Seattle LED Adaptive Lighting Study - NEEA

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1 Executive Summary

1.1 Project Background

The Northwest region operates approximately 1.7 million streetlights consuming an approximate average 150 MW. The City of Seattle has been actively converting its existing High Pressure Sodium (HPS) street lighting to light emitting diode (LED) lighting. The City reduced energy consumption by more than forty percent through this process (Smalley 2012). LED streetlights, coupled with controls enabling adaptive lighting, can save an additional twenty-five percent of energy.

The City can realize street light energy savings from both a reduction in wattage and from dimming. LED lamps are approaching the efficacy (lumens/watt) of HPS. Clanton & Associates and Virginia Tech Transportation Institute (VTTI) designed this study to test the idea that a lower quantity of better-quality light provides equal or better detection distance. This would create an opportunity for savings from luminaire lumen reductions and from dimming.

The Northwest Energy Efficiency Alliance (NEEA) and the City of Seattle partnered to evaluate the future of solid state street lighting in the Pacific Northwest with a two-night demonstration in Seattle's Ballard neighborhood in March 2012. The study evaluates the effectiveness of LED streetlights on nighttime driver object detection visibility as function of light source spectral distribution (color temperature in degrees K) and light distribution. Clanton & Associates and VTTI also evaluated adaptive lighting (tuning of streetlights during periods of reduced vehicular and pedestrian activity) at three levels: one hundred percent of full light output, fifty percent of full light output, and twenty-five percent of full light output.

The study, led by Clanton & Associates, Continuum Industries, and the VTTI, built upon previous visual performance studies conducted in Anchorage, Alaska; San Diego, California; and San Jose, California.

1.2 Study Description

Clanton & Associates and VTTI conducted the demonstration in Seattle's Ballard neighborhood along 15th Avenue NW, between NW 65th Street and NW 80th Street. They divided the fifteen-block stretch into six evaluation test areas with approximately one test area per two blocks. The demonstration used Philips Lumec LED luminaires equipped with the Schreder Owlet lighting control system.

Clanton & Associates and VTTI conducted the data collection demonstration over two evenings. Following an initial evening without data collection to allow representatives from the City and media to view the demonstration and the capabilities of the system, researchers conducted qualitative and quantitative testing the following two evenings. Each evening, three groups of participants evaluated the entire test site. The first group evaluated all of the lights at one hundred percent of full light output, the second group evaluated all of the LED lights at fifty percent of full light output (HPS remained at one hundred percent), and the final group evaluated all of the LED lights at twenty-five percent of full light output (HPS remained at one hundred percent). Full output of the luminaires represented the maximum output of the specified luminaires, which Clanton & Associates had selected to meet the Illuminating Engineering Society of North America (IES) *Recommended Practice for Roadway Lighting* (RP-8) criteria for a collector road with medium pedestrian conflict. The first night of general participant testing took place on dry pavement. On the second night, flusher trucks wetted the pavement and the process was repeated.

The written evaluation asked participants a series of general questions based upon where they live, in addition to demographic questions and site condition questions. For each test area, a participant next rated twelve statements on a five-point scale (strongly disagree to strongly agree).

VTTI conducted the user field test on both nights of general participant testing. On each evening, three participants at a time participated in the user field test. Two participants sat in the back seat of the test vehicle, while one participant sat in the front passenger seat. A representative from VTTI drove the car. The driver instructed each participant to depress a push button device when he or she identified a wooden visibility target through the front windshield. A GPS device recorded the detection distance between the vehicle and the target, thus creating data for quantitative comparison among luminaire types and light levels.

1.3 Research Results

The use of LED technology for city street lighting is becoming more widespread. While these lights are primarily touted for their energy efficiency, the combination of LEDs with advanced control technology, changes to lighting criteria, and a better understanding of human mesopic (low light level) visibility creates an enormous potential for energy savings and improved motorist and pedestrian visibility and safety.

Data from these tests support the following statements:

- LED luminaires with a correlated color temperature of 4100K provide the highest detection distance, including statistically significantly better detection distance when compared to HPS luminaires of higher wattage.
- The non-uniformity of the lighting on the roadway surface provides a visibility enhancement and greater contrast for visibility.
- Contrast of objects, both positive and negative, is a better indicator of visibility than is average luminance level.
- Dimming the LED luminaires to fifty percent of IES RP-8 levels did not significantly reduce object detection distance in dry pavement conditions.
- Participants perceived dimming of sidewalks as less acceptable than dimming to the same level on the roadway.

- Asymmetric lighting did reduce glare and performed similarly to the symmetric lighting at the same color temperature (4100K).

The results indicate that the 105-watt LED luminaire, with a correlated color temperature (CCT) of 4100K (symmetric and asymmetric), has the highest detection distance of all of the test areas, with a value of approximately 130 feet. This luminaire outperformed even the 250-watt (280 system watts) and 400-watt (450 system watts) HPS, with over two and four times the wattage respectively. Even when reduced to twenty-five percent of full light output during the dry pavement test, the LED 4100K luminaires did not have a significantly different detection distance compared to the same luminaires at one hundred percent of full light output. The wet roadway conditions did show a decrease in detection distance when the lighting system was dimmed, especially at twenty-five percent of full light output.

The illuminance uniformity ratio of the 4100K LED luminaire is the highest (least uniform) of all of the LED luminaires, yet this luminaire also has the greatest detection distance.

The contrasts of targets for all colors increased as the light levels dimmed. Participants assessed the contrast from 200 or more feet away from the vehicle, or beyond the reach of headlamp lighting, whereas most detections occurred within 200 feet, or within the headlamp span. A greater contrast ratio typically results in greater visibility; however, based on the average detection distances and the test vehicle’s headlamp assessment, VTTI concluded that headlamps are not the primary source of detection.

Luminance does not exhibit a correlation to detection distance; the two HPS luminaires and the 5000K LED provided greater levels of luminance than did either of the 4100K LEDs (symmetric or asymmetric) but did not show a related increase in the object visibility. This demonstrates that the primary indication of visibility is contrast and that a reduced luminance level with equivalent contrast may provide equivalent or better detection distances.

The user field test results indicate that the implementation of adaptive lighting does not significantly affect object detection distance for dry roads. However, coupling this data with the written evaluation results indicates that reducing the light level to twenty-five percent of full light output for all hours of the night raises concerns for the public, especially on the sidewalks. Tuning the light to a point such as twenty-five percent of full light output may be justified at low vehicular and pedestrian volumes and under dry pavement conditions, but not for all hours of the evening.

The asymmetric luminaires recorded the lowest glare values of all of the test areas, as the light was intended to be directed away from the driver. While the asymmetric luminaires performed on par with the symmetric 4100K LED luminaire, participants did not rate the asymmetric test area very high, especially at the lower light levels. Participants deemed the distribution to be patchy and claimed that signage was difficult to view.

1.4 Industry Implications

Standards

The user field test data findings demonstrate that less uniformity trends toward greater detection distance. The importance of uniformity in target detection constitutes another aspect to consider. The 4100K luminaire exhibited the highest illuminance uniformity ratio, indicating the most non-uniform appearance; it also showed the highest visual performance. While industry standards list maximum uniformity ratios, they do not address a lower limit. The IES research committee should explore both the maximum and minimum ratios to account for higher contrast with less uniform pavements. Visibility level (VL) concepts are addressed in the standards, but researchers should refine the values to replicate field data.

The data gathered from the user field test in this study also supports the use of mesopic corrections under IES RP-8. The contrast of objects illuminated by shorter wavelength light (from LEDs) at low light levels is a valid reason for reducing light levels while not affecting visual detection distance.

Future Product Designs

LED technology and the design of luminaires can address the sidewalk lighting issue. Ideally, the luminaire controller would maintain higher light levels on the sidewalks for pedestrians during conditions when roadway illumination is reduced. The authors believe that current LED drivers could be adapted to support this methodology. Such design changes would ensure that sidewalks remained illuminated and that pedestrians would likely feel safer than they did in this test, in which some participants expressed concern about under-lighted sidewalks with the luminaires at twenty-five percent of rated output. More uniform sidewalks may also play a greater role in pedestrians' perception of security.

Economic Analysis

The analysis indicates that the implementation of LEDs and controls can pay back in just over three years when replacing 400 W HPS luminaires with 105 W LED luminaires, and within six years when replacing 250 W HPS luminaires with 105 W LED luminaires. The payback values improve with more aggressive adaptive lighting.

1.5 Future Work

This project used a test site along a roadway with a speed limit of thirty-five miles per hour. In order to fully understand the magnitude of mesopic benefits, researchers should expand this study to take place on a roadway with a higher speed limit (fifty-five mph) to verify the existence of similar results. Future detection tasks may focus on foveal (line-of-sight) versus non-foveal (peripheral) vision; researchers may develop new adjustment factors to account for color contrast in foveal vision.

Given that researchers found contrast to be a strong indicator for detection distance, future research should delve further into Visibility Level (VL). The weighted average VL comprises the

Small Target Visibility (STV) within RP-8. Researchers should refine these values to more accurately predict STV based upon visibility research.

The test site was located in an urban environment with light contribution from several adjacent businesses. As researchers reduced the light from the LED luminaires, the influences of non-uniformity and contrast as strong indicators of visibility became evident. However, the light contribution from the adjacent businesses remained at full brightness throughout the demonstration, thus contributing to the contrast values. Subsequent studies would benefit from having adjacent businesses extinguish their lights for the duration of the demonstration to determine whether or not non-uniformity and contrast remain strong indicators of visibility without their contribution.

Researchers added the condition of wet pavement to this demonstration to test the impacts on visibility when pavement conditions change. Future research should look into other weather conditions such as fog and snow to determine visibility variance when introducing these common weather elements.

Future work should also include a more thorough look at sidewalk visibility: when pedestrians are navigating detached and attached sidewalks, what type and quantity of light achieves the highest level of visibility? Future studies should include both static and dynamic objects in-situ in a city to measure detection distance.

2 Introduction

2.1 Background

The use of light emitting diode (LED) technology for city street lighting is becoming more widespread. While these lights are primarily touted for their energy efficiency, the combination of LEDs with advanced control technology, changes to lighting criteria, and a better understanding of human mesopic (low light level) visibility creates an enormous potential for energy savings and improved motorist and pedestrian visibility and safety.

