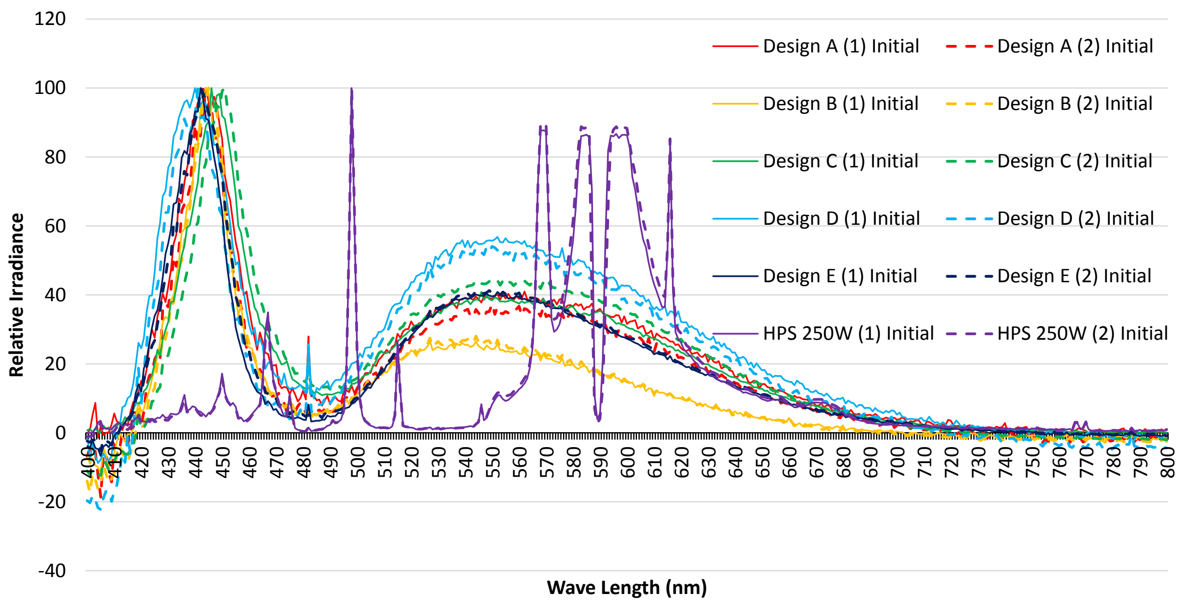



**Figure 37. SPD Curves for Evaluated LED and HPS Systems**

As Figure 37 indicates, the HPS systems showed high relative orange and reddish light content. In comparison, most LED systems contained relatively high relative of bluish/indigo light content. Figure 38 includes photos of the evaluated luminaire systems with an emphasis on their light colors.

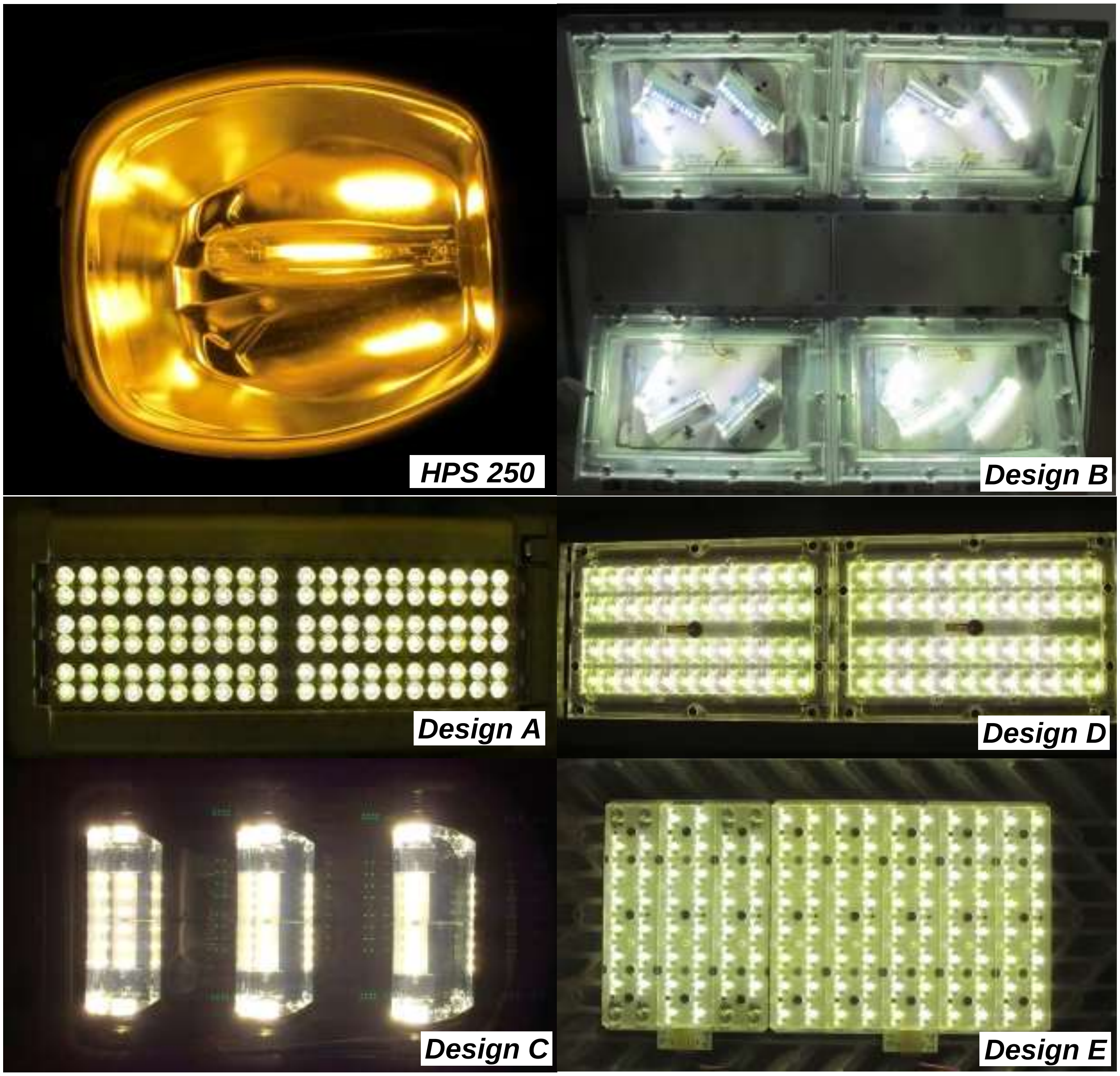


**Figure 38. Light Color of Evaluated Luminaire Systems**

## Initial Laboratory Power Consumption and Efficacy

Table 6 compares the actual wattages measured by the VTTI research team with the manufacturer-rated wattages of two luminaire systems of each type. Figure 39 further illustrates the wattage differences graphically. As shown by the illustrations, the measured wattages of most LED systems were consistent with their rated wattages.

**Table 6. Luminaire Power Consumption**

| System | Rated Wattage | Measured Wattage | Difference |
|---|---|---|---|
| Design A (1) | 195 | 198.4 | 1.7% |
| Design A (2) | 195 | 195.1 | 0.1% |
| Design B (1) | 120 | 124.6 | 3.8% |
| Design B (2) | 120 | 124.2 | 3.5% |
| Design C (1) | 148 | 146.8 | -0.8% |
| Design C (2) | 148 | 146.0 | -1.4% |
| Design D (1) | 150 | 174.3 | 16.2% |
| Design D (2) | 150 | 176.3 | 17.5% |
| Design E (1) | 200 | 202.1 | 1.1% |
| Design E (2) | 200 | 202.4 | 1.2% |
| HPS 250W (1)* | 250 | 304.9 | 22.0% |
| HPS 250W (2)* | 250 | 307.3 | 22.9% |

*The measured HPS wattages include driver wattage.

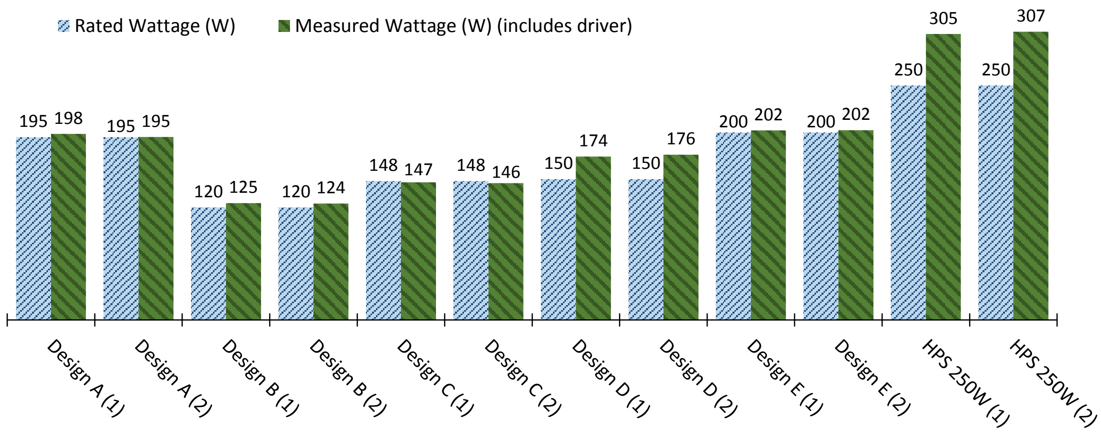



**Figure 39. Manufacturer-Rated Versus Measured (Including Driver) Wattage**

Table 7 and Figure 40 illustrate the estimated luminaire efficacy based on the average horizontal illuminance over the entire measuring grade and the measured luminaire wattage. The results showed that the estimated efficacy values of most LED systems evaluated were generally lower than that of the HPS systems. The exception was the Design C systems, which showed the highest efficacy among all systems evaluated.

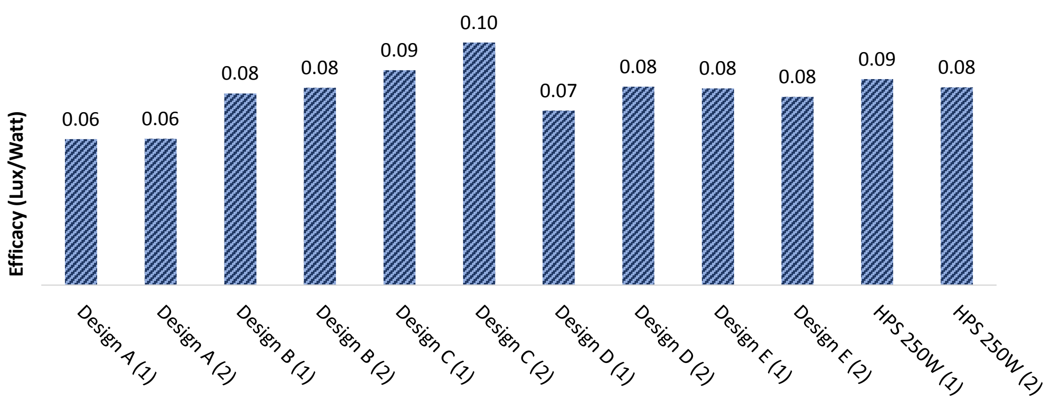



**Figure 40. Measured Luminaire Efficacy Based on Average Horizontal Illuminance**

**Table 7. Measured Luminaire Efficacy based on Average Horizontal Illuminance**

| Luminaire | Average Horizontal Illuminance (lux) | Average Vertical Illuminance (lux) | Measured Wattage (includes driver) | Horizontal Illuminance Per Wattage (lux/w) | Average |
|---|---|---|---|---|---|
| Design A (1) | 12.22 | 14.71 | 198.4 | 0.06 | 0.06 |
| Design A (2) | 12.07 | 14.99 | 195.1 | 0.06 | |
| Design B (1) | 10.09 | 10.28 | 124.6 | 0.08 | 0.08 |
| Design B (2) | 10.35 | 10.54 | 124.2 | 0.08 | |
| Design C (1) | 13.32 | 12.50 | 146.8 | 0.09 | 0.10 |
| Design C (2) | 14.95 | 12.64 | 146 | 0.10 | |
| Design D (1) | 12.84 | 14.70 | 174.3 | 0.07 | 0.08 |
| Design D (2) | 14.77 | 14.99 | 176.3 | 0.08 | |
| Design E (1) | 16.78 | 16.90 | 202.1 | 0.08 | 0.08 |
| Design E (2) | 16.08 | 16.28 | 202.4 | 0.08 | |
| HPS 250W (1) | 26.52 | 24.48 | 304.9 | 0.09 | 0.09 |
| HPS 250W (2) | 25.65 | 23.06 | 307.3 | 0.08 | |

## Laboratory Luminaire Performance Change Over Time

This section compares the results between first and second rounds of laboratory testing. The second round of laboratory testing was conducted after approximately 2 years (or 8,800 hours) of field operation.

### Change in Horizontal and Vertical Illuminance Over Time

Table 8 lists the average horizontal illuminance measurements for the evaluated luminaires based on the initial and second laboratory testing, followed by Figure 41 through Figure 43 comparing the differences graphically. To compare performance of different designs, the research team grouped the luminaires with exposed optic array design (i.e., Design A, D, and E). Note that the before and after testing results showed erratic performance for Design D (2) luminaire. When comparing average performance metrics, the researchers provided values both with and without that luminaire to account for its impact on results.

**Table 8. Change in Horizontal Illuminance: Laboratory Testing**

| Luminaire | Average Illuminance (Lux) | | | Lumen Depreciation | Dirt Depreciation | Overall Light Loss |
|---|---|---|---|---|---|---|
| | Before | After (Clean) | After (Dirty) | | | |
| Design A (1) | 11.3 | 10.7 | 10.6 | -5.5% | -0.8% | -6.3% |
| Design A (2) | 11.2 | 10.6 | 10.6 | -5.1% | 0.2% | -4.9% |
| Design B (1) | 8.8 | 8.4 | 8.4 | -4.0% | -1.0% | -5.0% |
| Design B (2) | 9.0 | 8.3 | 8.4 | -7.5% | 0.3% | -7.2% |
| Design C (2) | 12.8 | 12.3 | 11.9 | -3.8% | -2.7% | -6.5% |
| Design D (1) | 11.9 | 11.5 | 11.4 | -3.4% | -0.7% | -4.2% |
| Design D (2) | 13.2 | 10.4 | 11.5 | -20.9% | 7.9% | -13.0% |
| Design E (1) | 14.6 | 13.9 | 13.5 | -4.9% | -2.5% | -7.4% |
| Design E (2) | 14.2 | 13.5 | 13.5 | -4.5% | -0.2% | -4.7% |
| HPS 250 (2) | 22.5 | 21.3 | 20.3 | -5.1% | -4.7% | -9.8% |
| Optic Average (A, D, E w/o D(2)) | | | | -4.7% | -0.8% | -5.5% |
| Design B Average | | | | -5.8% | -0.3% | -6.1% |
| LED Average - with D (2) | | | | -6.5% | -0.4% | -6.9% |
| LED Average - without D (2) | | | | -4.9% | -1.3% | -6.2% |