LED efficacy (the amount of light generated per watt of electricity) continues to increase substantially as the technology and deployment improve. However, efficacy varies dramatically with the spectral distribution (color temperature) of the LED. Due to the current manufacturing process, cooler colors (higher Correlated Color Temperature, or CCT) result in higher efficacies than do warmer colors (lower CCTs). In fact, as of 2013, the Department of Energy (DOE) reported cool white LED packages (CCT=4746K to 7040K) with an average of 164 lumens per watt and warm white LED packages (CCT=2580K to 3710K) with an average of 129 lumens per watt (DOE 2013). However, public preference typically favors warm white light, or the lower color temperatures, such as 3500K. Ignoring this in favor of higher efficacies, manufacturers' marketing media push higher-color-temperature 5000K and 6000K light sources to gain a competitive edge. This results in installations that produce light very efficiently, but within a spectrum that can affect brightness perception, color rendering, discomfort glare, circadian rhythm, and other possible health issues (IES 2013).

Network control of exterior lighting provides another layer of energy savings potential to street lighting systems. Most street luminaires use photo sensors that detect a drop in ambient daylight, causing the luminaire to switch on. At dawn, the same sensor turns off the luminaire. Although a straightforward solution, this strategy results in the light source being activated all night and during periods of dusk and dawn. Additionally, photo sensors are typically the most likely component of the system to fail. Networked lighting controls link groups of luminaires together with either radio frequency or by power line carrier. When dimmable sources (such as LED) are controlled in this mesh network, the luminaires can be dimmed or turned off as a group, or individually.

The Illuminating Engineering Society (IES) roadway lighting criteria (RP-8) outlines decreasing light level requirements for decreasing levels of pedestrian and motorist conflict. However, without dimming and control technology available, changing light levels after installation has been impractical. A roadway lighting design provided the appropriate amount of light for the worst set of design conditions. Additionally, because light output diminishes with time (lumen maintenance), traditional design practice puts the initial light output well over the requirement so that the light level will still be met when light output has decreased at the end of the light source's life. Implementing dimming control, or "tuning" these light sources, can now provide the design level of light at all times, accounting for decreasing late night pedestrian activity and for lumen depreciation over the life of the light source.

LEDs also produce a white light with high color rendering ability as opposed to the yellow light produced by the high pressure sodium (HPS) sources commonly used in North American cities. With the revision of Technical Memorandum (TM 12-12) *Spectral Effects of Lighting on Visual Performance at Mesopic Lighting Levels*, the IES recognized that some spectral distributions provide better visibility under mesopic (low light level) conditions than do others. Although pinpointing it is difficult, TM 12-12 documents a method for calculating the *effective* luminance of a roadway lighting design. This means that designers can design for lower light levels when using a white light source and still achieve the same level of visibility provided by higher light levels produced by an HPS light source.

The energy savings from this combination of opportunities far exceeds the potential of the efficient technology alone. However, most pilot studies and tests evaluate the solid state technology alone without analyzing the potential synergies of these other opportunities.

Table 1. Potential Cumulative Energy Savings

Potential Cumulative Energy Savings	
	Energy Savings Potential
Luminaire Replacement	15-40%*
Lumen Maintenance	5-15% (at beginning of life)
Mesopic Multipliers	5-10% (4000K source compared to HPS at 2000K)
Adaptive Lighting	25%**
TOTAL ENERGY SAVINGS	**50-90%**

Notes: *This savings is in addition to the application of adaptive lighting, and greatly depends on whether the incumbent technology was currently meeting performance or prescriptive criteria.
**Assumes fifty percent light level reduction during fifty percent of the operating hours.

2.2 Technology and Market Overview

The cost effectiveness of LED street luminaires varies dramatically depending on site-specific factors and on the variables considered in the economic analysis. Using a Return on Investment or Net Present Value analysis captures not only energy costs but maintenance savings as well. Additionally, light source efficacy continues to improve each year. The DOE predicts that by 2020, even warm white LED packages will exceed 200 lumens per watt (DOE 2013). While efficacy continues to increase, the growing number of luminaire manufacturers in the market intensifies competition and reduces costs. However, quality also varies significantly among these manufacturers; the DOE reports payback periods from its gateway projects as short as three years and as long as twenty years(DOE 2013). The following variables affect the cost analysis of any project:

- Cost of current energy and future predicted escalation
- Maintenance costs (light source, driver/ballast, photocell replacements) and whether or not these are considered in the analysis
- Use of adaptive lighting and controls to reduce light output after hours
- Use of lumen maintenance tuning to keep lighting at design levels throughout the course of the system's life
- Change from current lighting levels that have over-lighted streets

2.3 Project Objectives

The large number of previous pilot and study projects has failed to sufficiently address the following objectives:

1. Test different color temperatures for the existence of preferences for a specific color and for performance advantages to a specific color temperature (spectral distribution).
2. Evaluate opinions of citizens toward various light sources that may be suitable candidates for selection of replacement luminaires.
3. Evaluate the performance of luminaires with an asymmetric distribution that maximizes the vertical brightness along a roadway.
4. Test three different light output levels (one hundred percent, fifty percent and twenty-five percent) to see the point at which the lower levels become undesirable.
5. Test different road conditions (wet and dry pavement) to identify potential luminaire and light source performance advantages for one condition over the other.
6. Evaluate object detection performance and community acceptance of white (broad-spectrum) LED lighting.

The results of this study will also support the development of LED streetlight design guidelines for the Northwest. With the rapid pace of change in this industry, this design guidebook will help municipalities and utilities to cost-justify and confidently select luminaires and control systems to meet their individual needs.

2.4 Project Hypotheses

Researchers developed the following series of hypotheses prior to beginning this project to help define the study parameters.

Luminance versus Illuminance

- Illuminance has constituted the basis of most lighting design criteria, yet it does not address visual adaptation. Luminance will more accurately predict object detection versus illuminance, since it best represents what one "sees": visual adaptation and object contrast. This distinction between illuminance and luminance will be emphasized under wet conditions where the difference between illuminance and luminance will be the highest.

- Since the earlier-mentioned experiments were illuminance-based, this experiment should perform both illuminance and luminance setups. Since the test areas will be identical, the luminance detection will be compared with the illuminance test in order to establish the relationship between the two, and also to confirm the hypothesis that luminance is the best object detector predictor.

Broad Spectrum versus HPS Lighting

- Broad spectrum lighting will yield object detection higher than that of HPS lighting under the same illuminance or luminance level. This occurred in three other streetlight experiments conducted by Clanton & Associates and Virginia Tech Transportation Institute and is predicted to have the same results with this experiment. See Work for additional information.

Adaptive Lighting

- Even under lower luminance or illuminance levels, broad spectrum lighting will have greater detection distances than HPS.

Asymmetric Lighting

- Asymmetric distribution will increase detection distances, especially under wet conditions. Since pavement reflectance and viewing angle both affect luminance values, wet pavement luminance increases when light is directed toward the driver. This increases veiling luminance and low contrast. Asymmetric distribution directs light away from the driver, similar to an extension of headlamps. These effects may also appear under dry conditions, since small target visibility increases with asymmetric distribution.

Energy Savings

- Asymmetric broad-spectrum lighting at dimmed levels will result in maximum energy savings due to increased detection distances even at dimmed lighting levels.

Vertical Illuminance and Luminance

- The asymmetric luminaire design approach relies on the propagation of light at higher angles, resulting in a greater ratio of vertical illuminance to horizontal illuminance. This will likely result in higher luminance conditions for vertical targets as well, which should result in greater contrast between vertical and horizontal surfaces (target versus background/foreground). This shift in the light propagation in a roadway lighting system may result in considerable improvements in visibility.

CCT Importance

- Changing CCT for broad-spectrum lighting will not lead to a linear decrease in detection differences and will not follow the lumens-per-watt efficacy. While lower CCT for broad spectrum lighting will have lower detection distances, the difference will be insignificant compared to higher CCT broad spectrum lighting within the range that is considered reasonable for roadway lighting. This will give communities the ability to choose CCT based on community preference without the penalty of reduced energy savings potential.

3 Methodology

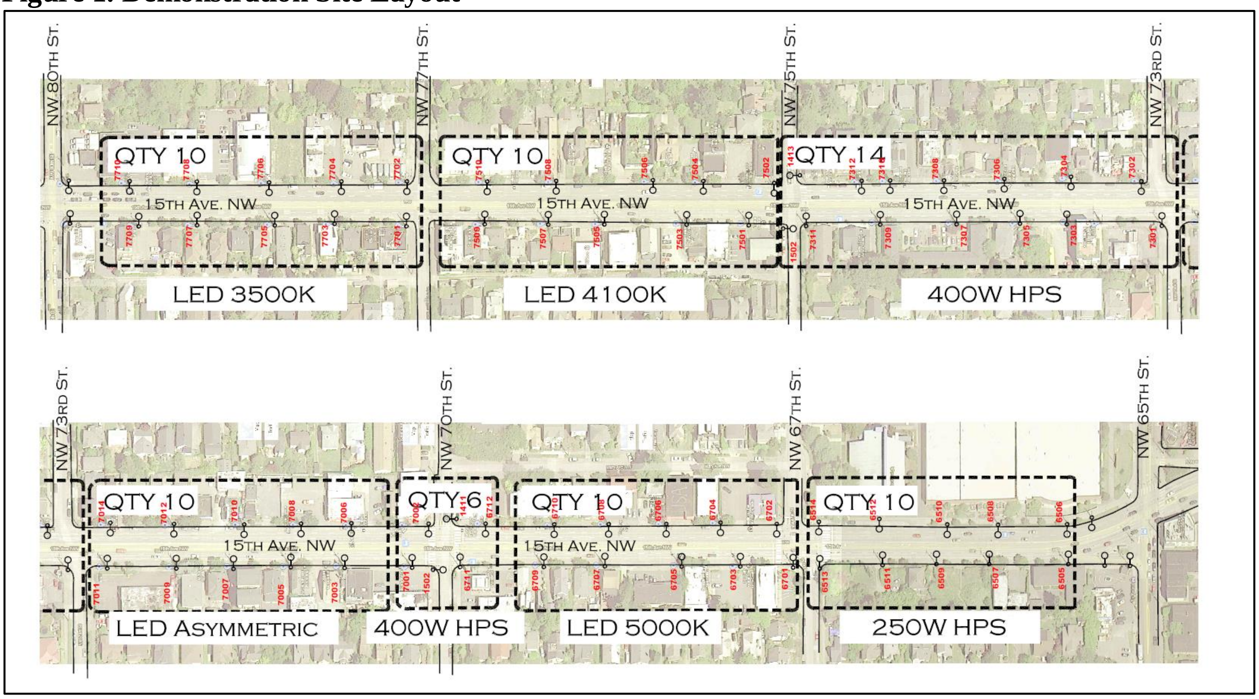
3.1 Overall Project Setup

This demonstration project targeted two audiences over the course of three evenings. On the first evening, industry professionals, media, and political representatives received an overview of the lighting system and the goals of the demonstration project. On the two succeeding evenings, participants from the general population of Seattle, Washington viewed the lighting with both a written evaluation and a user field test.

Researchers conducted the two surveys, a written evaluation and a user field test, to gain an understanding of the public's views on solid state street lighting using LED technology and to quantify the difference in visibility under the new technology and under traditional high pressure sodium (HPS) light sources.

Researchers conducted the demonstration along a portion of 15th Avenue Northwest in the Ballard neighborhood in Seattle, Washington. The 15-block stretch of the demonstration test site contained six test areas, as shown in Figure 1 below.

Figure 1. Demonstration Site Layout



While the test site contained two 400 W HPS sections, the study surveyed only the larger of the two. The integrity of the study required equal numbers of LED luminaires in each test area. Given the existing layout of the lighting along this street, the intersection at NW 70th Street has too few luminaires for its own test area, so it remained with the Seattle City standard 400 W HPS streetlights.

Two of the test areas used HPS, one with 400 W light sources and one with 250 W light sources. Both of these test areas used cobra-head-style luminaires. The other test areas used LED luminaires of varying distributions and color temperatures, as outlined in Table 2.

Table 2. Summary of Test Areas

Summary of Test Areas						
	Test Area 1	**Test Area 2**	**Test Area 3**	**Test Area 4**	**Test Area 5**	**Test Area 6**
Light Source	LED	LED	HPS	LED	LED	HPS
Color Temperature	3500K	4100K	2000K	4100K	5000K	2000K
Distribution	Type II	Type II	Type II	Type II	Asymmetric	Type II

Note: Color temperature values are as stated by the manufacturer; they were not measured.

3.2 Site Selection

Researchers began selection of the demonstration site in June 2011. The Seattle Department of Transportation (SDOT) provided a list of possible streets and vetted them for consistency of streetlight arrangement and spacing. Researchers also considered ease of closing the road to through traffic. Possible demonstration site locations included:

- *8th Avenue NW between NW 51st Street and NW 45th Street*
- *4th Avenue South between South Industrial Way and South Michigan Street*
- *Winona Avenue North between N 76th Street and North 66th Street*
- *West Nickerson Street between 13th Avenue West and Warren Avenue North*
- *Greenwood Avenue North between North 95th Street and North 74th Street*
- *1st Avenue between the West Seattle Bridge and East Marginal Way*
- *35th Avenue SW between SW Thistle Street and SW Roxbury Street*
- *California Avenue SW between SW Edmunds and SW Myrtle Street*
- *15th Avenue NW between NW 85th Street and NW 65th Street*

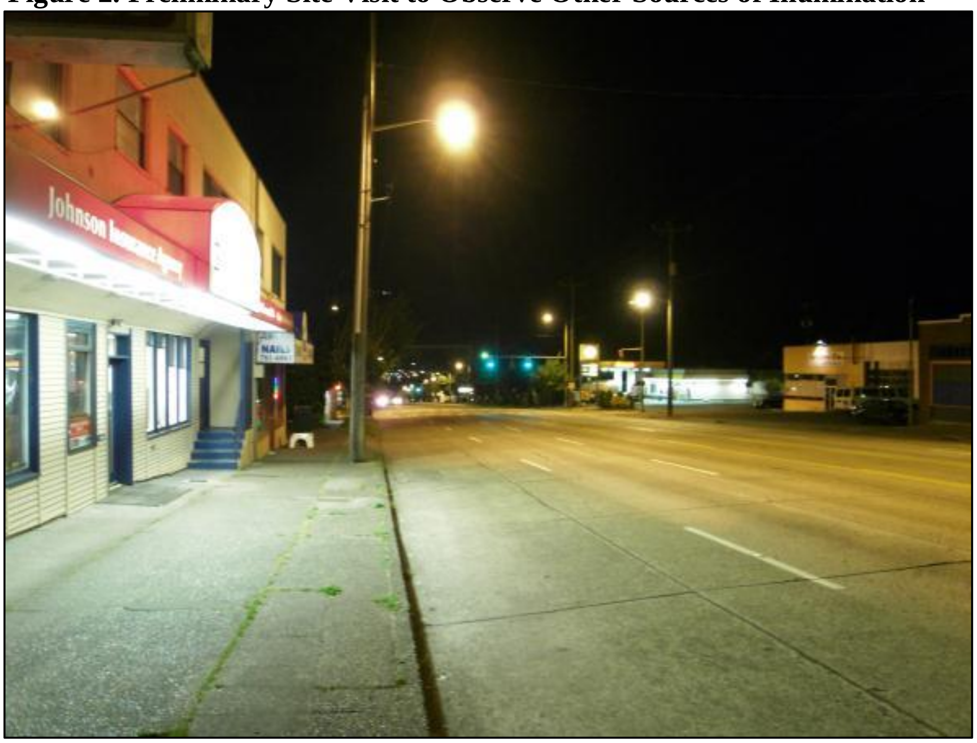
Researchers finalized the demonstration site at 15th Avenue NW because it is long enough to accommodate six test areas, it has a fairly uniform opposite pole arrangement, it does not cross major streets, and it is straight with a uniform width throughout. The demonstration site was originally intended to start at NW 85th Street and continue to NW 65th Street. A paving project in that area with a detour route along NW 83rd Street moved the demonstration site to the stretch from NW 80th Street to NW 65th Street.

Once researchers had selected the demonstration site, the SDOT conducted a truck turning movement study and developed a detour route. Coordination with the Metro bus service began to design a detour route that would minimize the impact on ridership.

While SDOT coordinated the road closure along 15th Avenue NW, Clanton & Associates and VTTI developed the characteristics of the lighting. Seattle City Light (SCL) conducted a site visit to observe the luminaire mounting height, existing light source wattage, light source type, arm length, pole spacing, and other sources of illumination along the site aside from street lighting. The characteristics of the roadway include:

- *Seventy feet curb to curb width*
- *Ten feet center lane – no median*
- *Three lanes of traffic in each direction*
- *Single head luminaire*
- *Six foot arm length*
- *Thirty foot luminaire mounting height*
- *Wooden poles*
- *Overhead electric feeds*
- *~130-foot spacing pole to pole*

Figure 2. Preliminary Site Visit to Observe Other Sources of Illumination



3.3 Public Outreach

In advance of the demonstration, SDOT notified business owners and residents in the vicinity of 15th Avenue NW. Each business owner received notice of the demonstration and street closure in a one-page handout. SDOT mailed residents in the area near the demonstration site a postcard notifying them of the street closure and detour routes. SDOT also contacted the local neighborhood blog, The Ballard Blog, to inform residents as well as to recruit participants for the demonstration. SDOT also provided a press release with details of the demonstration and street closure. Appendix J: Public Outreach shows all of the outreach documents.

3.4 Lighting Criteria

The existing HPS luminaires along the stretch of 15th Avenue NW consist of 400 W light sources meeting the current City of Seattle prescriptive standards. To provide a baseline for comparison, Clanton & Associates designed the new LED streetlights around performance criteria recommended by the Illuminating Engineering Society of North America (IES), *Recommended Practice for Roadway Lighting* (RP-8). The roadway and pedestrian classification determined the luminance criteria to use for the design. The area surrounding the demonstration site is mainly residential with some commercial buildings along 15th Avenue NW. During the daytime, 15th Avenue NW is heavily-used with three lanes of traffic in each direction with a center turn lane. At night, the street reduces to two lanes of traffic in each direction, with parallel parking in the third lane. These conditions classify the site as a collector roadway.

The IES defines a collector road as:

> "A roadway servicing traffic between major and local streets. These are streets used mainly for traffic movements within residential, commercial, and industrial areas. They do not handle long, through trips. Collector streets may be used for truck and bus movements and give direct service to abutting properties."

Two schools are located within two blocks of the demonstration site. Pedestrian activity is moderate during the nighttime. Many residents in the nearby area walk their pets along 15th Avenue NW. Given these conditions, the demonstration is classified as having medium pedestrian conflict.

IES RP-8 (2005) defines a medium pedestrian conflict as:

> "An area where lesser numbers of pedestrians utilize streets at night. Typical are downtown office areas, blocks with libraries, apartments, neighborhood shopping, industrial, older city streets, and streets with transit lines."

Clanton & Associates selected the wattage and distribution for the new LED streetlights based upon their performance in meeting the criteria in the following table.

Table 3. IES RP-8 Luminance Criteria for New LED Streetlights

Luminance Criteria for New LED Streetlights					
Roadway Classification	**Pedestrian Conflict Area**	**Average Luminance L_{avg} (cd/m^2)**	**Uniformity Ratio L_{avg}/L_{min} (max)**	**Uniformity Ratio L_{max}/L_{min} (max)**	**Veiling Luminance Ratio L_{vmax}/L_{avg} (max)**

Collector	Medium	0.6	3.5	6.0	0.4

Clanton & Associates used no luminance criteria for the HPS luminaires. The 400 W HPS luminaires represent the City of Seattle's standard luminaire on this type of roadway. The 250 W HPS luminaires compare the visibility performance to that observed in other studies and to the higher 400 W luminaire.

3.5 Luminaire Selection

Philips Lumec RoadStar provided the LED luminaires for the demonstration. Selecting one manufacturer streamlined the procurement and installation processes while eliminating any variables due to distribution types and reflector components. Clanton & Associates also considered the IES TM-15-11 Backlight Uplight Glare (BUG) ratings in luminaire selection. Clanton & Associates selected no luminaires with uplight ratings above 0 (U0) or glare ratings above 2 (G2) to limit options appropriate for a mixed-use neighborhood.

In order to meet the luminance criteria outlined in IES RP-8, Clanton & Associates selected the Lumec GPLM 105 W Type II luminaire. This luminaire comes standard with a correlated color temperature (CCT) of 4100K and consumes 105 W. Lumec provided the other, non-standard luminaires with CCTs of 3500K and 5000K for this demonstration. Lumec also provided a custom-designed asymmetric luminaire: CCT 4100K. Clanton & Associates used the lighting software AGi32 and a 0.765 light loss factor for all lighting calculations; this value is based upon Philips Lumec's 0.85 lamp lumen depreciation value and a 0.9 luminaire direct depreciation factor. Appendix E: Preliminary Luminaire Testing shows all calculations.

The four LED test areas each contained ten luminaires. Because the research included the effect of color temperature on participant opinions, the test areas also represented three different color temperatures: 3500K, 4100K, and 5000K. All ten luminaires have a standard Type II distribution for each of these color temperatures. The fourth test area also has a color temperature of 4100K with an additional custom asymmetric distribution designed specifically for this study.

3.6 Controls Selection

Owlet's Nightshift system controls the LED luminaires. Each luminaire contains one 2mW luminaire controller (LuCo) at 120 volts. One segment controller (SeCo) receives signals from each of the LuCos. This system can remotely meter energy consumption, provide two-way communication with status updates, and dim the lights on command or on schedule.
At the time of specification, the City of Seattle was also implementing the Owlet control system on another project.