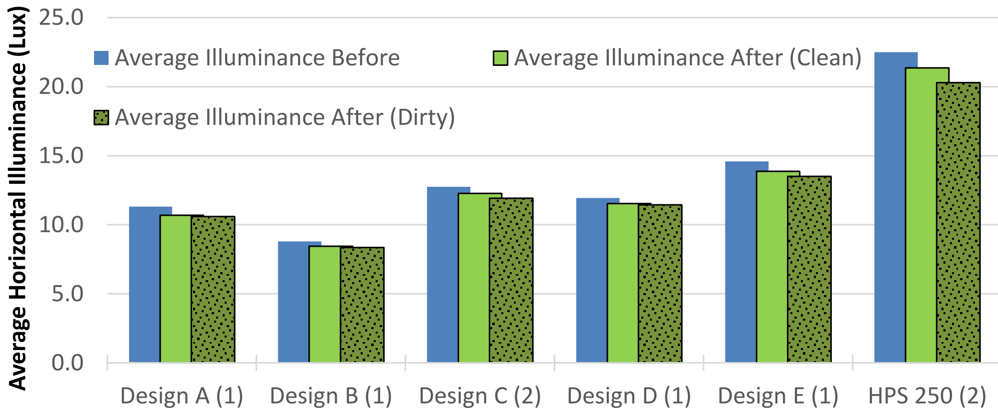



**Figure 41. Average Horizontal Illuminance – Initial Testing and Second Testing**

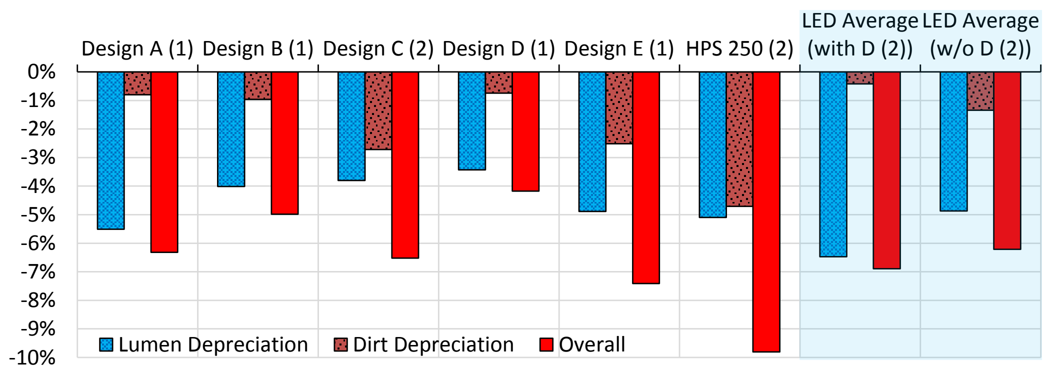



**Figure 42. Light Loss Based on Horizontal Illuminance**

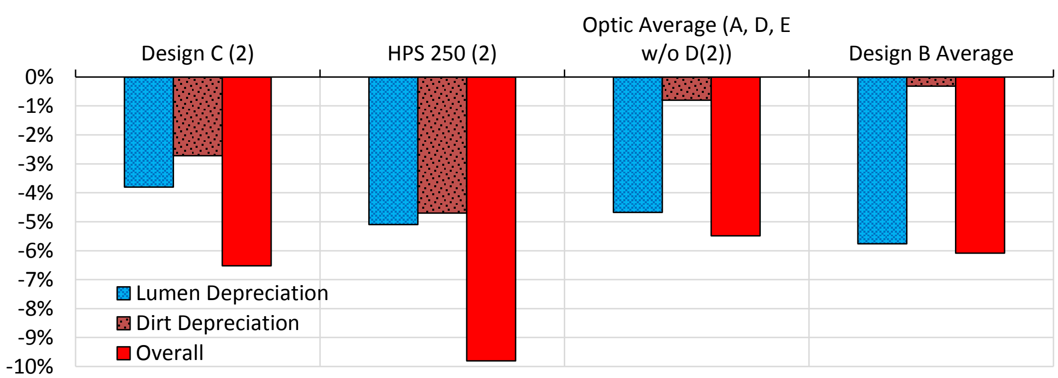



**Figure 43. Comparison of Horizontal Illuminance Loss Among LED Designs**

As the illustrations show, most luminaires showed light losses after the 2 years of field operation. Without considering the outlier (Design D [2]), the results suggested an overall light loss of 6% for the LED luminaires compared to 10% for the HPS system. When looking at the light loss due to dirt accumulated over time, the LED systems had a light loss about 1% compared to 5% for the HPS system. This result was confirmed during visual inspections as well. The warm HPS luminaire attracted a significant number of insects into the housing, and a large number of insect remains were found inside the lens. In contrast the LED systems are much less attractive to insects due to their cooler operating temperature. Their optical assemblies are sealed, and there was only minor dirty accumulation on the outside of their lenses.

When comparing among the different LED designs, the design B luminaires seemed to have the least light loss due to dirt depreciation while the Design C luminaire had the most light loss. On the other hand, the Design B luminaires had the most light loss due to lumen depreciation while Design C had the least lumen depreciation. Note that Design E (1) experienced more dirt depreciation than Design E (2) due to its exposure to more bus traffic.

The seemingly unreasonable results of the LED Design D (2) luminaire were likely due to its unstable light output, as the initial and clean measurements were not comparable to those of the luminaire D (1). Other factors that might have contributed to the results include ambient lighting, luminaire cleaning process, and to a lesser degree, issues with data collection equipment. Note that Luminaire Design D (2) was also installed above the bus route/station in the parking lot, which exposed more significant dirt/dust effect.

Table 9 lists the laboratory testing results for vertical illuminance, and Figure 44 through Figure 46 further illustrate the differences between the vertical illuminance readings of the two rounds of testing and between those of dirty and clean luminaires.

**Table 9. Change in Vertical Illuminance: Laboratory Testing**

| Luminaire | Average Illuminance Before (Lux) | Average Illuminance After (Clean) (Lux) | Average Illuminance After (Dirty) (Lux) | Lumen Depreciation | Dirt Depreciation | Overall Light Loss |
|---|---|---|---|---|---|---|
| Design A (1) | 13.6 | 13.2 | 12.9 | -2.4% | -2.6% | -5.0% |
| Design A (2) | 13.6 | 13.2 | 12.6 | -2.8% | -4.4% | -7.2% |
| Design B (1) | 9.5 | 9.5 | 9.3 | 0.1% | -1.5% | -1.4% |
| Design B (2) | 9.8 | 9.1 | 9.1 | -7.4% | -0.4% | -7.9% |
| Design C (2) | 11.4 | 10.5 | 10.2 | -7.9% | -2.5% | -10.3% |
| Design D (1) | 13.2 | 13.2 | 13.0 | -0.2% | -1.5% | -1.8% |
| Design D (2) | 13.5 | 11.1 | 12.2 | -17.6% | 7.9% | -9.7% |
| Design E (1) | 15.2 | 14.3 | 13.9 | -6.1% | -2.6% | -8.7% |
| Design E (2) | 14.8 | 13.3 | 13.2 | -9.7% | -0.8% | -10.5% |
| HPS 250 (2) | 21.0 | 21.3 | 20.3 | 1.9% | -5.1% | -3.2% |
| Optic Average (A, D, E w/o D(2)) | | | | -4.2% | -2.4% | -6.6% |
| Design B Average | | | | -3.7% | -1.0% | -4.6% |
| LED Average - with D (2) | | | | -5.2% | -1.3% | -6.6% |
| LED Average - without D (2) | | | | -3.8% | -2.4% | -6.2% |

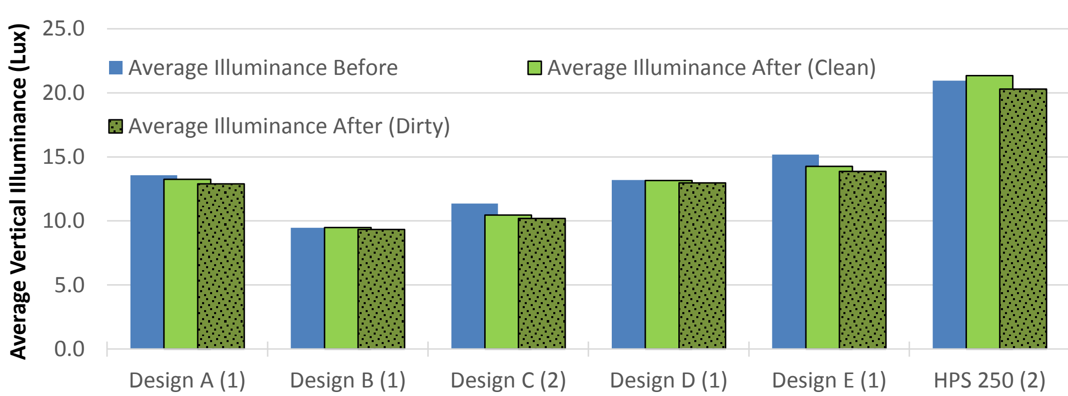



**Figure 44. Average Vertical Illuminance – Initial Testing and Second Testing**

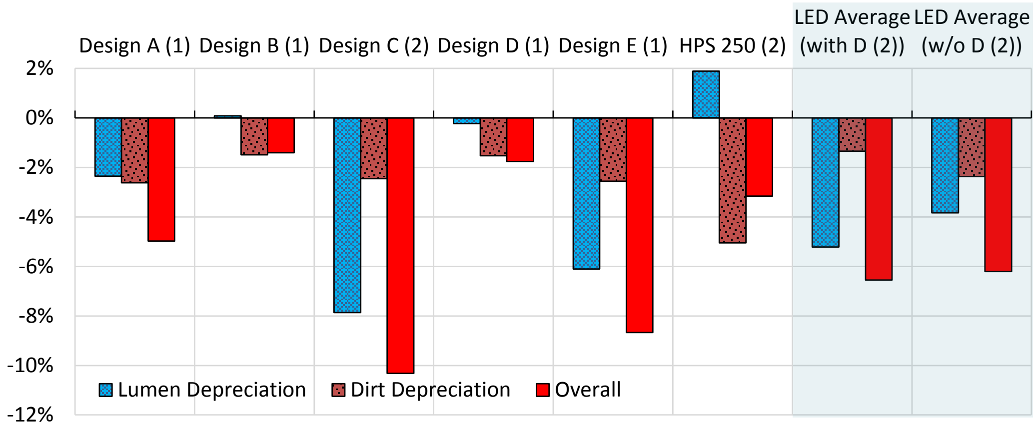



**Figure 45. Light Loss Based on Vertical Illuminance**

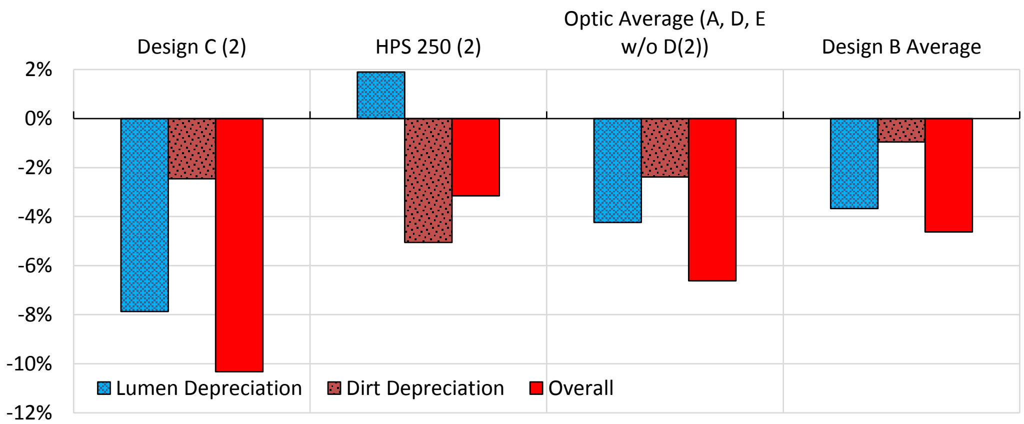



**Figure 46. Comparison of Vertical Illuminance Loss Among LED Designs**

Vertical illuminance results suggested a total of 6% light loss after 2 years of operation for the LED luminaires when accounting a more than 2% dirt depreciation, without considering the outlier D (2) luminaire. Interestingly, the HPS system had a 2% increase in vertical illuminance after 2 years of operation, although the vertical illuminance dirt depreciation was about 5%, comparable to that for horizontal illuminance. This is noteworthy as the light distribution of the luminaire is changed with a reduction in horizontal illuminance at the extents of the light distribution can cause an increase in the vertical illuminance.

Comparing the results for vertical and horizontal illuminance measurements, the lab testing results suggested somewhat different horizontal and vertical illuminating performance. In terms of the LED luminaires, the dirt depreciation effect had seemingly greater impact on vertical illuminance than on horizontal illuminance (2.4% versus 1.3%). When comparing among the different LED designs, dirt depreciation had a less significant impact on the Design B luminaires.

## Dirt Depreciation Distribution

To better understand the impact of dirt depreciation on the luminaires, the research team compared the light distribution of each luminaire before and after cleaning the lenses. Figure 47 through Figure 52 illustrate how dirt depreciation on horizontal illuminance for each luminaire is distributed over the laboratory grid using the ratio of dirty lens illuminance to clean lens illuminance.

The figures suggest that for the HPS luminaire, dirt depreciation primarily reduced the horizontal illuminance of the central area and the areas on the right and left sides. This result clearly demonstrates how dirt particles on the large lens reflected light from a central source. The dirt depreciation impact for the Design C LED luminaires (large LED sources enclosed by a large, flat lens) closely resembles that for the HPS luminaires, suggesting similar characteristics between the two types of luminaires in terms of dirt depreciation. For Designs A, D, and E LED luminaires with optic arrays, the dirt depreciation in general resulted in slightly higher horizontal illuminance levels in the central area while lower horizontal illuminance everywhere else. This phenomenon was found more evident for Design A, which seemed to attributable to its concave LED optic array design. For Design B Luminaires, on the other hand, dirt depreciation resulted in relatively uniform decrease of horizontal illuminance across the laboratory grid. Note that Design B luminaires had large LED sources symmetrically folding towards each other, therefore cancelling out to a certain extent the dirt reflection impact caused by each individual LED panel.

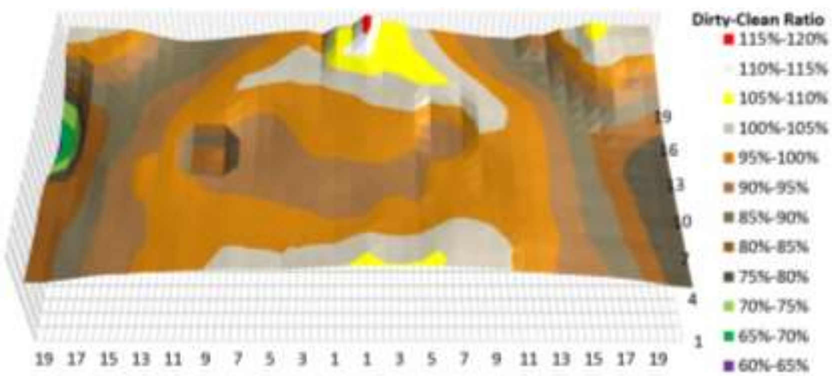



**Figure 47. Dirt Depreciation Distribution - HPS 250W (2)**

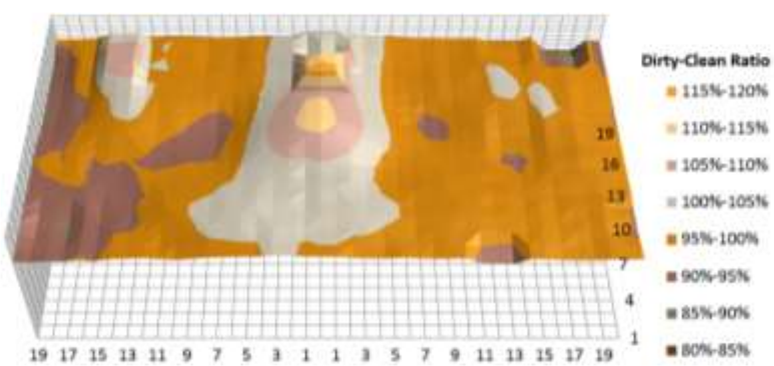



**Figure 48. Dirt Depreciation Distribution – Design A (1)**

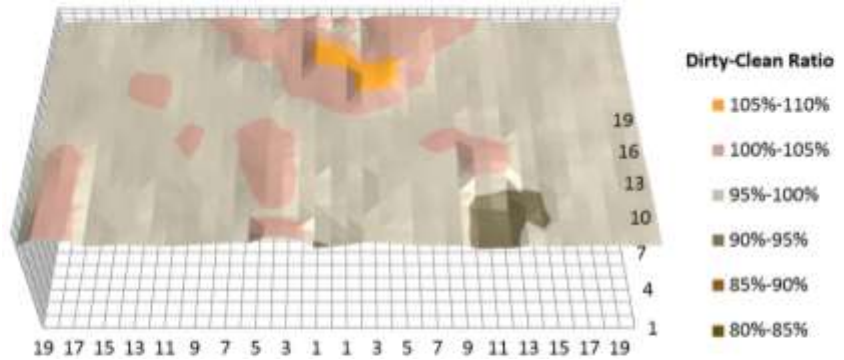


Figure 49. Dirt Depreciation Distribution – Design B (1)

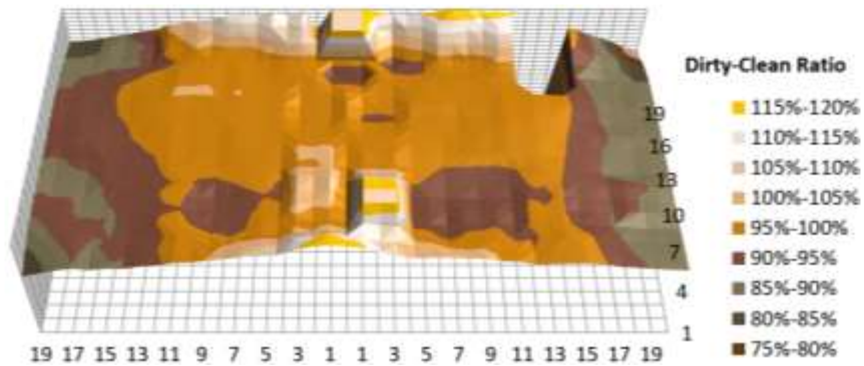


Figure 50. Dirt Depreciation Distribution – Design C (2)

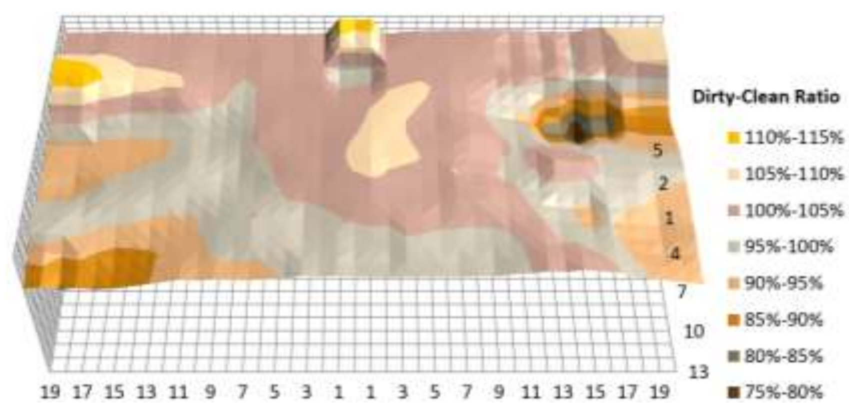


Figure 51. Dirt Depreciation Distribution – Design D (1)

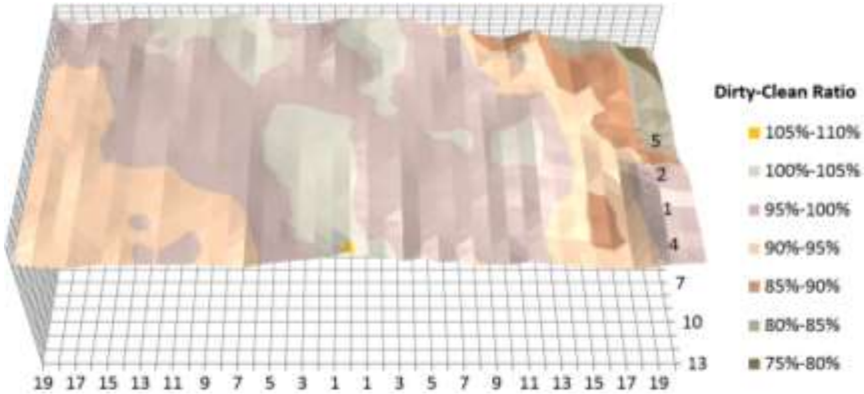



**Figure 52. Dirt Depreciation Distribution – Design E (1)**

## Spectral Power Distribution

Figure 53 through Figure 58 show the SPD curves for each type of luminaires, respectively. As the figures illustrate, the relative intensity of the yellowish light (wavelength between 500 and 600 nm) for most LED luminaires seemingly decreased after the 2 years' operation. According to the data, the accumulated dirt over the 2 years' operation affected the SPD of the LED Design C and E more. In both cases, the dirt tended to increase the output of the yellowish light (wavelength between 500 and 600 nm) in the spectrum.

In terms of the HPS system, the second lab testing results showed that the relative output of the reddish light (i.e., wavelength greater than 600 nm) increased after 2 years' operation. In addition, the accumulated dirt on the luminaire lens seemingly delayed this trend based on the results.

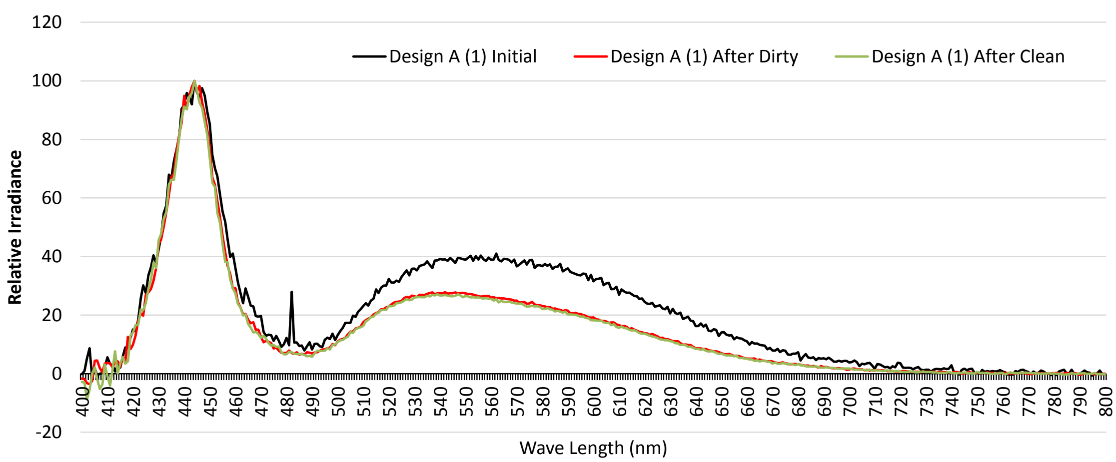



**Figure 53. Before and After Spectral Power Distribution – Design A**

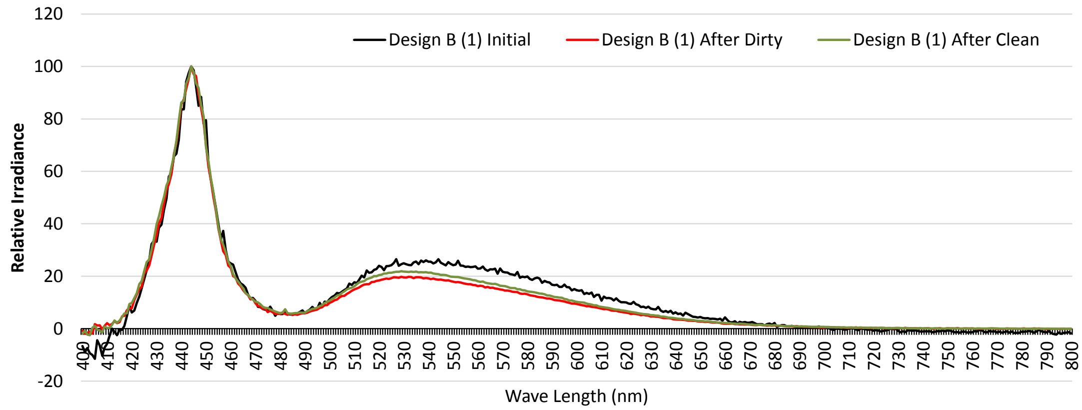



**Figure 54. Before and After Spectral Power Distribution – Design B**

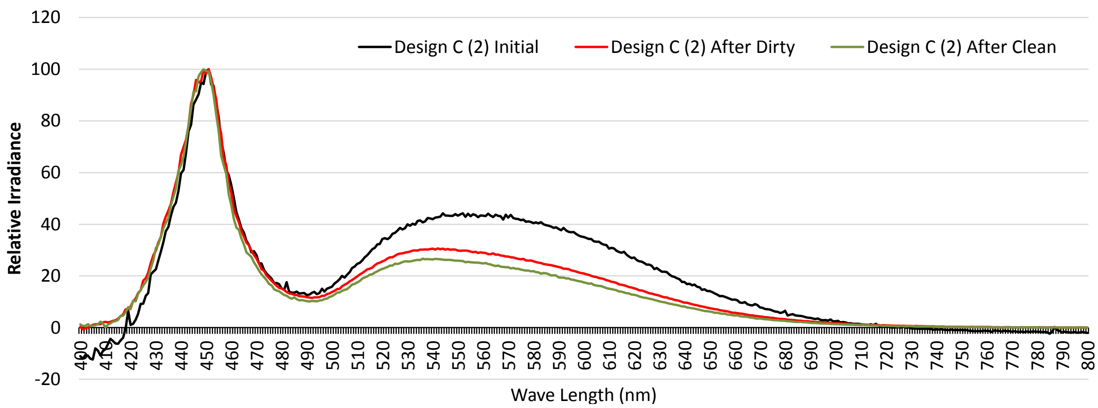



**Figure 55. Before and After Spectral Power Distribution – Design C**

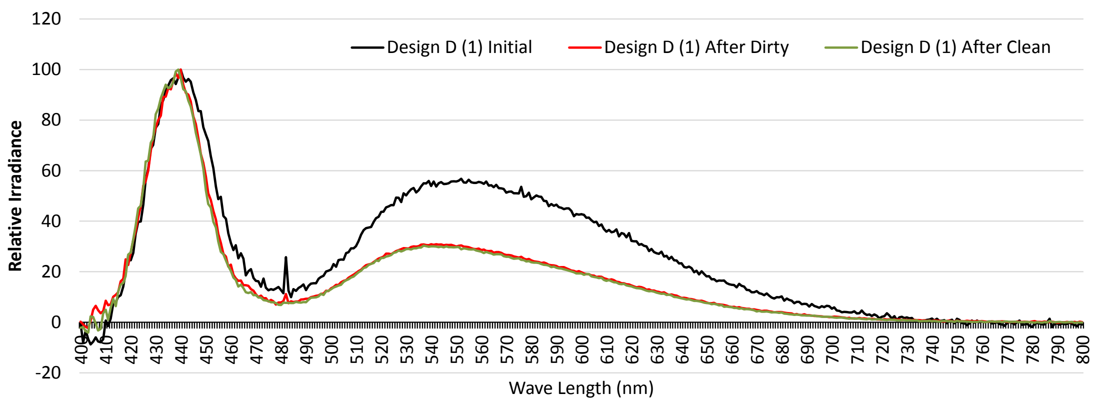



**Figure 56. Before and After Spectral Power Distribution – Design D**

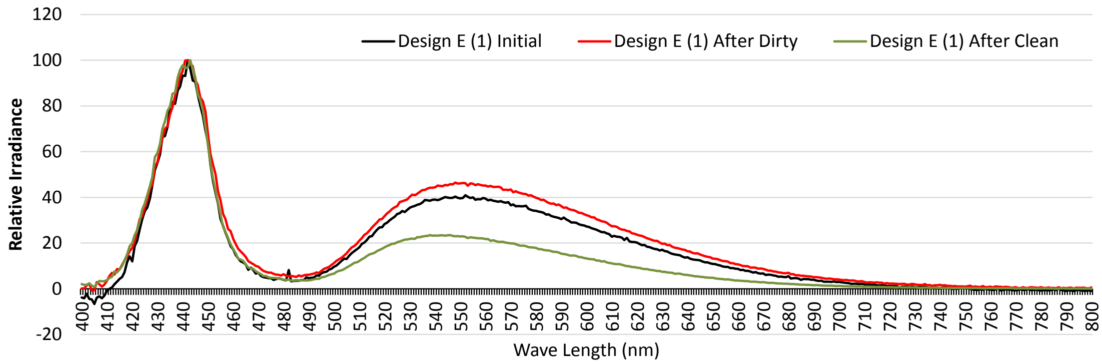



**Figure 57. Before and After Spectral Power Distribution – Design E**

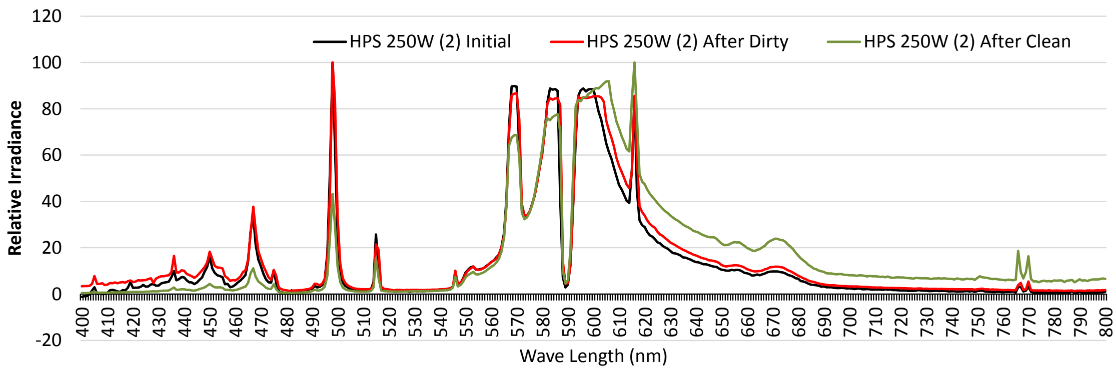



**Figure 58. Before and After Spectral Power Distribution – HPS**

## Power Consumption and Efficacy

Figure 59 and Figure 60 compare the before and after power consumption and measured efficacy, respectively, followed by the detailed values in Table 10. As Figure 59 suggests, most LED luminaires did not have significant changes in power consumption after 2 years of operation. The measured wattages for some LED luminaires even decreased. The measured wattage of the HPS luminaire, however, increased by a non-trivial percentage after 2 years of usage. Notice that the power consumption for the LED Design D (2) luminaire measured during the second lab testing was significantly lower than its initial wattage. This wattage decrease coincided with a significant decrease in light output as observed previously.