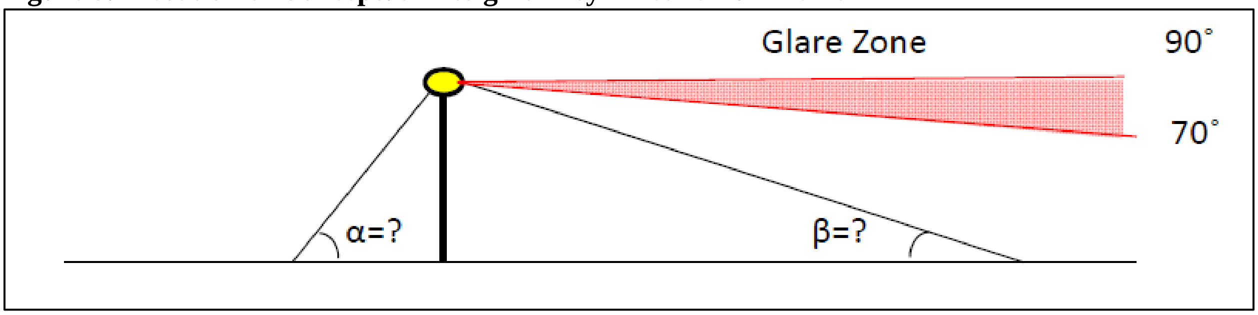
To ensure that the signal would propagate along the entire demonstration site, SCL installed two 10W LuCos within the 400 W HPS test area. These LuCos bypass the HPS luminaires and only act as repeaters to the next LED LuCos so the entire system receives a signal.

3.7 Asymmetric Luminaire Design

As mentioned above, the luminaires in test area 4 utilize a non-traditional distribution. Instead of offering even light distribution both toward and away from the driver, this design directs the majority of the light away from the oncoming car, effectively “leading” the driver (pro-beam) down the road, in a manner similar to extending the headlight range. This design is intended to compare the measured detection distance under the asymmetric luminaire to a standard Type II distribution luminaire. The reflected glare from wet pavement can cause discomfort and can impair a driver’s ability to see; however, if the majority of the light leaving the luminaire is pro-beam, reflected glare will be decreased and will, in theory, increase the visibility of the driver.

Coordination with Philips Lumec began in June of 2011. Because the demonstration site was not yet finalized and the luminaire design depended on the specific road dimensions, Lumec did not begin luminaire design until October 2011. Figure 3 shows one of the initial conceptual drawings for the demonstration.

Figure 3. Elevation of Conceptual Design of Asymmetric Luminaire



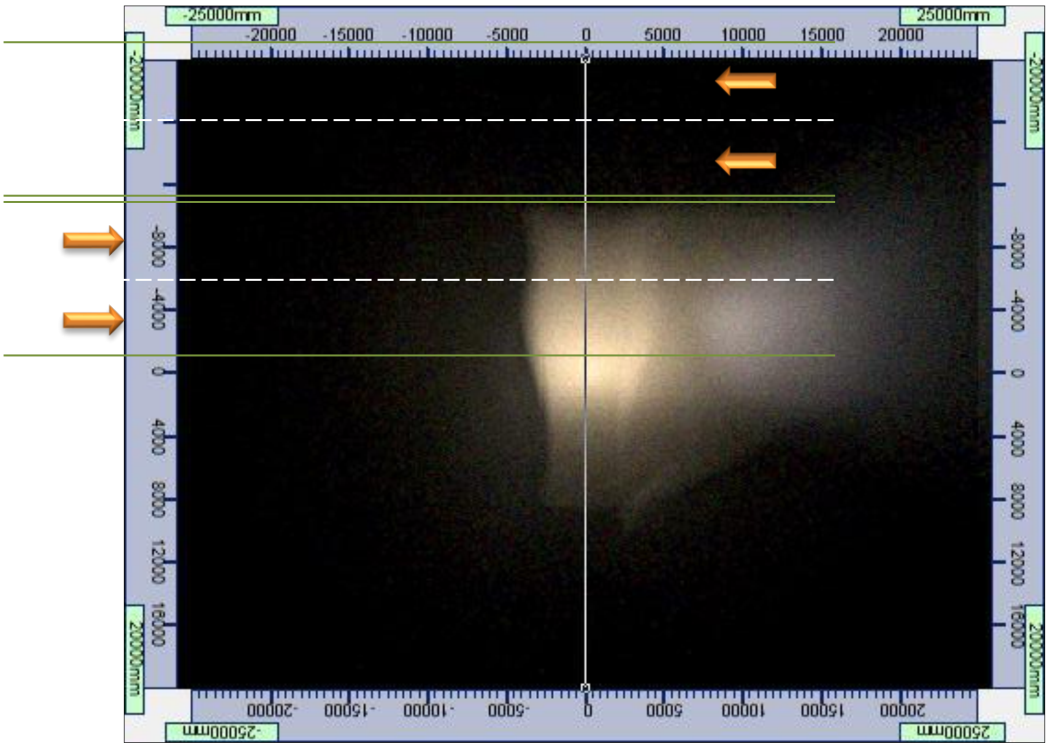
After the finalizing the demonstration site, Clanton refined and optimized the design to meet the exact conditions of the roadway. It provided Philips Lumec with the roadway characteristics as well as design parameters, which included:

- Maximize small target visibility (STV)
- Have a maximum to minimum luminance uniformity ratio of no greater than 10:1
- Maintain the same BUG glare rating of G2 as the symmetric luminaires
- Do not allow pro-beam (the forward distribution of the light) to cross into oncoming traffic, where it would become a glare source for motorists on the opposite side of the street

This new distribution design does not meet the average luminance values in IES RP-8. However, while the average luminance levels would be less, maximizing the STV may result in uncompromised visibility.

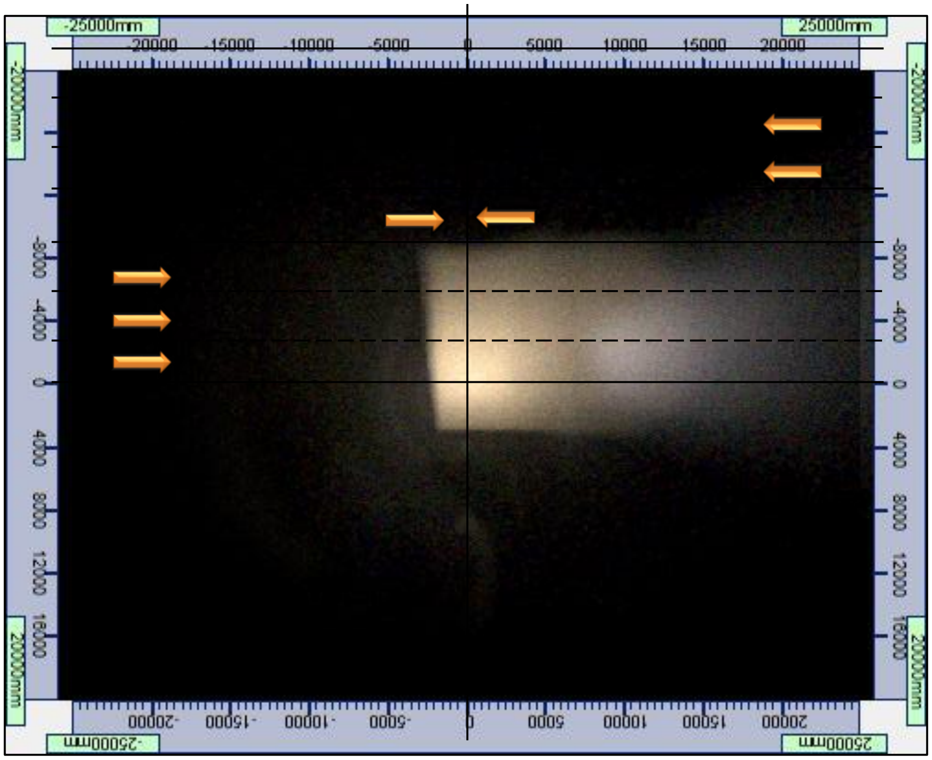
The initial design provided by Philips Lumec met these requirements, as illustrated in Figure 4. It shows minimal light crossing into oncoming traffic and the majority of the light from the luminaire leading the driver. A sharp light cutoff to the left of the luminaire creates a unique distribution, noticeable in the field.

Figure 4. Preliminary Asymmetric Luminaire Design by Philips Lumec



While the first design met all of the design requirements, Clanton & Associates directed Philips Lumec to revise the original design to an IES BUG uplight rating of 0, to further reduce the light crossing over onto oncoming traffic and to maintain or increase small target visibility. The second asymmetric luminaire design (Figure 5) increased the STV from 4.6 to 5.4, and lowered the glare threshold along with the average luminance.

Figure 5. Second Asymmetric Luminaire Design



Philips Lumec revised the second design to exclude the backlight mask and created a third and final design that was completed in early November 2011. Philips Lumec began production on this design in early 2012. It delivered one luminaire of each type to VTTI for preliminary testing, and shipped the remaining nine of each type to Seattle for installation.

3.8 Road Conditions

Because of the Pacific Northwest's rainy climate, the demonstration evaluated the streetlight performance with two different pavement conditions: dry and wet. Fog is also prevalent in this area but is quite difficult to generate on command. VTTI made plans to accommodate for fog in the calculation results should it be experienced during the demonstration, but it made no plans to generate artificial fog.

Clanton & Associates scheduled the demonstration for the first week of March 2012. Since wetting a dry road is easier than drying a wet road, Clanton & Associates scheduled the demonstration for a time when the probability of rain was small, but also prior to the onset of Daylight Saving Time. The demonstration had to begin no sooner than an hour after sunset. Later sunsets as summer approaches increases the difficulty of getting participants to attend a post-sunset demonstration later in the night. Given all these considerations, Clanton & Associates decided that the ideal time for the demonstration would be March 6, March 7 and March 8 from 8:00 p.m. to 1:00 a.m. each night.

Since the demonstration required one evening with dry roads and one evening with wet roads, Clanton & Associates along with SDOT had several contingency plans in place to address potential weather issues. If the roads were dry all three evenings, they would be artificially wetted one evening to simulate rain conditions. If the roads were wet all three evenings, Clanton & Associates and VTTI would conduct only two evenings (one with media and industry professionals and another for participants) of surveys, with a makeup date scheduled later in the year when the probability of dry roads would be higher. Continuum Industries printed all of the written evaluations on waterproof paper in the event of rain while participants completed their surveys.

3.9 Light Output Level

The study evaluated three light output levels for the LED luminaires: one hundred percent, fifty percent, and twenty-five percent of full light output. This effort evaluated the concept of adaptive lighting standards and determined the effect of reduced light levels at lower traffic volume conditions at nighttime.