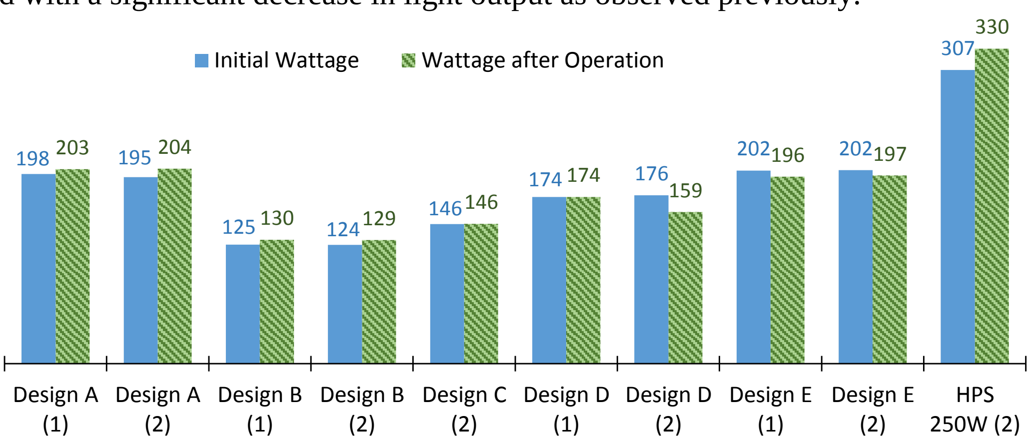



**Figure 59. Initial and After Power Consumption (Including Drivers)**

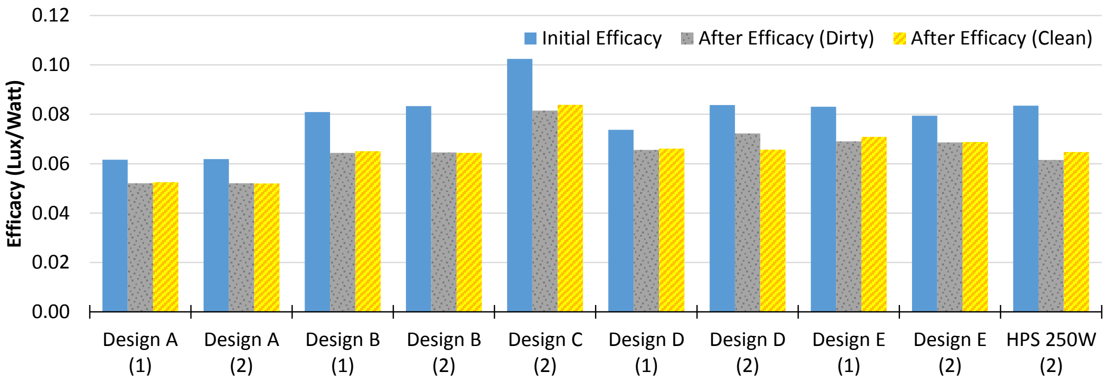



**Figure 60. Initial and After Efficacy**

**Table 10. Lab Measured Before and After Power Consumption and Efficacy**

| Luminaire | Rated Wattage | Initial Wattage | Wattage after Operation | | Initial Efficacy | After Efficacy (Dirty) | | After Efficacy (Clean) | |
|---|---|---|---|---|---|---|---|---|---|
| Design A (1) | 195 | 198.4 | 203.4 | 2.5% | 0.06 | 0.05 | -15.4% | 0.05 | -14.7% |
| Design A (2) | 195 | 195.1 | 204.0 | 4.6% | 0.06 | 0.05 | -15.7% | 0.05 | -15.9% |
| Design B (1) | 120 | 124.6 | 129.7 | 4.1% | 0.08 | 0.06 | -20.4% | 0.07 | -19.6% |
| Design B (2) | 120 | 124.2 | 129.4 | 4.2% | 0.08 | 0.06 | -22.5% | 0.06 | -22.8% |
| Design C (2) | 148 | 146.0 | 146.3 | 0.2% | 0.10 | 0.08 | -20.4% | 0.08 | -18.1% |
| Design D (1) | 150 | 174.3 | 174.4 | 0.1% | 0.07 | 0.07 | -11.0% | 0.07 | -10.3% |
| Design D (2) | 150 | 176.3 | 158.7 | -10.0% | 0.08 | 0.07 | -13.8% | 0.07 | -21.6% |
| Design E (1) | 200 | 202.1 | 195.8 | -3.1% | 0.08 | 0.07 | -16.9% | 0.07 | -14.6% |
| Design E (2) | 200 | 202.4 | 196.8 | -2.8% | 0.08 | 0.07 | -13.6% | 0.07 | -13.4% |
| LED Average | | | | 0.0% | 0.08 | 0.07 | -16.6% | 0.07 | -16.8% |
| HPS 250W (2) | 250 | 307.3 | 329.7 | 7.3% | 0.08 | 0.06 | -26.3% | 0.06 | -22.4% |

When combining changes in horizontal illuminance and wattages, the calculated luminaire efficacies for most luminaires decreased after 2 years of operation. When comparing between HPS and LED luminaires, the data suggested that the efficacy of the HPS luminaire decreased almost 10% more than that of LED luminaires without cleaning their lenses.

## Field Horizontal Illuminance

The research team took horizontal illuminance measurements over the field grid during each site visit. Table 11 and Figure 61 illustrate the mean horizontal illuminance values over the field grid for all light systems. Figure 62 through Figure 67 compare the field horizontal illuminance values of different luminaires along the 0-meter grid line (i.e., directly under the luminaires. Figure 68 shows the changes of light output for the evaluated LED systems based on the field testing data in an effort to understand the overall light loss factor of the LED technology. All readings shown in the illustrations have been corrected for ambient lighting and temperature impacts. Note that this analysis focused on the illuminance changes over time of different LED designs. The absolute illuminance values were based on a custom grid that may not necessarily meet lighting design requirements.

**Table 11. Mean Horizontal Illuminance Measurements on Field Grid**

| Date | Mean Horizontal Illuminance (Lux) and Percent Illuminance Change Against 2012/09 Value | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Design A (1) | | Design B (1) | | Design C (1) | | Design D (1) | | Design E (1) | | HPS 250W | |
| 2012/09 | 9.4 | 0% | 9.17 | 0% | 16.23 | 0% | 11.97 | 0% | 13.93 | 0% | 23.63 | 0% |
| 2012/12 | 10.17 | 8.2% | 9.83 | 7.2% | 16.89 | 4.1% | 12.27 | 2.5% | 14.12 | 1.4% | 25.45 | 7.7% |
| 2013/03 | 9.77 | 3.9% | 9.19 | 0.2% | 16.11 | -0.7% | 10.58 | -11.6% | 13.2 | -5.2% | 27.33 | 15.7% |
| 2013/06 | 9.67 | 2.9% | 9.48 | 3.4% | 16.08 | -0.9% | 12.05 | 0.7% | 13.48 | -3.2% | 26.56 | 12.4% |
| 2013/09 | 9.37 | -0.3% | 10.12 | 10.4% | 16.1 | -0.8% | 11.38 | -4.9% | 13.41 | -3.7% | n/a | n/a |
| 2013/12 | 10.5 | 11.7% | 10.13 | 10.5% | 17.22 | 6.1% | 10.41 | -13.0% | 14.68 | 5.4% | 27.48 | 16.3% |
| 2014/03 | 10.18 | 8.3% | 9.85 | 7.4% | 16.94 | 4.4% | 10.65 | -11.0% | 13.04 | -6.4% | 28.34 | 19.9% |
| 2014/06 | 8.29 | -11.8% | 8.35 | -8.9% | 13.78 | -15.1% | 10.9 | -8.9% | 12.02 | -13.7% | 24.88 | 5.3% |
| 2014/09 | 9.27 | -1.4% | 8.89 | -3.1% | 15.26 | -6.0% | 11.78 | -1.6% | 13.76 | -1.2% | 26.71 | 13.0% |

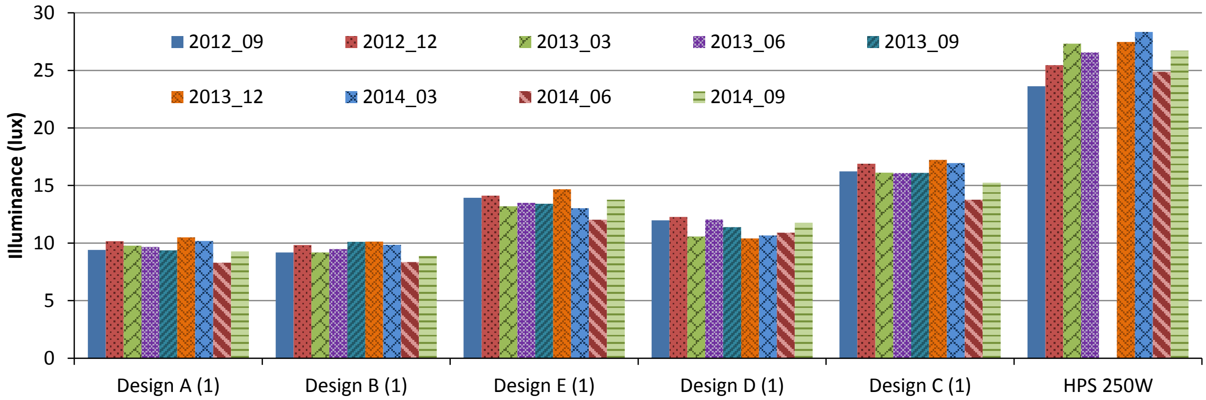



**Figure 61. Average Horizontal Illuminance on Field Grid**

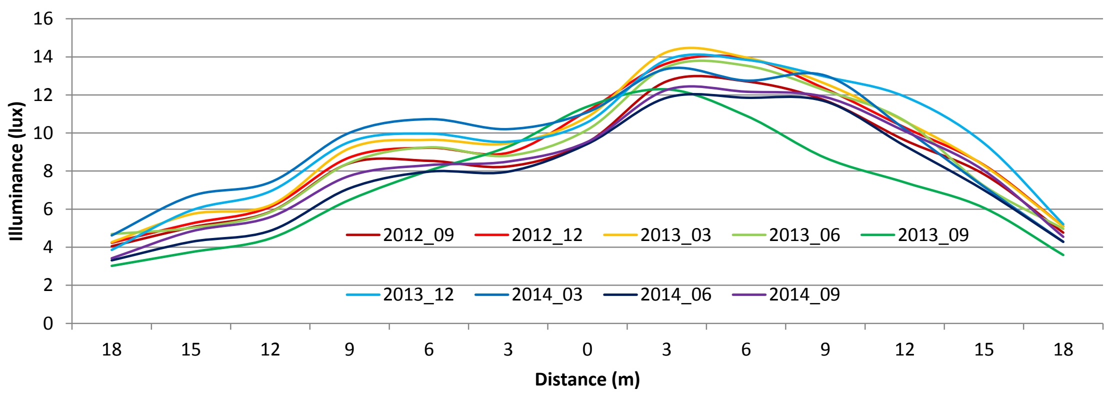



**Figure 62. Field Horizontal Illuminance Along 0-Meter Grid Line – Design A (1)**

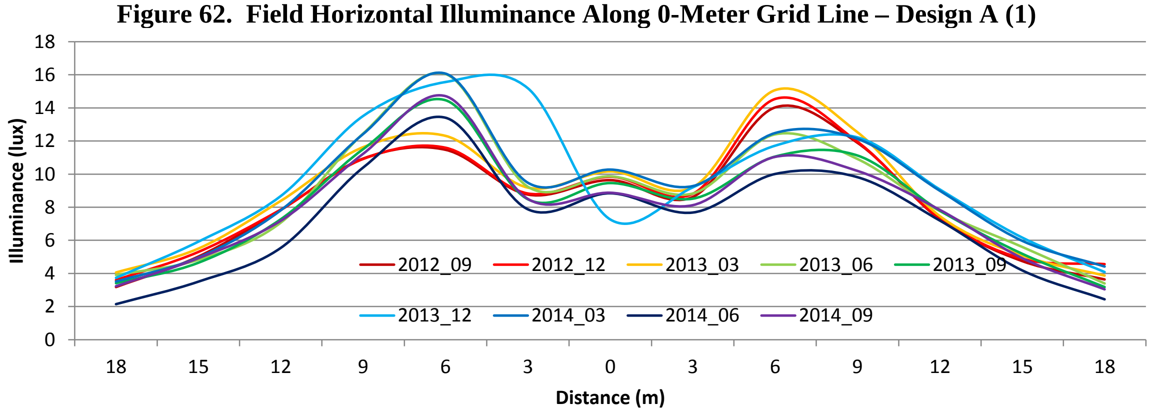



**Figure 63. Field Horizontal Illuminance Along 0-Meter Grid Line – Design B (1)**

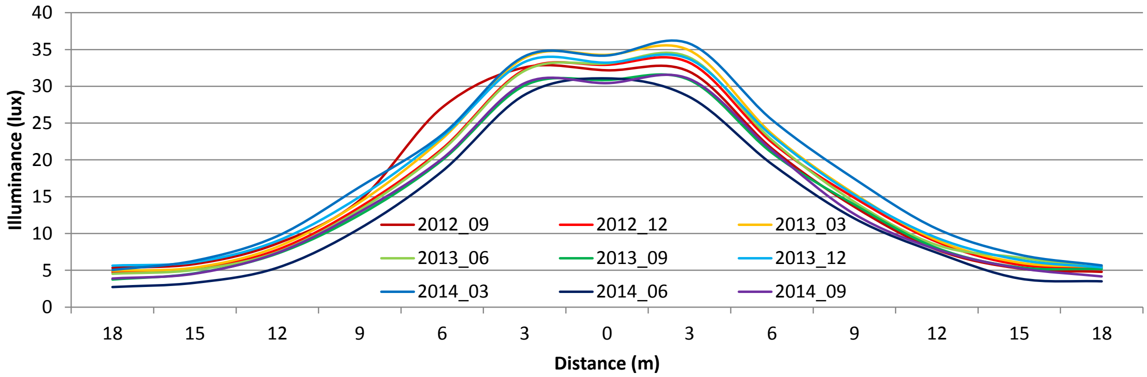



**Figure 64. Field Horizontal Illuminance Along 0-Meter Grid Line – Design C (1)**

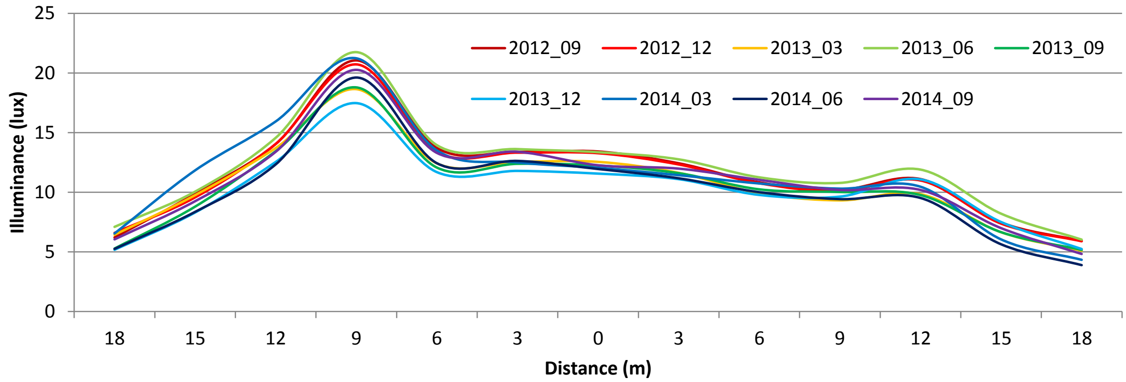



**Figure 65. Field Horizontal Illuminance Along 0-Meter Grid Line – Design D (1)**

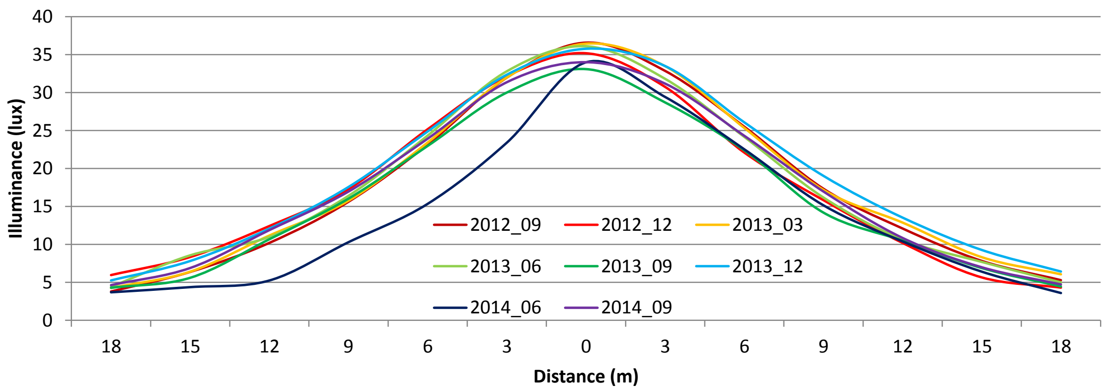



**Figure 66. Field Horizontal Illuminance Along 0-Meter Grid Line – Design E (1)**

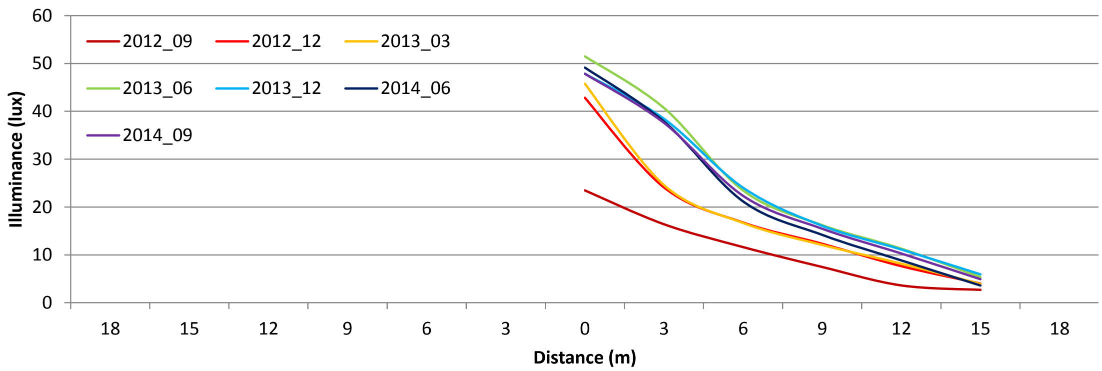



**Figure 67. Field Horizontal Illuminance Along 0-Meter Grid Line – HPS 250W**

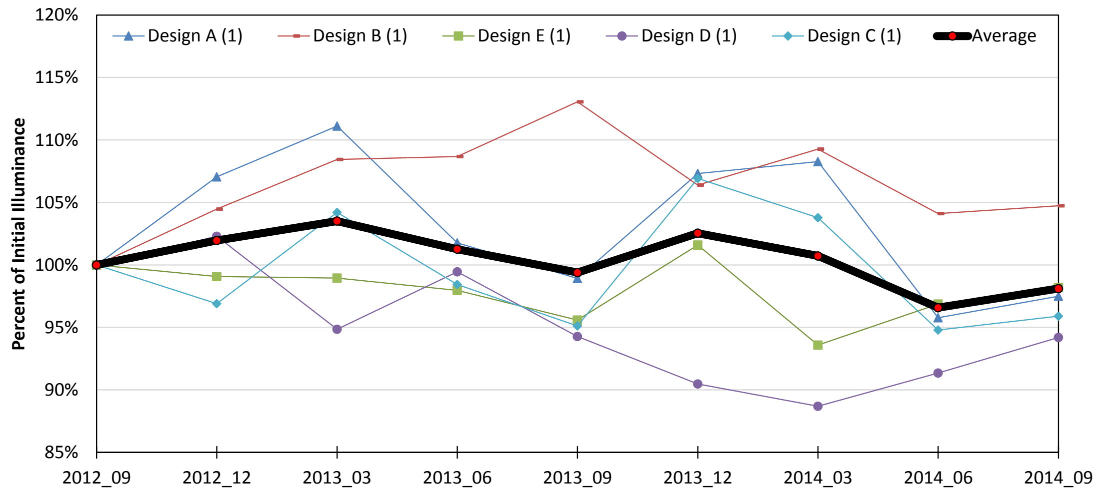
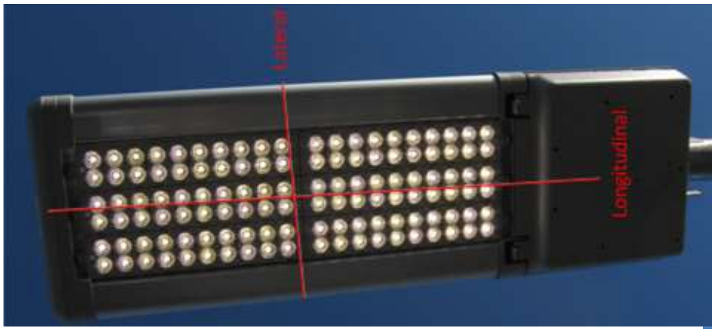



**Figure 68. Changes in Light Output for LED Luminaires During Field Testing**

Based on the field horizontal illuminance data, the researchers could not conclude a clear trend in significant light reduction over the 2-year field evaluation period. Note that Figure 62 and Figure 63 suggest that horizontal light distribution of the LED Design A and B luminaires changed over time in the field. This phenomenon might be due to tilt/roll of the luminaires over time and/or irregular changes of the performance of luminaire LED optics.

One aspect that impacted the horizontal illuminance readings (including their uniformity and symmetry) of the luminaires was how the luminaire was initially installed in terms of its orientation and tilt (levelness). This factor also affected the vertical illuminance results as discussed in the following sections. Due to human factors and available lighting fixture characteristics, not all luminaires were installed perfectly level. Figure 69 shows the orientation of the evaluated luminaires that can be used to better understand the horizontal illuminance measurements. Notice that the luminaire found to be installed in the least level orientation was the Design A (1) luminaire (Figure 70).




| | Tilt (°) | Roll (°) |
|---|---|---|
| Design A (1) | 9 | 2 |
| Design B (1) | 2 | 1 |
| Design C (1) | 0 | 0 |
| Design D (1) | 0 | 0 |
| Design E (1) | 0 | 6 |

**Figure 69. Luminaire Orientation Measurements**

**Figure 70. Field Luminaire Orientation – Design A (1)**

## Field Vertical Illuminance

Table 12 and Figure 71 show the average vertical illuminance values along the field grid used for evaluation. Figure 72 through Figure 77 further illustrate the vertical illuminance values along the 0-meter grid line in the field. The figures suggest that, other than Design B, most LED luminaires in general exhibited decreasing vertical illuminance levels over time. As Table 12 shows, the overall vertical illuminance reduction during the 2 years of operation was around 10% for most LED luminaires. The only exception for this trend was the Design B luminaire, which had a three-panel folding design with the central panel facing directly downwards and the other two folding towards the center. These observations may suggest that dirt depreciation has a more significant impact on vertical illuminance than on horizontal illuminance, which is consistent with the lab testing results.

Field vertical illuminance analysis did not reveal noticeable changes in vertical illuminance distribution. Figure 72 through Figure 77 also suggested that the vertical illuminance distribution along the 0-meter grid line (i.e., underneath the luminaire) maintained the same pattern in most cases over the 2 years.

**Table 12. Mean Vertical Illuminance Measurements on Field Grid**

| Date | Mean Vertical Illuminance on Field Grid (Lux) | | | | | |
|---|---|---|---|---|---|---|
| | Design A (1) | Design B (1) | Design C (1) | Design D (1) | Design E (1) | HPS 250W |
| 2012/09 | 9.5 | 8.6 | 11.6 | 12.9 | 12.6 | 17.2 |
| 2012/12 | 10.1 | 8.9 | 11.1 | 13.0 | 12.3 | 17.3 |
| 2013/03 | 9.9 | 8.7 | 11.3 | 11.5 | 11.7 | 17.8 |
| 2013/06 | 9.5 | 9.1 | 11.2 | 12.6 | 12.1 | 18.6 |
| 2013/09 | 9.5 | 9.8 | 11.1 | 12.3 | 12.1 | - |
| 2013/12 | 9.6 | 8.6 | 11.6 | 11.0 | 12.0 | 16.1 |
| 2014/03 | 9.6 | 8.7 | 11.3 | 10.7 | 11.0 | 17.4 |
| 2014/06 | 8.5 | 8.3 | 10.4 | 11.2 | 11.6 | 16.7 |
| 2014/09 | 8.6 | 8.3 | 10.3 | 11.4 | 11.5 | 17.3 |
| 2-Year Change | -10.1% | -3.5% | -10.8% | -12.0% | -8.2% | 0.3% |

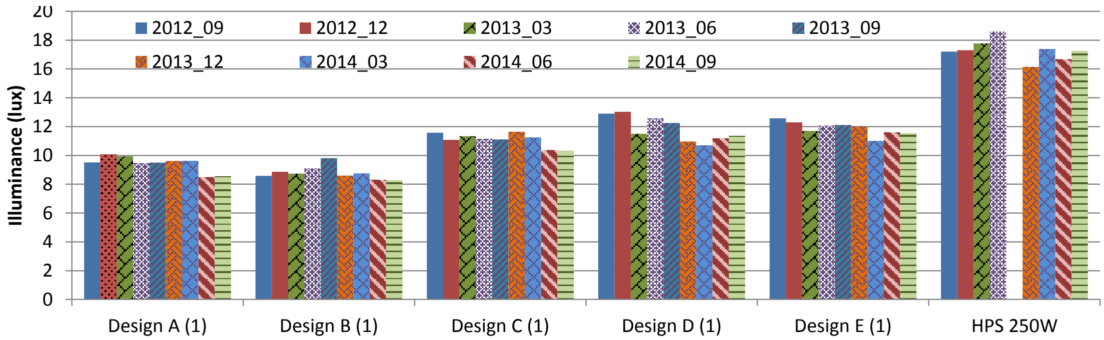



**Figure 71. Mean Vertical Illuminance on Field Grid**

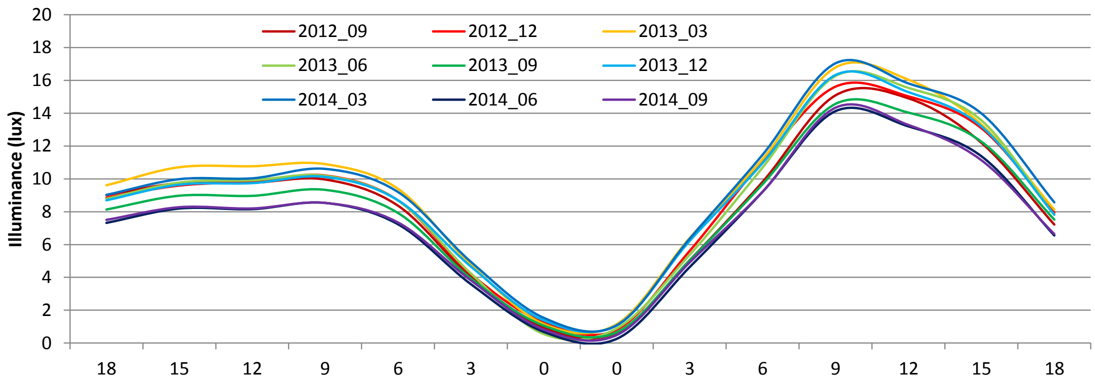



**Figure 72. Field Vertical Illuminance Along 0-Meter Grid Line – Design A (1)**

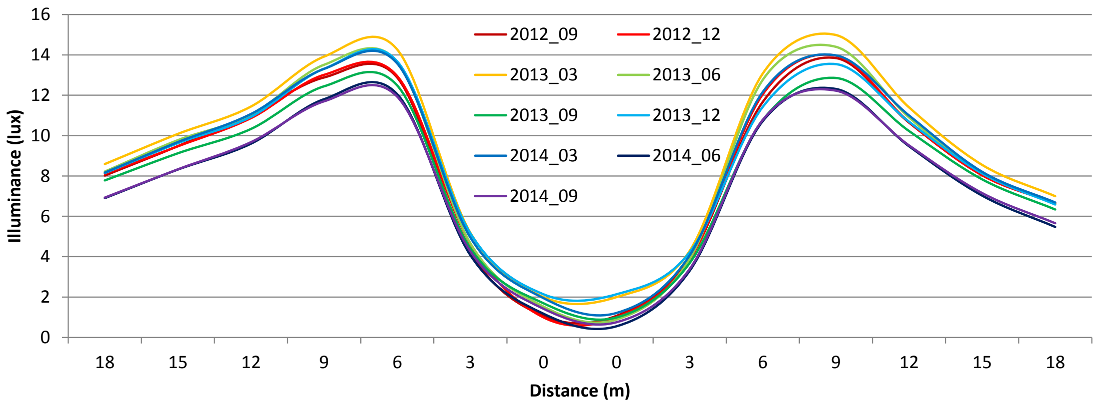



**Figure 73. Field Vertical Illuminance Along 0-Meter Grid Line – Design B (1)**

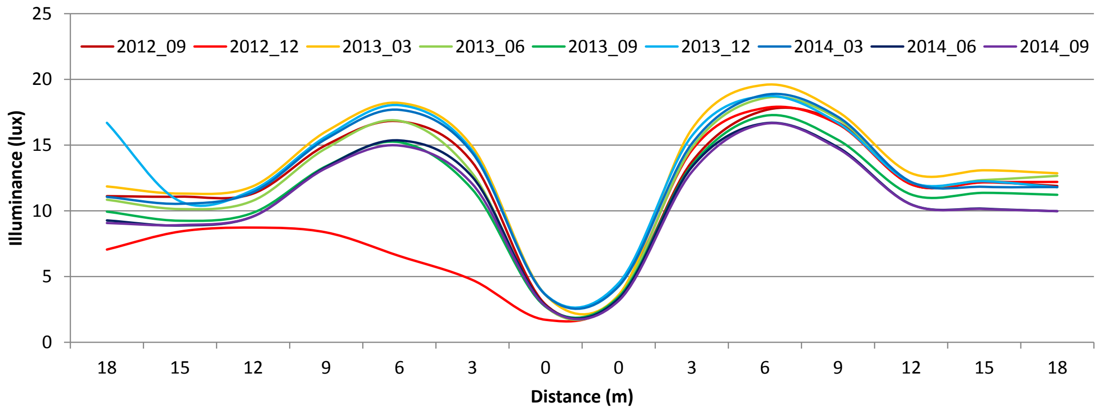



**Figure 74. Field Vertical Illuminance Along 0-Meter Grid Line – Design C (1)**

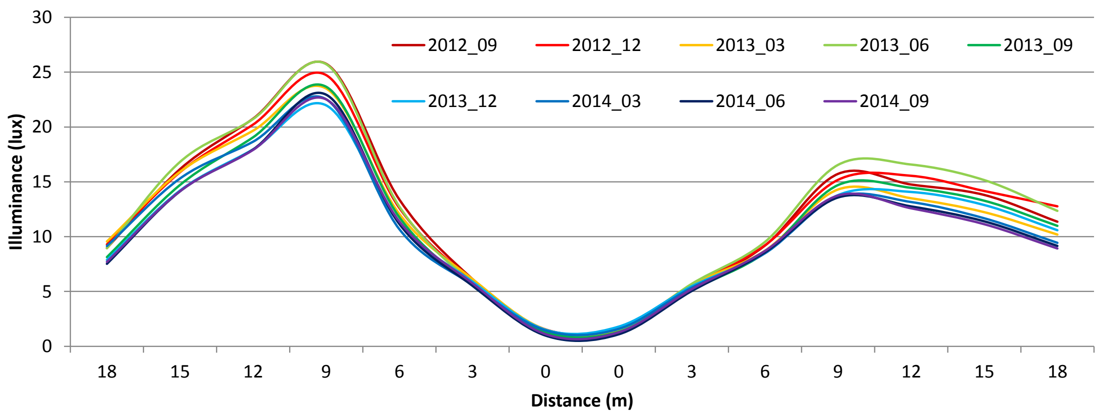



**Figure 75. Field Vertical Illuminance Along 0-Meter Grid Line – Design D (1)**

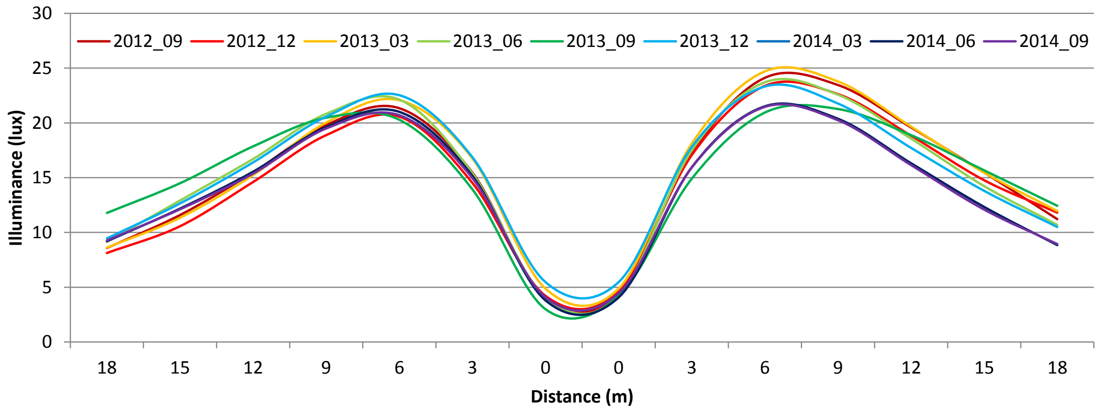



**Figure 76. Field Vertical Illuminance Along 0-Meter Grid Line – Design E (1)**

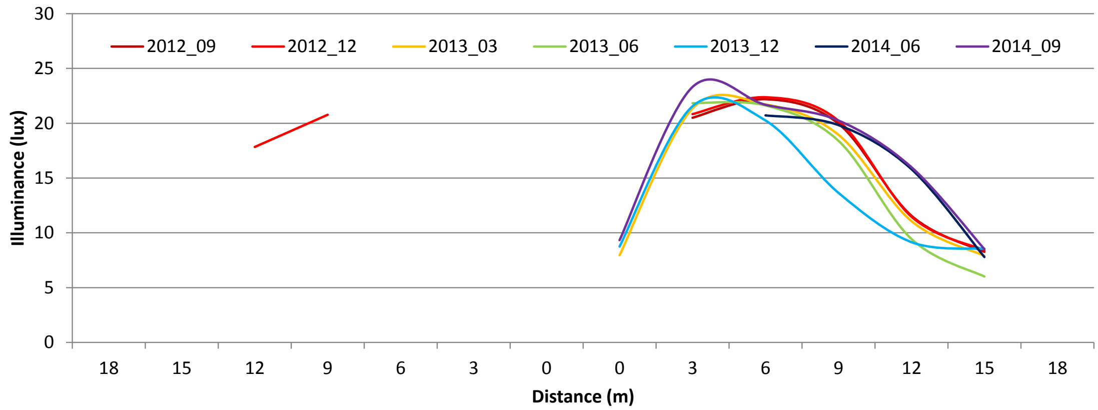



**Figure 77. Field Vertical Illuminance Along 0-Meter Grid Line – HPS 250W**

## Correlated Color Temperature

The color temperature of the electromagnetic radiation emitted from an ideal black body is defined as its surface temperature in Kelvin. LEDs emit light primarily by processes other than thermal radiation and the emitted radiation does not follow the form of a black-body spectrum. The lighting community uses CCT as a standard for comparing the color of LED light sources. CCT is the color temperature of a black-body radiator which to human color perception most closely matches the subject LED light.