Adjustments to the voltage inputs provided to the luminaire via the Owlet control system tunes the light output of the luminaires. Prior to the demonstration, Philips Lumec sent a sample of each luminaire to VTTI, where preliminary testing determined the corresponding voltage inputs for each light output value (one hundred percent, fifty percent, and twenty-five percent). See Appendix E: Preliminary Luminaire Testing for additional information.

3.10 Participant Recruitment

Continuum Industries recruited approximately 180 participants for each night of the demonstration, sixty for each of the three light levels. VTTI determined the number of recruits for the user field test based on the required number of eighteen participants for each light level. The fact that historically many participants choose not to ride in the user field test vehicle dictated an over-recruit of approximately three times the required number of participants for each light level.

SDOT provided assistance for recruitment outlets throughout the City. Continuum offered each potential recruit a forty-dollar gift card as an incentive for participation.

Continuum recruited participants from across Seattle through colleges and universities, as well as through employment offices and non-profits. It encouraged non-profits to alert their constituents about the survey, and several used the forty-dollar gift cards as fund-raising opportunities by having members donate their gift card directly to the organization. Continuum also targeted participants from sources closer to the test site, including neighborhood associations and assisted living facilities. It also informed businesses affected by the street closures of the opportunity to participate in the test as means of generating community interest and goodwill.

Individuals interested in participating signed up online via a recruitment website that collected contact information, availability by date and time, gender, and age. The recruitment website also educated participants on what the demonstration would require of them. As the survey dates drew near, Continuum Industries contacted participants via email and phone with priority based on the dates of their online registration and on their age groups. To account for changes to the human eye over a lifetime, Continuum made every effort to evenly represent each age group for each light level of the test. Given the weather contingency plans and the intent to have a representative sample of age groups, some participants were recruited for both nights of testing, at different light levels.

3.11 Written Evaluation

On each of the two nights of general participant testing, participants completed subjective surveys for each test area. Clanton & Associates modified a survey originally developed for parking lot lighting surveys by Dr. Peter Boyce, formerly of the Lighting Research Center, to render it suitable for use in street lighting demonstrations. The team used this same survey to evaluate the street lighting in Anchorage, Alaska; San Diego, California; San Jose, California; and Roseville, California.

The written evaluation asked participants a series of general questions based upon where they live, in addition to demographic questions and site condition questions. For each test area, a participant next rated twelve statements on a five-point scale (strongly disagree to strongly agree). Following are the statements that comprised the written evaluation:

1. It would be safe to walk here, alone, during daylight hours.
2. It would be safe to walk here, alone, during darkness hours.
3. The lighting is comfortable.
4. There is too much light on the street.
5. There is not enough light on the street.
6. The light is uneven (patchy).
7. The light sources are glaring.
8. It would safe to walk on the sidewalk here at night.
9. I cannot tell the colors of things due to the lighting.
10. The lighting enables safe vehicular navigation.
11. I like the color of the light.
12. I would like this style of lighting on my city streets.

Participants also answered an additional question on the scale of much worse to much better

13. How does the lighting in this area compare with the lighting of similar Seattle city streets at night?

3.12 User Field Test

Equipment

The data collection equipment used during the experiment consisted of a variety of components for collecting illuminance, luminance, color temperature, and participant response data. Most of these are part of the Roadway Lighting Mobile Measurement System (RLMMS), a device created by the Center for Infrastructure Based Safety Systems (CIBSS) at VTTI as a method for collecting roadway lighting data in addition to participant response data.

VTTI mounted a specially-designed “Spider” apparatus containing four waterproof Minolta illuminance detector heads horizontally onto the vehicle roof in a manner that positioned two illuminance detector heads over the right and left wheel paths and positioned the other two illuminance detector heads along the centerline of the vehicle. VTTI positioned an additional vertically-mounted illuminance meter in the vehicle windshield as a method to measure glare from the lighting installations. VTTI connected the waterproof detector heads and the windshield-mounted Minolta head to separate Minolta T-10 bodies that sent data to the data collection PC positioned in the trunk of the vehicle.

VTTI positioned a NovAtel Global Positioning Device (GPS) at the center of the four roof-mounted illuminance meters and attached it to the “Spider” apparatus. It connected the GPS device to the data collection computer via USB so the vehicle latitude and longitude data was incorporated into the overall data file.

VTTI mounted two separate video cameras on the vehicle windshield. One collected color images of the forward-driving luminous scene and the second collected luminance information for the forward-driving luminous scene. VTTI connected each camera to a standalone computer that was in turn connected to the data collection computer. The data collection computer recorded illuminance, human response (reaction times), and GPS data and synchronized the camera computer images with a common timestamp. Additional equipment inside the vehicle consisted of individual input boxes for participant-entered responses and a Controller Area Network (CAN) reader for collecting vehicle network information.

A specialized software program created in LabVIEW™ controls each component of the RLMMS. The software synchronizes the entire hardware suite and sets data collection rates at 20Hz. VTTI set the video image capture rate for this demonstration at 3.75 frames per second (fps). The final output file used during the analysis contained a synchronization stamp, GPS information (such as latitude and longitude), input box button presses, individual images from each of the cameras inside the vehicle, vehicle speed, vehicle distance, and the illuminance meter data from each of the four Minolta T-10s. VTTI incorporated the vehicle’s latitude and longitude data into the overall data file via USB connection to the data collection computer.

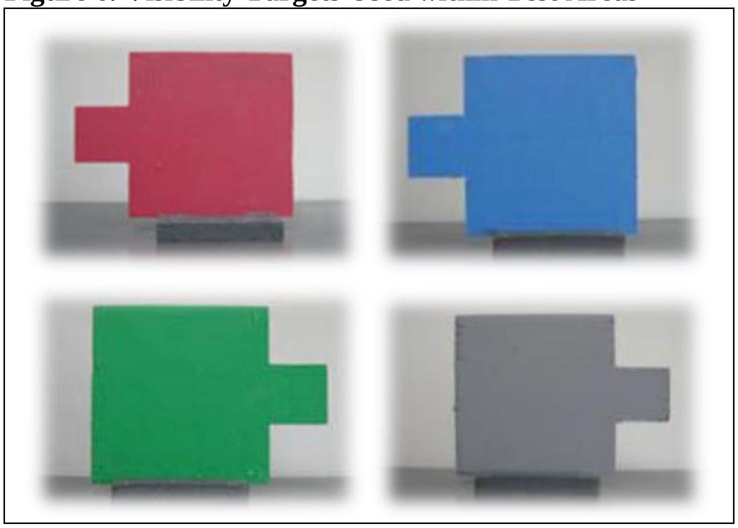
Visibility Targets

Research has established a relationship between certain visibility metrics and the detection and avoidance of a small object on a roadway. Research has also established a correlation between these visibility metrics and the frequency of vehicular accidents at night. Small Target Visibility (STV) is a method to calculate this relationship.

The STV method (as defined by IES RP-8) is used to determine the visibility level of an array of targets along the roadway when considering certain factors such as the luminance of the targets, the luminance of the immediate background, the adaptation level of the adjacent surroundings, and the disability glare. The weighted average of the visibility level of these targets results in the STV value.

The visibility targets for this demonstration are wooden squares seven inches on each side, with a tab measuring 2.375 inches by 2.375 inches on one side (pictured in Figure 6). The targets came in four colors: red, green, gray, and blue. VTTI painted the target bases to be similar to the road surface. VTTI placed these objects along the roadway as the objects of interest in the performance portion of the project.

Figure 6. Visibility Targets Used within Test Areas



VTTI positioned targets of each color within each of the test areas to achieve a consistent level of vertical illuminance for all luminaire types. Each target location had fourteen lux of vertical illuminance except for the 400 W HPS section, where twenty lux was the lowest achievable vertical illuminance.

VTTI's goals in setting up the visibility targets consisted of exposing each luminaire type to each target color and matching each location by vertical illuminance. VTTI paired the target colors (green/gray and red/blue) and intermittently shifted them among luminaires during breaks when the luminaires were dimmed. The percent reflectance by each target color is shown in Table 4.

Table 4. Percent Reflectance by Target Color

Color	Reflectance
Gray	17%
Green	17%

Blue	15%
Red	12%

Illuminance more directly characterizes a luminaire’s output, whereas luminance more directly characterizes the amount of light perceived. Matching the targets for illuminance isolates the lighting output, thus making the luminaires comparable on that basis. Matching the targets for luminance would require considerations of target surface reflectance, road surface reflectance, and target color.

4 Procedure

4.1 Equipment Pretesting

Prior to the demonstration, VTTI received four luminaires (one of each of the four types of LED luminaires) and all equipment necessary to operate the control system. This preliminary testing ensured that the luminaires were operating as specified and determined the driver voltage inputs corresponding to the desired light output levels of one hundred percent, fifty percent, and twenty-five percent. While the testing also included correlated color temperature measurement, the results of the color temperature test were inconclusive.

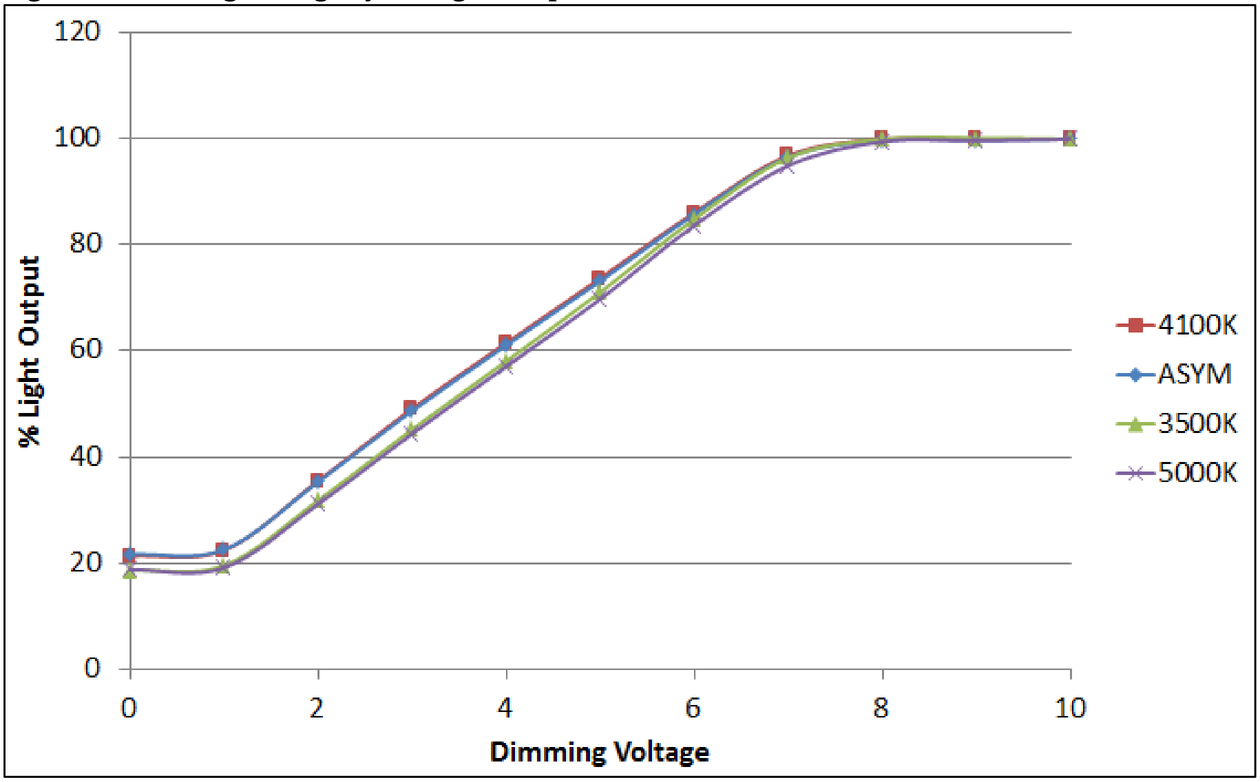
The testing process entailed mounting each luminaire in the VTTI test facility for a “burning-in” time of approximately one hundred hours. Next, VTTI individually mounted the luminaires in the outdoor environment at the VTTI test facility (Figure 7). In this location, VTTI measured the output of the luminaire in terms of horizontal and vertical illuminance along a grid of test locations beneath and to the side of the luminaire.

Figure 7. Laboratory Evaluation Grid

Dimming Data

VTTI also measured the effects of dimming each LED luminaire. Figure 8 shows the relationship between the dimming voltage and the percent of light output for each luminaire. The results indicate that as dimming voltage increases, the percent of light output also increases similarly for each luminaire.

Figure 8. Dimming Voltage by % Light Output



VTTI used the 1-10 dimming voltage inputs collected through this preliminary testing to allow the control system to tune the lights at the desired light levels. The values calculated are:

- One hundred percent *light output – 8V*
- Fifty percent *light output – 3.1V*
- Twenty-five percent *light output – 1.2V*

VTTI modified the final voltage inputs from the above values because the control system needs to have a linear curve between the low and high value in order to function properly. Therefore, the low voltage inputs used during the demonstration are:

- One hundred percent *light output – 8V*
- Fifty percent *light output – 3.3V*
- Twenty-five percent *light output – 1V*

The relationship in Figure 9 shows the illuminance for each luminaire as it is dimmed or brightened. Illuminance differs among the luminaires, but the relationship is similar for each.

Figure 9. Dimming Voltage by Illuminance (lx)

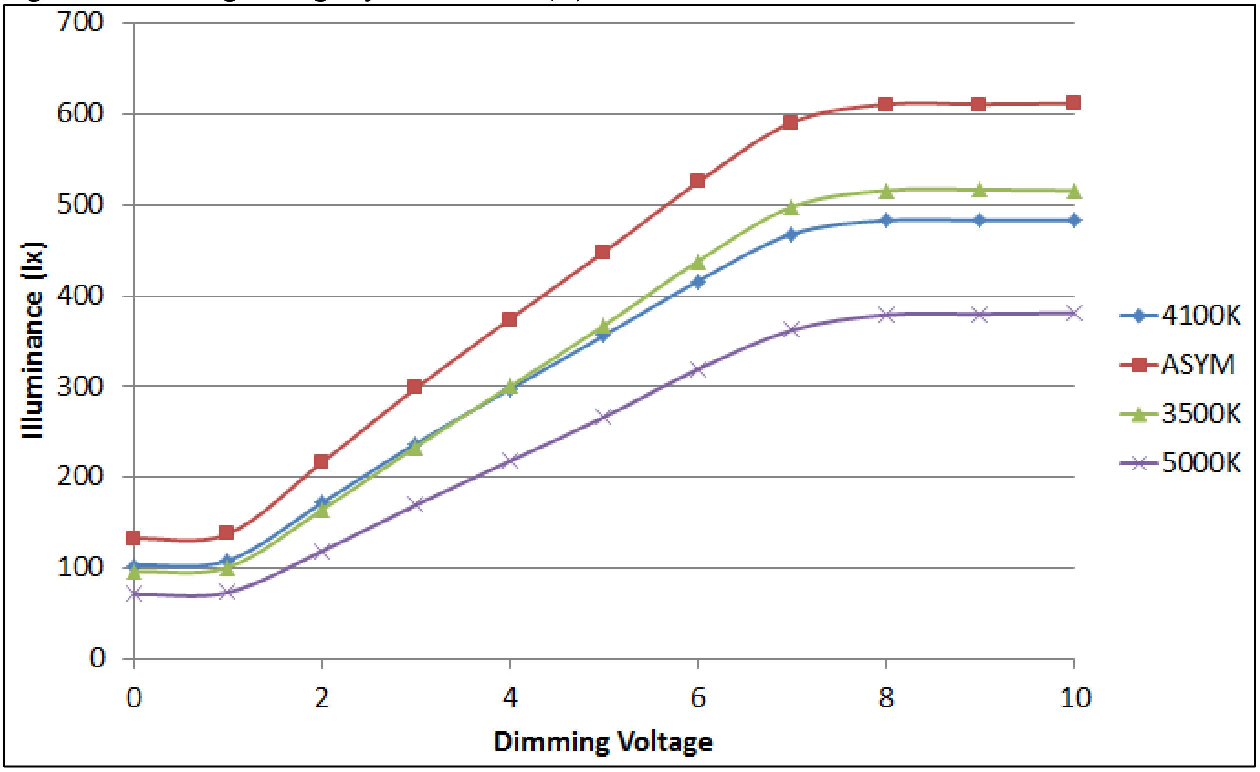


Table 5. Summary of Lab Light Trespass

Summary of Lab Light Trespass								
	4100K		**ASYM**		**3500K**		**5000K**	
	HS	**SS**	**HS**	**SS**	**HS**	**SS**	**HS**	**SS**
Average Lab Measured Light Trespass (lux)	4.21*	2.23	1.68*	1.99	2.37*	4.67	2.22*	4.74
Max (lux)	4.88	4.75	4.13	4.42	4.64	5.51	4.42	5.36
Min (lux)	3.37	0.53	0.37	0.22	0.69	3.26	0.61	4.05

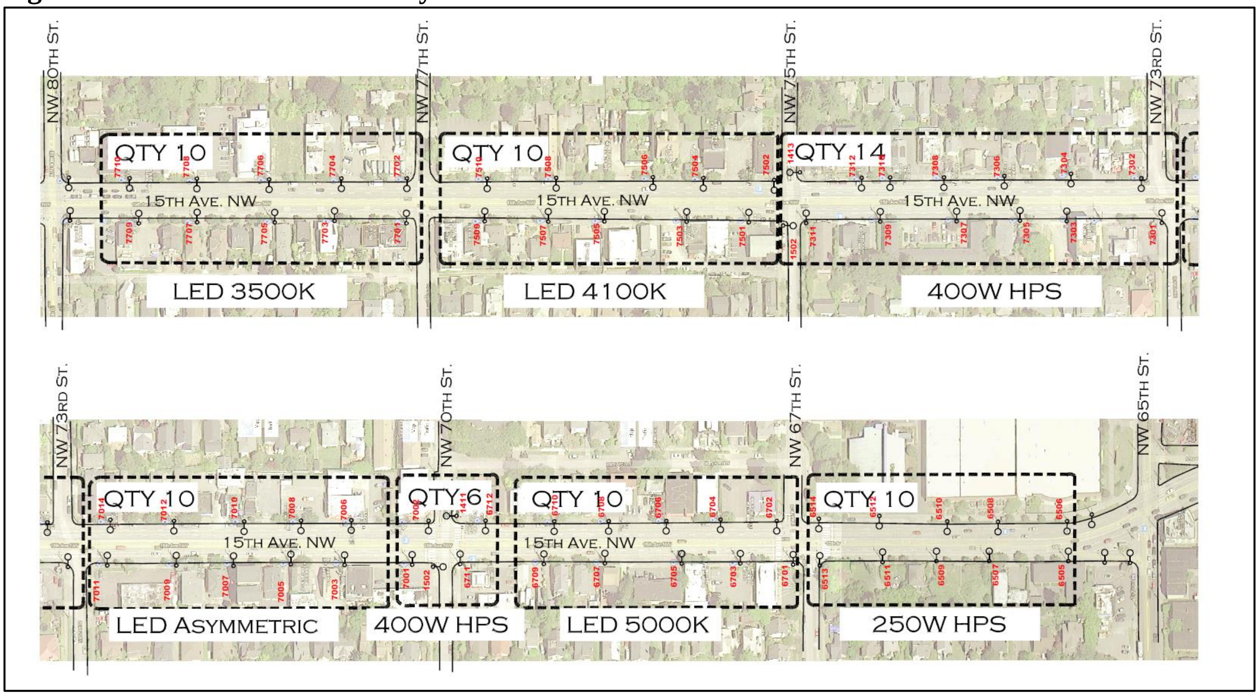
Note: * Meets pre-curfew and post-curfew limit

Based on the IES recommendation, the four luminaires evaluated are below the light trespass limit. Appendix E: Preliminary Luminaire Testing contains additional collected data.

4.2 Equipment Installation

SCL installed all new light sources and cleaned luminaires to ensure that all 400W HPS luminaires along the demonstration site were not subject to dirt or luminaire depreciation. SCL also purchased and installed ten 250 W HPS cobra head luminaires. Lumec shipped forty LED luminaires to the City in late January and early February for installation. Figure 10 illustrates the sequence of each of the test areas.

Figure 10. Demonstration Site Layout



Seattle City Light began installing the HPS luminaires first. No luminaire controllers were installed within the housings of the either the 250 W or the 400 W HPS luminaires. Two of the 400 W HPS luminaires have externally-mounted LuCos on their poles; however, the LuCos do not control the light output of the HPS luminaire but instead propagate the signal to the next LED series of luminaires.

Seattle City Light next installed the LED luminaires after completing all of the HPS luminaire installations. Because Philips Lumec had installed the LuCos in the luminaires at the factory, they did not require field installation. SCL staff correlated each LED luminaire with a badge number matching the pole displayed on an aerial image of the demonstration site. A description of the luminaire along with the pole badge number is hand-written on the inside of each housing to help properly identify the placement of the luminaire, as indicated in Figure 11.