Table 13 and Figure 78 compare the manufacturer-rated CCTs with the CCTs measured during the field evaluation. It is important to note that the Design B luminaires had a higher rated CCT than the other designs. The data showed that most LED luminaire systems exhibited CCTs consistent with the manufacturer specifications. The Design B luminaire was the only one that resulted in measured CCTs not consistent with the specification. It is important to note that LEDs with higher CCT typically have a higher light output than those with a lower CCT due to the efficiency of the phosphor in the LED chip. Typically, a 6500K luminaire would not be compared to a 4100 K luminaire.

The field measurements also seemed to suggest that most LED luminaires had moderately decreasing CCTs and become slightly more yellowish/reddish over time (Figure 79) over time.

**Table 13. Specified and Measured CCTs for Evaluated LED Luminaires**

| Luminaire | Specification CCT (K) | 12-Sep | 13-Jun | 13-Sep | 13-Dec | 14-Mar | 14-Jun | 14-Sep | 2-Year Change |
|---|---|---|---|---|---|---|---|---|---|
| Design A (1) | 4300 | 4331 | 4276 | 4295 | 4253 | 4188 | 4159 | 4091 | -5.5% |
| Design B (1) | 5000+/-300 | 6501 | 5881 | 6404 | 6381 | 6148 | 6169 | 5974 | -8.1% |
| Design C (1) | 4000 | 4394 | 4427 | 4549 | 4325 | 4352 | 4373 | 4306 | -2.0% |
| Design D (1) | 4000 | 4135 | 4080 | 4108 | 4076 | 4035 | 4053 | 4012 | -3.0% |
| Design E (1) | 4000 | 4390 | 4355 | 4368 | 4323 | 4342 | 4302 | 4206 | -4.2% |

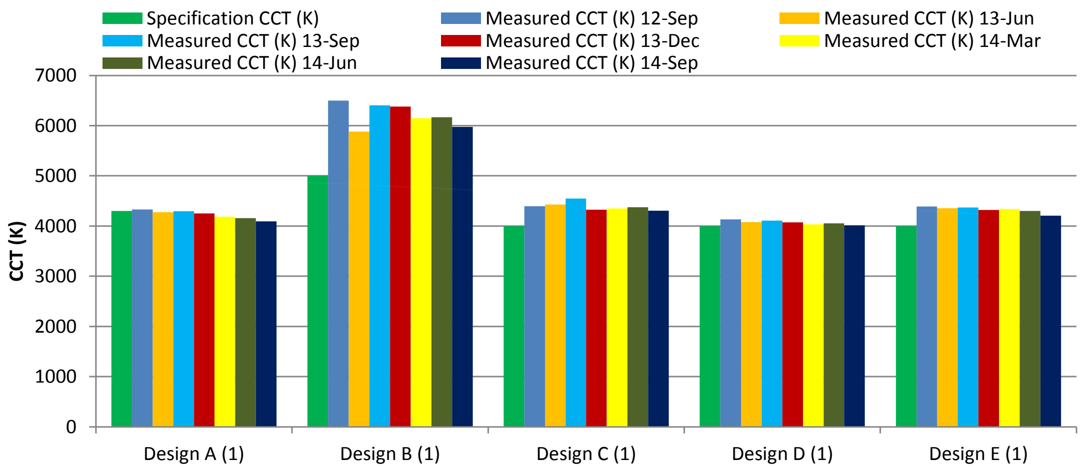



**Figure 78. Specified and Measured CCTs for Evaluated LED Luminaire Systems**

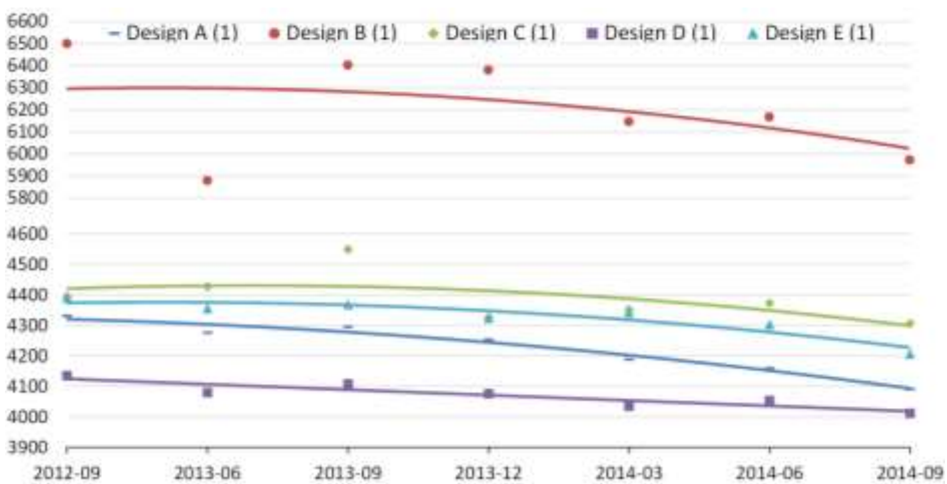



**Figure 79. CCT Trendlines (Polynomial) During First 2 Years of Operation**

## Field Luminaire Inspection

During each field trip, the research team also conducted a thorough inspection of the evaluated luminaires. The field inspection of the luminaires included visual inspection of exterior and interior conditions of the luminaire housing and measuring the luminaire temperature.

### Visual Inspection

Upon visual inspection of the luminaires beginning in the December 2012 data collection, comments were made regarding dirt buildup as well as other factors (these are the same luminaires that were selected for the detailed photometric analysis, not all of the luminaires). A summary of the visual inspection findings is shown in Table 14.

**Table 14. Visual Inspection Comments**

| Category | Design A (1) | Design B (1) | Design C (1) | Design D (1) | Design E (1) | HPS 250W |
|---|---|---|---|---|---|---|
| Wildlife intrusion device installed | No | Yes | No | No | Yes | No |
| Level of presence of wildlife (e.g., Insects) | Low | High | Medium | Medium | Medium | Low |
| Level of rust in component housing | Low | Low | High | Low | Medium | Low |
| Level of dirt inside component housing | Low | Low | Medium | Low | Low | Low |
| Level of dirt buildup on optics cover | Low | Low | Medium | Low | Low | High |
| Level of damage to electrical components | Low | Low | Low | Low | Low | Low |

The visual inspection suggested that a number of luminaire systems did not have a wildlife intrusion device installed. Over time, some of the evaluated luminaire exhibited dirt accumulation and/or wildlife intrusion both in and out of the luminaire housing units. It should be noted that even with luminaires with intrusion devices, wildlife and dirt were still found in the luminaires. Figure 80 shows examples of such issues identified during field visual inspections.

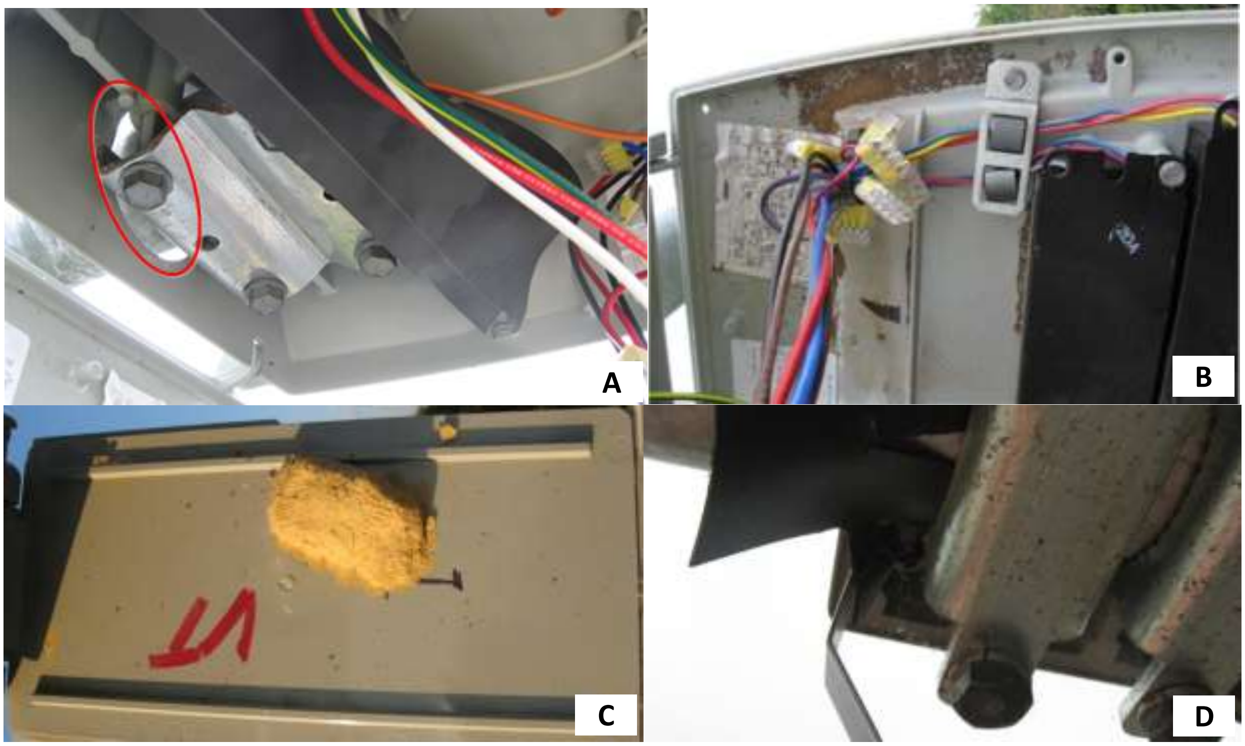



**Figure 80. Examples of Lack of Ingress Protection on Housing – Design C. A: Large opening around tenon; B: Rust on housing door; C: Dirt/wildlife on housing door; D: Rust/wildlife in housing.**

## Cost-Benefit Analysis Results

Table 15 and Figure 81 show the total annual and accumulative lighting maintenance and operational costs predicted for a 25-year horizon for all scenarios, including a base scenario that assumed no HPS systems would be converted to LED in the next 25 years. The results suggested that the investment would be returned (compared to the base scenario) in the 8th year for all scenarios, although scenario S2 (the existing HPS systems are converted over 5 years) corresponded with the shortest investment return time (as noted in bold in Table 15). Over the 25-year analysis period, the return-on-investment (ROI) for the different scenarios ranged between 3.25 and 5.76, with 3.25 projected for scenario 1; 4.45 for the 5-year replacement scenario; and 5.76 for the 10-year replacement scenario. ROI in this context is defined as the ratio between the total accumulative cost savings over the 25-year period and the cost of purchasing LED luminaires.

Table 15. Total Accumulative Lighting Costs for All Scenarios ($millions, 2015)

| Year | Total Accumulative Cost-Base (only HPS) (based on Eq. 1 - 3) | Total Accumulative Cost-S1 (based on Eq. 4 – 7) | Total Accumulative Cost-S2 (based on Eq. 8 – 11) | Total Accumulative Cost-S3 (based on Eq. 12 – 15) |
|---|---|---|---|---|
| 1 | 21.62 | 55.15 | 28.00 | 24.61 |
| 2 | 43.68 | 71.97 | 54.34 | 48.60 |
| 3 | 66.17 | 89.13 | 79.13 | 72.03 |
| 4 | 89.12 | 106.64 | 102.49 | 94.97 |
| 5 | 112.52 | 124.49 | 124.49 | 117.45 |
| 6 | 136.39 | 142.70 | 142.48 | 139.51 |
| 7 | 160.74 | 161.28 | 160.83 | 161.16 |
| **8** | 185.58 | **180.22** | **179.54** | **182.41** |
| 9 | 210.91 | 199.55 | 198.64 | 203.27 |
| 10 | 236.75 | 219.26 | 218.11 | 223.74 |
| 11 | 263.11 | 239.36 | 237.97 | 243.37 |
| 12 | 289.99 | 259.87 | 258.23 | 263.40 |
| 13 | 317.42 | 280.79 | 278.90 | 283.82 |
| 14 | 345.39 | 302.13 | 299.98 | 304.66 |
| 15 | 373.92 | 323.89 | 321.48 | 325.91 |
| 16 | 403.02 | 346.09 | 343.41 | 347.58 |
| 17 | 432.70 | 368.73 | 365.78 | 369.69 |
| 18 | 462.97 | 391.83 | 388.59 | 392.25 |
| 19 | 493.85 | 415.38 | 411.87 | 415.25 |
| 20 | 525.35 | 439.41 | 435.61 | 438.71 |
| 21 | 557.48 | 463.92 | 459.82 | 462.64 |
| 22 | 590.25 | 488.92 | 484.52 | 487.05 |
| 23 | 623.68 | 514.42 | 509.71 | 511.95 |
| 24 | 657.78 | 540.43 | 535.40 | 537.35 |
| 25 | 692.55 | 566.96 | 561.61 | 563.26 |

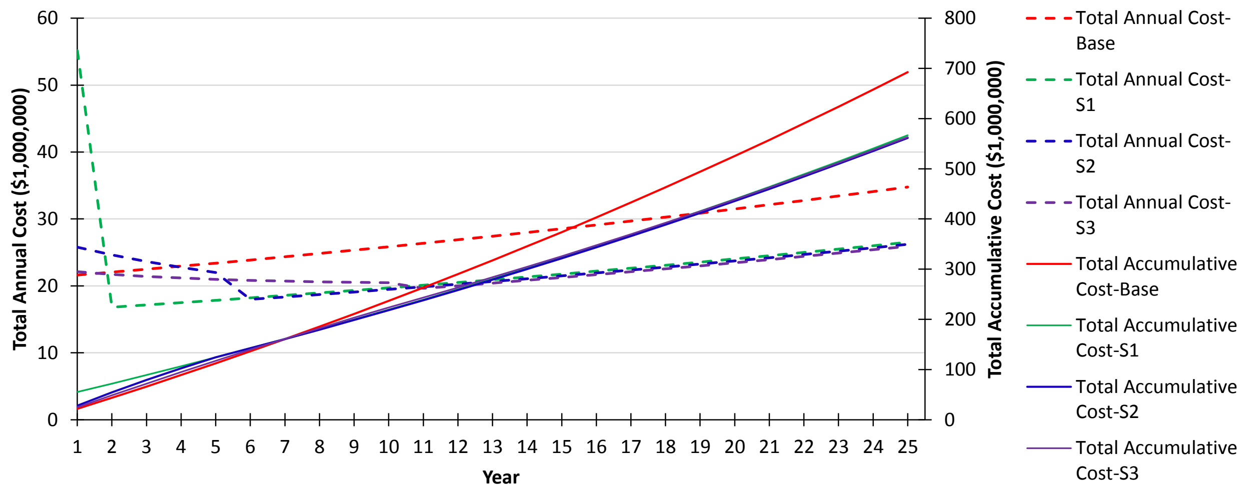



Figure 81. Total Annual and Accumulative Lighting Costs for All Scenarios (2015 $)

Table 16 and Figure 82 show the annualized and total electricity costs for all scenarios. As the illustrations show, over the 25-year analysis period, scenario S1 (replacing HPS systems at once) would reduce the lighting energy cost by $56.6 million (48%), scenario S2 would cut the energy cost by half ($58.8 million), and scenario S3 would reduce by $58.1 million (49%) compared with the scenario where no LED technology would be used.