Figure 11. Example of Handwritten Description and Badge ID within Housing

Each LuCo has a unique ZigBee label on the module describing the LuCo, luminaire, and GPS location. The installation process also used three other identical labels for each LuCo: one is placed in the luminaire housing, one on the pole that can be read by someone standing on the ground, and the last label is placed on a commissioning spreadsheet.

4.3 Setup of Visibility Targets

The team set up the small visibility targets the night before the demonstration began. The team placed signs along 15th Avenue NW restricting residents from parking on the street.

The team placed each of the four colors of targets (red, blue, green and gray) under each test area and measured the vertical illuminance, with the goal of finding locations within each of the test areas where each target location measured an equal vertical illuminance value under each of the test areas. The team marked the location of the target on the pavement with spray chalk. This demonstration did not use yellow targets because the researchers could not find a yellow paint color with a reflectance comparable to the other target colors.

The researchers found target locations with achieved vertical illuminance values of fourteen lux for five of the six test areas. The 400 W HPS test area was unable to achieve a fourteen-lux vertical illuminance value; this area achieved a lowest vertical illuminance value of twenty lux. Researchers do not expect this higher illuminance level to affect the results, as visibility is based on contrast and illuminance. While this area exhibited a higher target illuminance, the roadway illuminance was higher as well, and the contrast should remain unaffected. The contrast is explored in more detail later in this investigation.

To simulate rain on the roads, SDOT flusher trucks artificially wetted the roads for the March 8 demonstration. They sprayed the entire width of 15th Avenue NW from NW 80th Street to NW 65th Street. The flusher trucks sprayed down the road three times: once immediately after the road closure, and then again before both the first and second dimming tests while the lights were being dimmed. The sidewalks where participants were completing the written evaluations received no water from the flusher trucks.

4.4 Written Evaluations and User Field Tests

Three groups of participants took part in the written evaluations on each of the two nights of general participant testing. Each of the three groups arrived at different times throughout the evening. The first group arrived at 7:00 p.m.; the second group at 8:30 p.m.; the third group at10:00 p.m. At the arrival of each group, the participants where then divided into two subgroups based upon assigned color of their written evaluations.

A bus dropped off the first subgroup at the intersection of 15th Avenue NW and NW 80th Street. This group of participants made its evaluations on the west side of the street and took advantage of the slight downhill topography. The second subgroup started at the intersection of 15th Avenue NW and NW 65th Street. This group walked slightly uphill and made its evaluations from the east side of the street.

Beginning at 8:00 p.m. each night, SDOT and the Seattle Police Department began closing 15th Avenue NW between NW 65th Street and NW 80th Street. The road remained closed until 1:00 a.m. One police officer stayed at each end of the demonstration site throughout the duration of the survey, and one additional police officer roamed the site throughout the evening. Once the police officers gave clearance to begin the surveys, a team member gave instructions to each group of participants.

Two project team members led each survey group and answered questions. At the beginning of the survey, team members instructed participants not to look up at the streetlights, but rather to evaluate the whole field of view into the street. Team members also instructed participants not to talk to one another to avoid influencing other participants' opinions. In addition to the two team members per group, SCL staff members helped on site to manage traffic and to keep the visibility targets in the correct standing positions. Two private security officers also remained on site for the duration of the demonstration.

The bus picked up each subgroup of participants approximately an hour after they had been dropped off. All participants returned to Salmon Bay middle school and turned in their surveys in exchange for the forty-dollar gift card incentive.

4.5 Experimental Protocol

A member from the VTTI team drove the experimental vehicle at a maximum speed of thirty-five mph. Researchers selected the thirty-five mph speed as a typical speed for a commercial lighting roadway, and simulated stopping distances outside of headlamp range. The experimental vehicle drove in the middle of the three lanes, as the far right lane was used for target placement. Along the route, participants pressed buttons when they were confident they had detected the targets located along the roadway. The total testing time for the detection task lasted approximately five minutes.

4.6 Dry Pavement

The dry pavement demonstration ran a total of eighty-three participants in the user field tests. As many as three participants could take part in the driving test at one time. Some runs contained fewer than three participants, depending on the number of volunteers from each subgroup. Table 7 details the number of runs and the number of participants by light level. The light levels are divided into number of runs (or laps) and the number of participants.

Due to a failed video card, VTTI could not record the luminance data concurrently with the participant target detections. It conducted a second data collection effort approximately four months later (July 2012) to gather the necessary luminance data. This data is included in the analysis.

Table 6. Dry Pavement Written Evaluation Test Numbers

Pavement Condition	Light Level	Number of Participants
Dry	100%	62
Dry	50%	54
Dry	25%	49

Table 7. Dry Pavement Participants User Field Test Numbers and Computer Conditions

Pavement Condition	Light Level	Number of Runs (Laps)	Number of Participants	Computer Condition
Dry	100%	9	24	No Video Card
Dry	50%	12	35	No Video Card
Dry	25%	11	24	No Video Card
	TOTAL	**32**	**83**	

4.7 Wet Pavement

As mentioned earlier, SDOT flusher trucks wet the roads for the second evening of general testing. Two trucks arrived on site shortly after the road barricades were up and 15th Avenue NW was officially closed. Each truck held 3,000 gallons of water. Starting full, both trucks began wetting the road near the intersection of NW 15th Avenue and NW 80th Street.

Figure 12. Flusher Truck Wetting the Roads

A total of fifty-one participants participated during the wet pavement portion, thirty-two fewer than the dry pavement portion. Researchers reduced the time for each evaluation group due to the allowance of time for flusher trucks to wet the pavement, thus reducing the number of participants per run. Table 9 details the number of runs, number of participants, and computer conditions for the wet pavement portion of the user field test.

Table 8. Wet Pavement Written Evaluation Test Numbers

Pavement Condition	Light Level	Number of Participants
Wet	100%	59
Wet	50%	59
Wet	25%	49

Table 9. Wet Pavement Participants User Field Test Numbers and Computer Conditions

Pavement Condition	Light Level	Number of Runs (Laps)	Number of Participants	Computer Condition

Wet	100%	10	24	Normal
Wet	50%	7	21	Normal
Wet	25%	2	6	System Error
	TOTAL	**19**	**51**	

Only six participants were able to be tested for the twenty-five percent light level condition as the mobile computer system encountered further communication errors. However, complete luminance data exists for the wet portion, given its ability to record during participant testing.

4.8 Luminance Measurements

As mentioned earlier, a video card failure meant the inability to measure all of the luminance conditions on the first day of the experiment. Luminance data for the dry condition was recorded prior to the wet pavement test after repair of the video card the following day. Unfortunately, time restrictions led to recording only of the one-hundred-percent-lighted scenario; no luminance data of the visibility targets was recorded for the fifty percent or twenty-five percent dim conditions. Table 10 details the available luminance data. In the analysis, the one hundred percent dry data was scaled by the illuminance measurements to provide estimates for the background luminance and the target luminance. Researchers undertook a secondary effort in July 2012 to re-collect luminance data to ensure quality. Unfortunately, wet pavement was not available on this attempt. A discussion of the user field test measurements can be found in Section 5: Discussion.

Table 10. Recorded Luminance Data

Recorded Luminance Data		
March 2012		
Pavement	**Light Level**	**Luminance Data**
Dry	100%	Recorded Luminance
Dry	50%	Unable to Record - Estimated based on the illuminance ratio
Dry	25%	Unable to Record - Estimated based on the illuminance ratio
Wet	100%	Recorded Luminance
Wet	50%	Recorded Luminance
Wet	25%	Recorded Luminance
July 2012		
Pavement	**Light Level**	**Luminance Data**
Dry	100%	Recorded Luminance
Dry	50%	Recorded Luminance
Dry	25%	Recorded Luminance
Wet	100%	Wet Pavement not available
Wet	50%	Wet Pavement not available

Wet	25%	Wet Pavement not available

5 Findings

5.1 Written Evaluation

Researchers administered the written evaluation to participants on each night of the experiment. Each participant rated twelve statements on a scale from “strongly disagree” to “strongly agree.” The statements address perceptions of safety, comfort, glare, preference for light color and color rendering, and overall style. Overall, 332 participants surveyed the test area, roughly split between the wet and dry nights.

Table 11. Written Evaluation Results

Written Evaluation Results		
Topic		**Result**
Statement 1	Safe, daylight hours	Participants considered the street a safe area
Statement 2	Safe, darkness hours	Participants considered the street a safe area, at night, even with dimming.
Statement 3	Comfortable	No statistical difference between responses within a given test area when the light output is reduced to 25% light level.
Statement 4	Too much light	Participants did not rate the HPS luminaires as having too much light.
Statement 5	Not enough light	Asymmetric luminaire showed agreement at all light levels.
Statement 6	Uneven (patchy)	Asymmetric luminaire showed agreement at all light levels.
Statement 7	Glare	Asymmetric had the best glare rating (lowest), followed by the 3500K and 4100K.
Statement 8	Safe on sidewalk	HPS 400 W received highest rating, followed by HPS 250 W.
Statement 9	Cannot tell colors	No statistical differences across color temperatures, including HPS, across all dim levels.
Statement 10	Safe vehicular navigation	HPS luminaires received the highest ratings, while the asymmetric received the lowest ratings.
Statement 11	Color of light	Both HPS sources showed nearly the same neutral preference as the LED sources.
Statement 12	Style of light	With the exception of the asymmetric luminaire, participants preferred the LED luminaires as much as the current 400 W and 250 W HPS standards.

In an effort to recruit enough survey participants, some participants came to both nights of testing. The duplicate participants evaluated different road conditions and light levels each night. The participants had a full twenty-four hours and bright daylight between the two nights of testing, and researchers did not expect their participation on both evenings to significantly affect the results. However, researchers analyzed the duplicate surveys as a group and compared their responses to the larger population to identify any differences.

Statements S3, S5, S10, and S12 (*comfortable, not enough light, vehicular navigation, and style*) exhibited different agreement ratings among those who saw the test areas twice. The participants who saw the test areas twice agreed more strongly with these statements for the 250 watt HPS under the wet condition than did those who went through the test areas once.

Statement S7, *the light sources are glaring*, participants viewing the asymmetric luminaire test area for the second time, under dry conditions and at 25% of full light output, rated their agreement with this statement higher than those who saw the asymmetric luminaire test area for the first time.

When responding to statement S10, *the lighting provides for safe vehicular navigation*, for the asymmetric and 3500K LEDs, participants seeing these areas, under wet conditions, for the second time disagreed with this statement more strongly than did the first-time viewers.

Second-time viewers agreed with statement S12, *I would like this style of lighting*, more strongly than did first-time viewers when evaluating the 250 watt and 400 watt HPS on the wet road conditions.

When responding to statement S13, *comparison of lighting to other City of Seattle streets,* for the 3500K LED, participants seeing these areas for the second time disagreed with this statement more strongly that did the first-time viewers.