**Table 16. Annual and Accumulative Electricity Cost ($millions, 2015)**

| Year | Energy Consumption (Base, Eq. 1) | | Energy Consumption (S1, Eq. 5) | | Energy Consumption (S2, Eq. 9) | | Energy Consumption (S3, Eq. 13) | |
|---|---|---|---|---|---|---|---|---|
| | Annual | Accumulative | Annual | Accumulative | Annual | Accumulative | Annual | Accumulative |
| 1 | 3.69 | 3.69 | 1.93 | 1.93 | 3.34 | 3.34 | 3.52 | 3.52 |
| 2 | 3.77 | 7.46 | 1.97 | 3.89 | 3.02 | 6.37 | 3.40 | 6.91 |
| 3 | 3.84 | 11.30 | 2.01 | 5.90 | 2.67 | 9.04 | 3.26 | 10.17 |
| 4 | 3.92 | 15.22 | 2.05 | 7.94 | 2.29 | 11.33 | 3.10 | 13.28 |
| 5 | 4.00 | 19.22 | 2.09 | 10.03 | 1.87 | 13.20 | 2.93 | 16.21 |
| 6 | 4.08 | 23.30 | 2.13 | 12.16 | 1.91 | 15.11 | 2.75 | 18.96 |
| 7 | 4.16 | 27.46 | 2.17 | 14.33 | 1.95 | 17.05 | 2.55 | 21.50 |
| 8 | 4.24 | 31.70 | 2.21 | 16.54 | 1.99 | 19.04 | 2.33 | 23.83 |
| 9 | 4.33 | 36.03 | 2.26 | 18.80 | 2.02 | 21.06 | 2.09 | 25.92 |
| 10 | 4.41 | 40.45 | 2.30 | 21.10 | 2.07 | 23.13 | 1.84 | 27.76 |
| 11 | 4.50 | 44.95 | 2.35 | 23.45 | 2.11 | 25.24 | 1.88 | 29.64 |
| 12 | 4.59 | 49.54 | 2.40 | 25.85 | 2.15 | 27.39 | 1.91 | 31.55 |
| 13 | 4.68 | 54.23 | 2.44 | 28.29 | 2.19 | 29.58 | 1.95 | 33.50 |
| 14 | 4.78 | 59.01 | 2.49 | 30.79 | 2.24 | 31.81 | 1.99 | 35.50 |
| 15 | 4.87 | 63.88 | 2.54 | 33.33 | 2.28 | 34.09 | 2.03 | 37.53 |
| 16 | 4.97 | 68.85 | 2.59 | 35.92 | 2.33 | 36.42 | 2.07 | 39.60 |
| 17 | 5.07 | 73.92 | 2.65 | 38.57 | 2.37 | 38.79 | 2.11 | 41.71 |
| 18 | 5.17 | 79.09 | 2.70 | 41.27 | 2.42 | 41.21 | 2.16 | 43.87 |
| 19 | 5.28 | 84.37 | 2.75 | 44.02 | 2.47 | 43.68 | 2.20 | 46.06 |
| 20 | 5.38 | 89.75 | 2.81 | 46.83 | 2.52 | 46.20 | 2.24 | 48.31 |
| 21 | 5.49 | 95.24 | 2.86 | 49.69 | 2.57 | 48.77 | 2.29 | 50.59 |
| 22 | 5.60 | 100.84 | 2.92 | 52.61 | 2.62 | 51.39 | 2.33 | 52.93 |
| 23 | 5.71 | 106.55 | 2.98 | 55.59 | 2.67 | 54.06 | 2.38 | 55.31 |
| 24 | 5.82 | 112.38 | 3.04 | 58.63 | 2.73 | 56.78 | 2.43 | 57.73 |
| 25 | 5.94 | 118.32 | 3.10 | 61.73 | 2.78 | 59.56 | 2.48 | 60.21 |

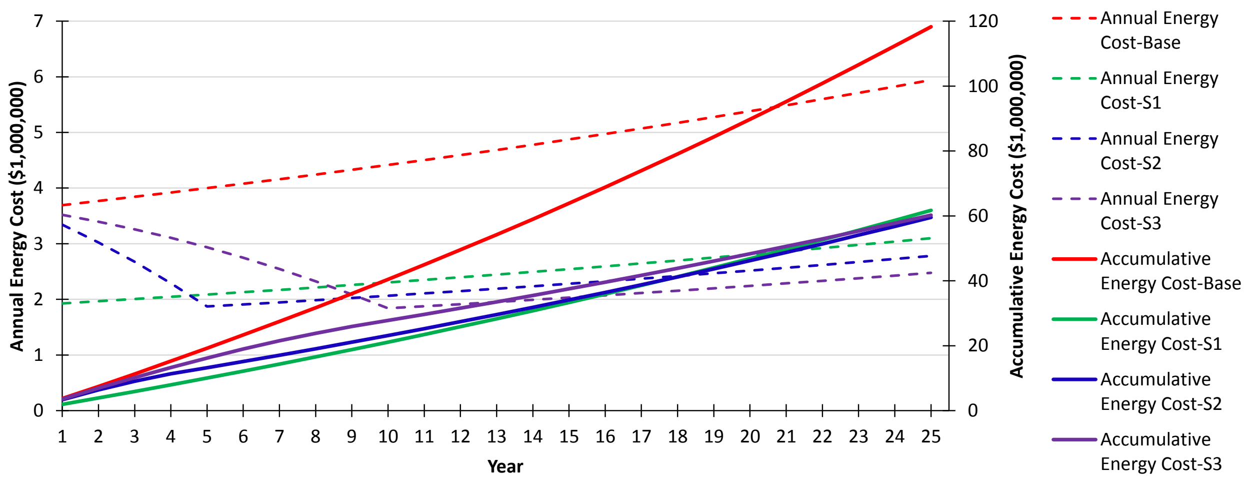



**Figure 82. Annual and Accumulative Energy Consumption for All Scenarios (2015 $)**

Table 17 and Figure 83 further show the luminaire and ancillary structure maintenance costs (including HPS lamp replacement costs) required for all scenarios. According to the analysis, replacing all HPS luminaires at the first year would result in a 19% saving in maintenance and related costs, the 5-year scenario would result in an 18% saving, and the 10-year scenario corresponded to a 16% saving in maintenance costs. LED luminaires require less maintenance over time (arguably maintenance free) due to their much longer service lives.

**Table 17. Annual and Accumulative Maintenance Cost ($millions, 2015)**

| Year | Maintenance Cost (Base, Eq. 2) | | Maintenance Cost (S1, Eq. 6) | | Maintenance Cost (S2, Eq. 10) | | Maintenance Cost (S3, Eq. 14) | |
|---|---|---|---|---|---|---|---|---|
| | Annual | Accumulative | Annual | Accumulative | Annual | Accumulative | Annual | Accumulative |
| 1 | 17.93 | 17.93 | 14.57 | 14.57 | 16.93 | 16.93 | 17.23 | 17.23 |
| 2 | 18.29 | 36.21 | 14.86 | 29.42 | 16.67 | 33.60 | 17.27 | 34.50 |
| 3 | 18.65 | 54.87 | 15.15 | 44.58 | 16.39 | 49.99 | 17.31 | 51.81 |
| 4 | 19.03 | 73.89 | 15.46 | 60.04 | 16.09 | 66.07 | 17.34 | 69.15 |
| 5 | 19.41 | 93.30 | 15.77 | 75.80 | 15.77 | 81.84 | 17.37 | 86.52 |
| 6 | 19.79 | 113.09 | 16.08 | 91.89 | 16.08 | 97.92 | 17.39 | 103.91 |
| 7 | 20.19 | 133.28 | 16.40 | 108.29 | 16.40 | 114.33 | 17.40 | 121.31 |
| 8 | 20.59 | 153.87 | 16.73 | 125.02 | 16.73 | 131.06 | 17.41 | 138.72 |
| 9 | 21.01 | 174.88 | 17.07 | 142.09 | 17.07 | 148.13 | 17.41 | 156.14 |
| 10 | 21.43 | 196.31 | 17.41 | 159.50 | 17.41 | 165.53 | 17.41 | 173.55 |
| 11 | 21.85 | 218.16 | 17.76 | 177.25 | 17.76 | 183.29 | 17.76 | 191.30 |
| 12 | 22.29 | 240.45 | 18.11 | 195.37 | 18.11 | 201.40 | 18.11 | 209.41 |
| 13 | 22.74 | 263.19 | 18.47 | 213.84 | 18.47 | 219.88 | 18.47 | 227.89 |
| 14 | 23.19 | 286.38 | 18.84 | 232.68 | 18.84 | 238.72 | 18.84 | 246.73 |
| 15 | 23.66 | 310.04 | 19.22 | 251.90 | 19.22 | 257.94 | 19.22 | 265.95 |
| 16 | 24.13 | 334.16 | 19.60 | 271.51 | 19.60 | 277.54 | 19.60 | 285.56 |
| 17 | 24.61 | 358.78 | 20.00 | 291.50 | 20.00 | 297.54 | 20.00 | 305.55 |
| 18 | 25.10 | 383.88 | 20.40 | 311.90 | 20.40 | 317.94 | 20.40 | 325.95 |
| 19 | 25.61 | 409.48 | 20.80 | 332.71 | 20.80 | 338.74 | 20.80 | 346.75 |
| 20 | 26.12 | 435.60 | 21.22 | 353.93 | 21.22 | 359.96 | 21.22 | 367.97 |
| 21 | 26.64 | 462.24 | 21.64 | 375.57 | 21.64 | 381.61 | 21.64 | 389.62 |
| 22 | 27.17 | 489.41 | 22.08 | 397.65 | 22.08 | 403.68 | 22.08 | 411.70 |
| 23 | 27.72 | 517.13 | 22.52 | 420.17 | 22.52 | 426.20 | 22.52 | 434.22 |
| 24 | 28.27 | 545.40 | 22.97 | 443.14 | 22.97 | 449.17 | 22.97 | 457.19 |
| 25 | 28.84 | 574.24 | 23.43 | 466.57 | 23.43 | 472.60 | 23.43 | 480.61 |

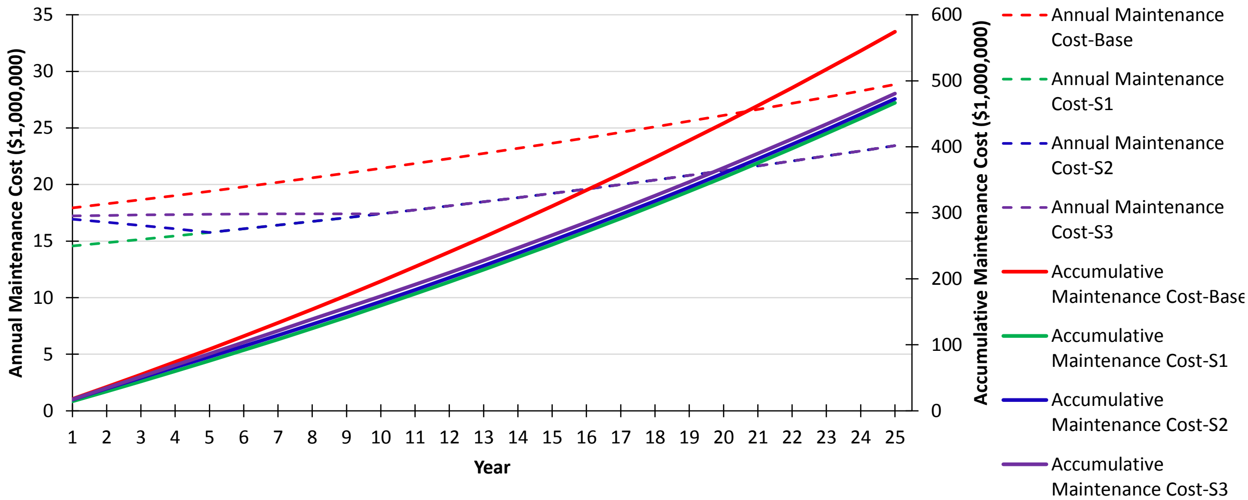



**Figure 83. Annual and Accumulative Maintenance Cost for All Scenarios (2015 $)**

# DISCUSSION

## Discussion of Laboratory Testing Results

The following discusses the findings based on the laboratory testing results:

- *Horizontal illuminance.* Laboratory testing results suggested that the LED luminaires evaluated provided lower levels of horizontal illuminance over the VTTI laboratory grid compared to the HPS luminaires. However, light output of the HPS systems concentrated in a relatively limited area, suggesting poor performance in achieving light uniformity. Among the different LED designs, the Design C LED luminaires contained large LED light sources and therefore resembled the horizontal illuminance distribution of the HPS systems more than other LED designs. Overall, the different LED designs exhibited very different horizontal illuminance distribution patterns, with Design C and E more elongated while Design A, B, and D more circular. The different patterns suggest that a clear understanding of the horizontal illuminance pattern of a LED luminaire is critical for developing the most cost-effective lighting design of a specific application.

- *Vertical illuminance.* The evaluated HPS luminaires provided a higher level of average vertical illuminance over the VTTI laboratory grid than the LED luminaires. In addition, the HPS systems provided highly concentrated vertical illuminance levels within the close vicinity of the luminaire, resulting in relatively intensive glare and poor vertical illuminance uniformity. In contrast, most LED designs (e.g., Design A, B, D, and E to a less extent) provided a much more uniform distribution of vertical illuminance. In addition, the rear trespass levels of LED luminaires (along the outmost grid line behind the luminaire) was all found to be lower than the HPS luminaires.

- *Spectral power distribution and light quality.* All LED luminaires evaluated emitted light that is much closer to natural light in color. The HPS luminaires emitted yellowish lights with high special power within the 490 – 510 nm (green) and 560 – 620 nm (yellow) ranges. It is widely recognized that whiter, or more naturally colored light help drivers to better discern objects on roadways compared to traditional light. Among the different LED designs, Design D contained the most yellow light distribution while Design B contained the lowest yellow light.

- *Power consumption and efficacy.* The measured wattages of most LED luminaires were consistent with manufacturer ratings with the only exception of Design D LED luminaires. The measured efficacy of most LED luminaires is comparable to that of the HPS systems, with Design C luminaires slightly exceeding the HPS systems.

- *Light loss and light quality deterioration over time.* Based on before- and after-operation laboratory testing results, the LED luminaires had a 6% overall reduction in light output after 2 years due to light loss and dirt depreciation, compared to the 10% (for horizontal illuminance) or 3% (for vertical illuminance) reduction of the HPS systems. The testing results suggested a much more significant light loss due to lumen depreciation than due to dirt depreciation for LED luminaires. In addition, the evaluated LED luminaires generally had much less dirt depreciation than did the HPS systems. Interestingly, the lab results seemed to suggest that lumen depreciation was more obvious in the form of horizontal illuminance than in the form of vertical illuminance for LED luminaires. In contrast, the light loss attributable to dirt was more significant in the form of vertical illuminance than horizontal illuminance.

- *Dirt depreciation distribution.* The laboratory testing results suggested that, for the HPS luminaire, dirt depreciation primarily reduced the horizontal illuminance of the central area and the areas on the right and left sides. The dirt depreciation impact for the Design C LED luminaires with large LED sources closely resembled that for the HPS luminaires, suggesting similar characteristics between the two types of luminaires in terms of dirt depreciation. For Designs A, D, and E LED luminaires with optic arrays, the dirt depreciation in general resulted in slightly higher horizontal illuminance levels in the central area while lower horizontal illuminance everywhere else. For Design B Luminaires, on the other hand, dirt depreciation resulted in relatively uniform decrease of horizontal illuminance across the laboratory grid due to its unique three-panel folding design that evened out the dirt reflection effect.

- *Technological comparison.* Overall, the LED systems exhibited much whiter light output, better light uniformity, and lower glare and backlight. Among the different LED designs, luminaires with LED optic arrays (e.g., Design A, B, and D) had better uniformity than luminaires with large LED optics (e.g., Design C). Exposed LED optic arrays did not attract more dirt than those covered with larger lenses, although it would be more difficult to clean individual optics when they get dirty. Dirt depreciation analysis results suggested that dirt accumulation on luminaires with large light sources tend to reduce their horizontal illuminance level in the central area and on right and left side of the light grid. From this perspective, the three-folding panel design and/or the use of optic arrays will result in less significant impact from dirt depreciation over time.

## Discussion of Field Testing Results

The following discusses the findings based on the field testing results:

- *Field horizontal illuminance.* Based on the field measurements, the research team could not conclude a clear trend in significant reduction of light output during the first 2 years of field operation. When comparing with the HPS systems, the LED luminaires in general exhibited more stable performance (i.e., less significant performance variations over time) than the HPS systems. Among the LED designs, the research team observed changes in horizontal light distribution over time, which might be due to tilting/rotation of the luminaires over time and/or irregular changes of the performance of individual LED packages.

- *Field vertical illuminance.* Although not significantly, the field vertical illuminance measurements suggested a decreasing trend for most LED designs. The overall vertical illuminance reduction during the 2 years of operation was around 10% for most LED luminaires. The only exception for this trend was the Design B luminaire, which had a three-panel folding design with the central panel facing directly downwards and the other two folding towards the center. These observations, combined with the horizontal illuminance results, seem to suggest that dirt depreciation has a more significant impact on vertical illuminance than on horizontal illuminance. In addition, field vertical illuminance analysis did not reveal noticeable changes in vertical illuminance distribution, which seems to indicate that the changes in horizontal illuminance distribution for Design A and B were due to the performance of LED optics instead of tilting of the luminaires.

- *LED luminaire light color.* The study showed that CCTs measured on the field for most LED designs were generally consistent with the manufacturer-rated CCTs. The Design B luminaire with the highest manufacturer-rated CCT was the only one that resulted in measured CCTs not consistent with the specified CCT. The field measurements also suggested that most LED luminaires had a moderately decreasing trend in CCTs over time, which indicates that the colors of the evaluated LED lights would become slightly yellowish/reddish over time. The 2-year reduction in measured CCTs for all LED luminaires was found to be between 2% and 8%.

- *Visual inspection results.* Data analysis and visual inspection results suggested that, without proper installation procedures and/or strict measurements, luminaires could fail to meet tilt and roll requirements during installations. In addition, installed luminaires may rotate/tilt over time when they are not securely mounted. Many evaluated luminaires did not have sufficient ingress protection for the housing, resulting in significant rust/dirt accumulation and wildlife intrusion inside the electrical compartment. The researchers did not find issues with the optical assembly ingress protection for any of the LED designs. In contrast, the HPS systems had significant dirt and wildlife accumulation inside the optical lens.

- *Ambient factors affecting field study results.* The field study took place over a relatively significant duration of time. During the different field visits, a large number of ambient factors, such as moon light, presence and change over time of vegetation (e.g., tree leaves and grass), ambient temperature, and artificial light (although minimal) all played a role in the lighting measurement results. Although the research team devoted significant effort to control such factors, their impact seemed to have affected the field study results.

## Discussion of Life Cycle Cost Analysis

The results suggested that it is important to start utilizing LED technology to save energy. However, because LED technology is expected to continually improve, the greatest benefit is realized when LED systems are implemented gradually and systematically, which is shown in the results of different scenarios taking into account the expected improvements in LED luminaire price and efficacy. Although the research team collected a significant amount of data, they also had to make a number of assumptions to perform the cost-benefit analysis:

- *Electricity cost.* Currently, VDOT pays roadway lighting electricity fees both by actual usage (i.e., kWh) and by flat fees calculated based on service areas. As such, it was not feasible to obtain accurate rates of VDOT electricity expenditures for roadway lighting. In addition, to materialize the energy savings when LED luminaires are used, it is important to phase out the flat fee approach and use electricity meters for all LED luminaires.

- *Implementation scenarios.* In this analysis, the research team assumed three LED implementation scenarios: replacing all HPS luminaires at once, in even increments over 5 years, and in even increments over 10 years. If the HSP luminaires are to be replaced on a project-by-project basis, the cost-benefit results most applicable to VDOT will be those for the second and third scenarios: replacing all traditional luminaires within 5 to10 years. However, VDOT is currently going through a comprehensive energy audit that may result in much faster replacement of LED luminaires. If this is the case, scenario S1 and, to a certain extent, S2 will be more applicable.

- *Other assumptions.* The research team made reasonable assumptions on several factors, such as future LED technology improvement and price decrease, inflation rate, and lighting maintenance needs. The results may change depending on the accuracy of those assumptions.

## LED Implementation Implications and Needs

To facilitate the implementation of LED luminaires and their long-term maintenance, there are several strategies that can be beneficial:

- *Establish a LED luminaire prequalification and testing program.* With the recent advance of the LED industry, there have been a significant number of LED roadway lighting products developed by manufacturers of different sizes and qualifications. For each lighting project, there can be potentially a large number of products submitted for bidding. Understanding and testing these products requires significant expertise and in many cases is considerably time-consuming. To ensure that only suitable and reliable products are submitted for bidding, an LED prequalification program should be established to identify and characterize existing LED products meeting VDOT requirements. Such a program would reduce the technical and liability burden for product selection by contractors and project managers within tight project schedules, and therefore reduce project delays. It would also minimize the possibility of using faulty products for VDOT projects by allowing more expertise in product selection and more time for thorough product testing.

- *Continuously monitor the performance of different LED luminaires to better understand and utilize the technology.* This research was based on results from a 2-year study, which did not allow sufficient analysis of LED performance change over time. After VDOT starts to implement LED luminaires, it will provide a great opportunity for VDOT to continuously track the performance of the LED luminaires for a much longer period of time. Such continuous performance monitoring will provide critical knowledge for VDOT to update the LED specification and lighting design standards/processes. The research team recommends that VDOT continuously monitor the field performance of LED luminaires for at least 10 years.

- *Consider an on-call technical support group for LED-related issues. The vast array of LED products with varying design and performance has challenged agencies in ways not encountered with traditional lighting technologies.* Identifying reliable and cost effective LED products suitable for a specific application now requires more technological know-how and product testing. Agencies may experience times when in-house expertise cannot meet tasks such as evaluating LED lab testing reports and technical cut sheets that are frequently not standardized within the industry, understanding light distribution characteristics and their implications to specific lighting designs, and identifying products with suitable/reliable photometric performance. An on-call technical support group with reputable expertise in critical LED and related subject areas therefore becomes beneficial to aid VDOT designers and engineers in LED luminaire selection and testing.

- *Develop LED specifications for high-mast, sign, and tunnel/under-bridge lighting.* This study primarily studied LED luminaires for traditional roadway lighting. Other roadway lighting applications, such as high-mast lighting, sign lighting, and tunnel lighting have different requirements. The potential of using LED technology for such applications need to be studied and specifications applicable to such applications should be developed as well.

- *Phase out unmetered electrical services.* Currently, VDOT still maintains unmetered electrical services for many of the roadway luminaires. With the use of LED luminaires, it is important to start phasing out the unmetered electrical services so that the actual energy savings can be harvested.

## CONCLUSIONS

- *Over the lifetime of the luminaires, the use of LED luminaires will result in significant savings in energy consumption and total lighting-related costs.* The economic analysis results suggested that the investment would be returned (compared to the base scenario) in 7 to 8 years for all scenarios, although scenario S2 (the existing HPS systems are converted over 5 years) corresponded with the shortest investment return time. Over the 25-year analysis period, the ROI for the different scenarios ranges between 3.25 and 5.76, with 3.25 projected for scenario 1; 4.45 for the 5-year replacement scenario; and 5.76 for the 10-year replacement scenario. In addition, over the 25-year analysis period, converting HPS luminaires to LED would cut the lighting energy cost at VDOT by 48% to 50% depending on the conversion scenario. Due to the minimal maintenance required by LED luminaires, replacing the traditional HPS luminaires will also significantly reduce the maintenance and related costs.

- *LED luminaires outperformed the HPS system in light quality, distribution, and stability*. Overall, the LED systems exhibited much whiter light output, better light uniformity, and lower glare and backlight. All LED luminaires evaluated emitted light that was much closer in color natural light. In contrast, the HPS luminaires emitted yellowish light with high special power within the 490 – 510 nm (green) and 560 – 620 nm (yellow) ranges. The LED luminaires in general had a lower level of average horizontal and vertical illuminance compared to the HPS luminaires. Note that this difference does not necessarily indicate insufficient light output of the LED luminaires since lighting designs typically consider multiple factors such as uniformity, light distribution, and BUG (backlight, uplight, and glare) as required by different applications. The light output of most LED systems was much more uniformly distributed over a larger area compared to that of the HPS system. Most evaluated LED luminaires also exhibited a much more widely-spread vertical illuminance distribution, indicating better vertical illuminance uniformity and less glare for travelers. In addition, all LED luminaires evaluated showed a lower level of rear trespass light than the HPS systems.

  Compared to the LED systems, the HPS luminaires were much more prone to dirt accumulation, particularly inside the lens due to poor ingress protection. Results also suggested that the LED luminaires in general exhibited more stable performance (i.e., less significant performance variations over time) than the HPS systems. The measured efficacy of most LED luminaires was comparable to that of the HPS system, with Design C luminaires slightly exceeding the HPS systems in efficacy.

- *Different LED designs showed differences in light distribution and lighting performance over time.* Among the different LED designs, luminaires with LED optic arrays (e.g., Design A, B, and D) had better uniformity than luminaires with large LED optics (e.g., Design C). The Design C luminaires with large LED light sources resembled the horizontal and vertical illuminance distribution of the HPS systems more than the other LED designs. Overall, the different LED designs exhibited very different horizontal illuminance distribution patterns, with Design C and E more elongated while Design A, B, and D more circular. This suggests that LED luminaires should be carefully chosen based on the application to result in the most cost-effective lighting designs.

  Exposed LED optic arrays did not attract more dirt than those covered with larger lenses within the first 2 years of operation. However, it was more difficult to clean the individual optics forming an array. The research team observed changes in horizontal light distribution over time for Design A and B, likely due to irregular changes of the performance of individual LED packages. The measured wattages of most LED luminaires were consistent with manufacturer ratings with the single exception of Design D LED luminaires. The

Design B luminaire with the highest manufacturer-rated CCT was the only one that had a CCT inconsistent with the manufacturer specification.

- *The light output of LED systems decreased during the first 2 years but not significantly when performance variation and ambient factors are considered.* Laboratory testing results showed that the LED luminaires had 6% less output after 2 years of operation due to light loss and dirt depreciation. The laboratory testing results suggested a much more significant light loss due to lumen depreciation than due to dirt depreciation for LED luminaires. Results also showed that dirt depreciation had a more significant impact on vertical illuminance than on horizontal illuminance. Field data did not suggest a clear decrease in horizontal illuminance over the 2 years, but the vertical illuminance decreased between 4% and 12% for the LED luminaires. The lowest decrease in vertical illuminance was that of the Design B luminaire, which had a three-panel folding design with the central panel facing directly downwards and the other two folding towards the center.

- *The light color of most LED luminaires degraded over time during the 2 years of field operation.* This finding indicated that the color of the evaluated LED lights becomes yellowish/reddish over time. The 2-year decrease in measured CCTs for all LED luminaires was found to be between 2% and 8%.

- *LED fixtures need to be installed properly and have proper ingress protection.* Data analysis and visual inspection results suggested that, without proper installation procedures and/or strict measurements, luminaires could fail to meet leveling and orientation requirements during installation. In addition, installed luminaires may rotate and tilt over time if they are not securely mounted. Many evaluated luminaires did not have housings with sufficient ingress protection, resulting in significant rust/dirt accumulation and wildlife intrusion inside the electrical compartment. The researchers did not find issues with the optical assembly ingress protection for any of the LED designs. In contrast, the HPS system had significant dirt and wildlife accumulation inside the optical lens.

## RECOMMENDATIONS

1. *VDOT's TED should adopt LED technology for roadway lighting but implementation should be project specific.* LED roadway lighting must be project specific, and the project engineer must review it on a project-by-project basis.

2. *VDOT's TED should develop and maintain a lighting inventory in the current/future asset management framework.* With the more widespread use of LED luminaires, it becomes urgent to develop and implement a statewide lighting inventory system to manage, store, and track the LED roadway luminaires and related files. Traditional luminaires (e.g., HPS) do not involve warranty issues. In addition, retrofitting HPS luminaires is performed frequently and at minimal costs. LED luminaires are relatively expensive, with a long service life (e.g., 10 to 25 years); they vary in photometric performance (e.g., each product has a different light distribution type, CCT, and/or fixture lumens); change rapidly (e.g., old models become

unavailable in a few years); and are warranted for a significant period (e.g., 100,000 hours). Without an accurate and up-to-date lighting inventory system, VDOT will have difficulties tracking the service lives of the luminaires against their warranties. In addition, VDOT will likely lose original lighting design and technical files, resulting in difficulties in selecting replacement luminaires without going through a new lighting design process. A good lighting inventory system will also provide institutional information for energy consumption and cost-benefit analyses if needed.

3. *VDOT's TED should update the VDOT Special Provision for LED Roadway Luminaires as needed to reflect the latest technology status.* Currently, roadway LED lighting technology is rapidly improving. In the near future, many of the LED products on the market today will no longer be available. Various new products with a potentially significantly different design and materials will emerge, rendering many established performance metrics obsolete. As an example, most LED luminaires acquired in 2012 for evaluation in this study were not in production in late 2014 according to the venders contacted by the research team. Within this context, VDOT should update the VDOT LED luminaire specifications as needed, with a major revision every 4 to 5 years, until LED technology reaches its full maturity.

# BENEFITS AND IMPLEMENTATION

## Benefits

This study provides the needed know-how relevant to LED technology, the laboratory and field performance of common LED roadway luminaires over time, and the expected cost-benefit ratios if LED technology were implemented. The use of LED luminaires will result in significant savings in energy consumption and total lighting-related costs. Over the 25-year analysis period, the ROI for the different scenarios ranges between 3.25 and 5.76. Lighting energy cost at VDOT after converting to LED lighting technology would be reduced by 48% to 50%.

## Implementation

Implementation of the recommendations in the report is underway. VDOT is currently in the process of phasing out the existing HPS luminaires on VDOT maintained roadways and replacing them with LED luminaires. Based on the findings of this study, a *VDOT Special Provision for LED Roadway Luminaires* document was developed to facilitate the selection of LED luminaires for VDOT lighting projects. The following are the plan for and the status of implementing the recommendations of this study:

- *Implementing LED technology and the VDOT Special Provision for LED Roadway Luminaires.* VDOT is currently in the process of implementing LED roadway lighting technology statewide. Based on the findings of this study, the special provision was finalized on July 23, 2015. VDOT Location and Design Division (L&D) designers and consultants have begun using the special provision on design projects. In addition, the special provision will be used for all future design projects by October 2015. Statewide distribution of the special provision to VDOT staff for use of the special provision was made on August 20, 2015.

- *Implementing a lighting inventory in the current/future asset management framework.* Currently, VDOT is expecting that a lighting inventory will be implemented as part of VDOT's Highway Maintenance Management System. The procurement process for this system is underway.

- *Updating the VDOT Special Provision for LED Roadway Luminaires.* VDOT's TED will determine the need to update the special provision at a future date as it deems necessary. It is expected that the need will be reviewed no later than 4 to 5 years after the special provision was implemented.

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