These variations between the responses of the repeat participants and the larger study population do not change the overall conclusions drawn from the written evaluation. While most of the variations occurred when participants were viewing the existing HPS luminaires, it is unclear why participants might have rated these more highly on the second night of viewing. Under wet conditions, the standard LED products may have produced more reflected glare on the pavement. The relatively lower glare of the more diffuse HPS sources may have been more noticeable to individuals who had seen a less dramatic difference on the previous night.

To address potential bias in the experiment, researchers divided each of the three groups of participants into two subgroups; half of the participants walked down one side of the street and the other half walked down the other side of the street. For instance, the participants who traveled from south to north generally viewed the LED test areas lower than those who traveled north to south. Although evaluation ratings between the two groups exhibited some trends, the majority of the values are not significantly different from one another. Researchers combined the entire dataset, essentially averaging the two different vantage points.

When researchers analyzed this question by gender, women generally preferred the warmer color temperatures while men tended to prefer cooler color temperatures, as shown in Figure 41 and Figure 42.

Figure 13. Survey Question 11: "I like the color of the light"– Dry Pavement at One Hundred percent (Light Level by Gender)

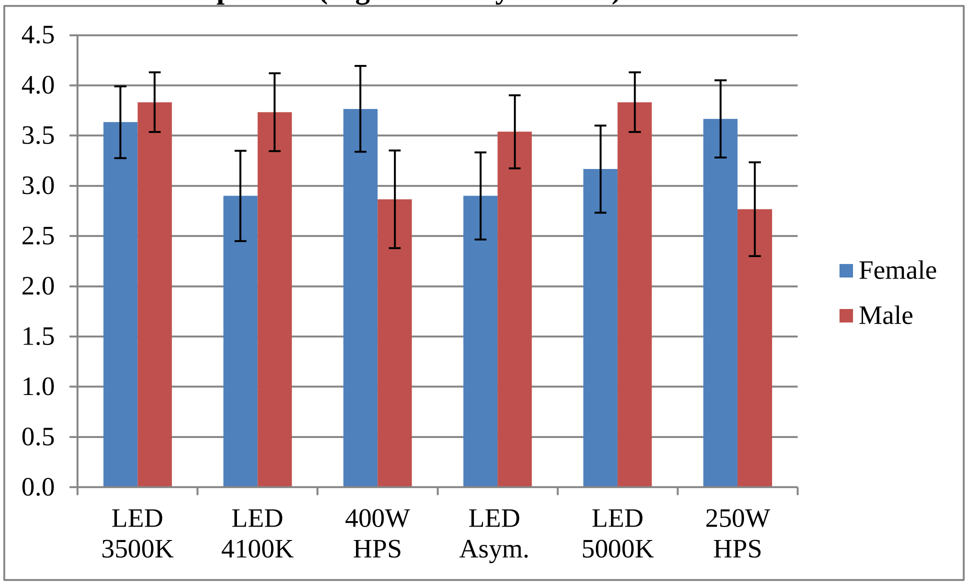
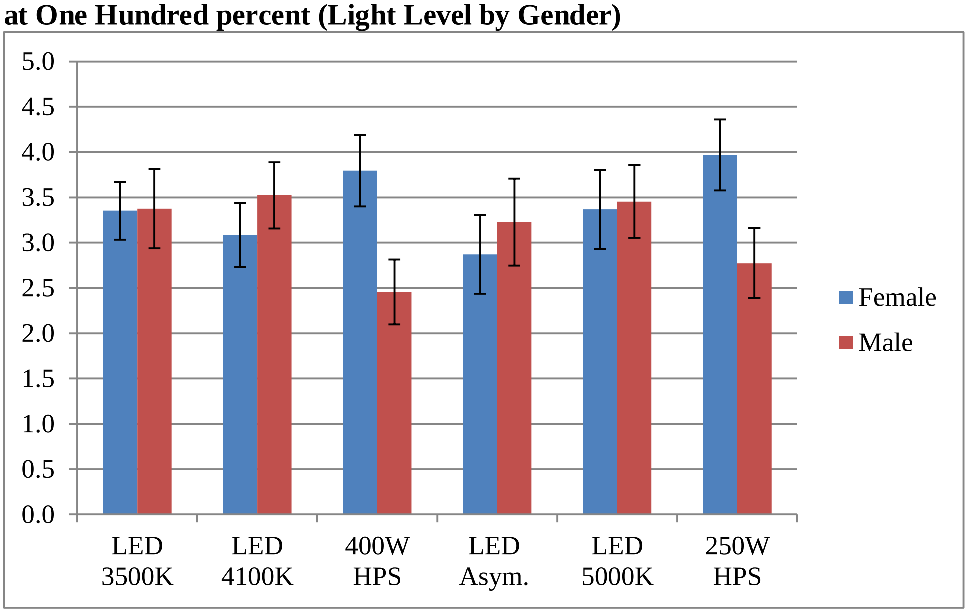


Figure 14. Survey Question 11: "I like the color of the light"– Wet Pavement at One Hundred percent (Light Level by Gender)



Research explains the reasoning behind women's preference for warmer color temperatures (. Some studies on gender and color indicate that women can match colors more accurately and quickly than men. Only the X chromosome contains genes for pigments in red and green cones; since women have two X chromosomes, they have a potential advantage over men for superior vision if their two X chromosomes align in such a way that activates two red and two green cones.

5.2 User Field Test

Data Analysis Approach

Researchers performed analyses for visibility data and for illuminance sensor data. For the user field test visibility analysis, researchers conducted an initial data cleaning in which they located targets via GPS coordinates, verified responses and matched them to each target section, and removed additional data anomalies (outliers) from the data. For example, researchers excluded all data that exceeded three standard deviations away from the mean. Researchers performed an additional data check to look for any other outliers and to check the images associated with the data file. They did so by checking the data in Arc Map and verifying the image information.

Next, the entire data file, including the button input box, latitude and longitude information, and respective images from the color and luminance cameras, was imported into a Statistical Analysis Software (SAS) program for review and analysis. As an example, researchers obtained the detection distance calculation by calculating the distance using latitude and longitude coordinates for each button press. The coordinates for the target locations were registered separately and also integrated to determine the distance from the button press to the target location. Researchers rechecked these calculations using the distance calculation obtained from the vehicle network data. When they had completed the distance calculations, the dataset underwent additional data checking for outliers, and researchers made necessary corrections (including deletions for false button presses and frame corrections, and deletions of anomalous data). Researchers used Analysis of Variance (ANOVA) as the statistical tool to investigate differences among lighting type, lighting location, target color, target location, travel direction, and vertical illuminance level. Findings are shown in Table 12.

Table 12. Luminaire Type, Target Color, Pavement, and Light Level ANOVA Results

ANOVA Results			
Source	**F value**	**Pr>F**	**Significant**
Luminaire Type	38.13	<0.0001	*
Target Color	39.6	<0.0001	*
Light Level	0.01	0.9289	
Pavement Condition	2.22	1.438	
Luminaire Type * Light Level	0.24	0.8704	
Luminaire Type * Pavement	0.83	0.5104	
Luminaire Type * Light Level * Pavement	1.08	0.3675	
Luminaire Type * Target Color	10.42	<0.0001	*

The illuminance data for the lighting sections underwent the same data cleaning process as the visibility (or detection distance) data. Researchers checked the entire data file for anomalies and verified sections with GPS information. They conducted additional spot checks using the color images collected during the drive to verify the section location and starting/ending points for each run.

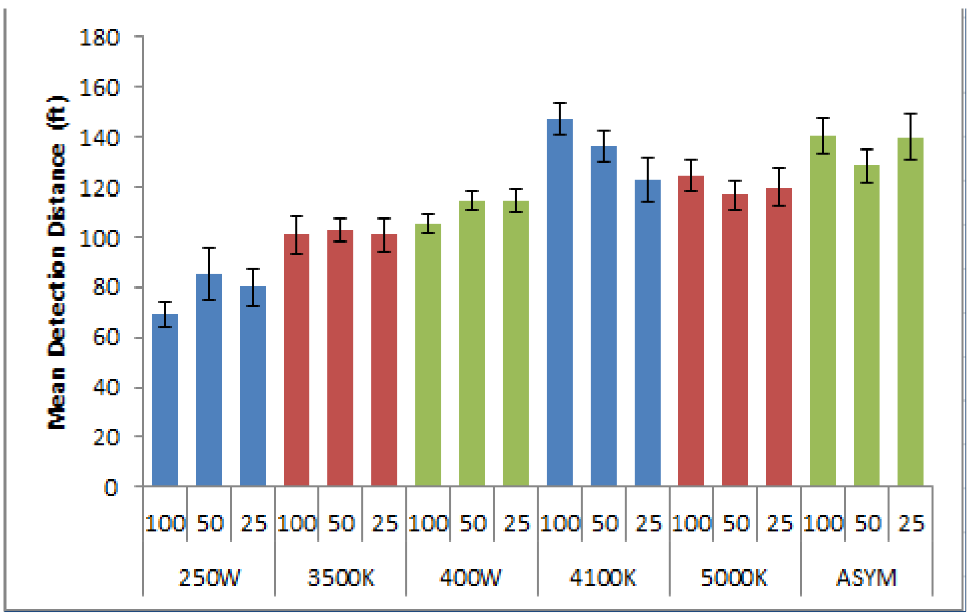
Researchers next imported the cleaned data file into SAS for review and analysis. The illuminance data gave an approximation of the light intensity reaching the road surface, which provided further understanding of the performance of the different lighting sections.

Researchers conducted an additional analysis using detection distance, illuminance, and luminance in a linear regression model. This model allowed better visualization of the linear relationship among the three variables.

Detection Distance

Researchers conducted an Analysis of Co-Variance (ANCOVA) on the detection distance and illuminance data to identify any differences among the lighting sections. They used the Student Newman-Keuls (SNK) test to identify where the significant differences occurred. Figure 15 below highlights the results.

Figure 15. Luminaire Type and Light Level by Detection Distance (Wet and Dry Pavement Combined)



As Figure 15 shows, detection distance is not predictable based on the luminaire's light level. Note that the 250 W and 400 W HPS luminaires were not dimmed for the experiment; the lighting level of the LED luminaires surrounding the HPS luminaires likely affected the contrast of the targets in these sections.

Figure 16 shows comparisons of luminaire types and the pavement conditions by mean detection distance. Dry and wet conditions alone did not exhibit statistically significant differences; however, this relationship shows that the difference in pavement wetness condition did affect some luminaires. The HPS luminaire types (250 W and 400 W) shared a similar trend with the effect of the wet conditions. The differences for the LED luminaire types were more muted.

Figure 16. Luminaire Type and Pavement Condition by Detection Distance (All Light Levels Combined)

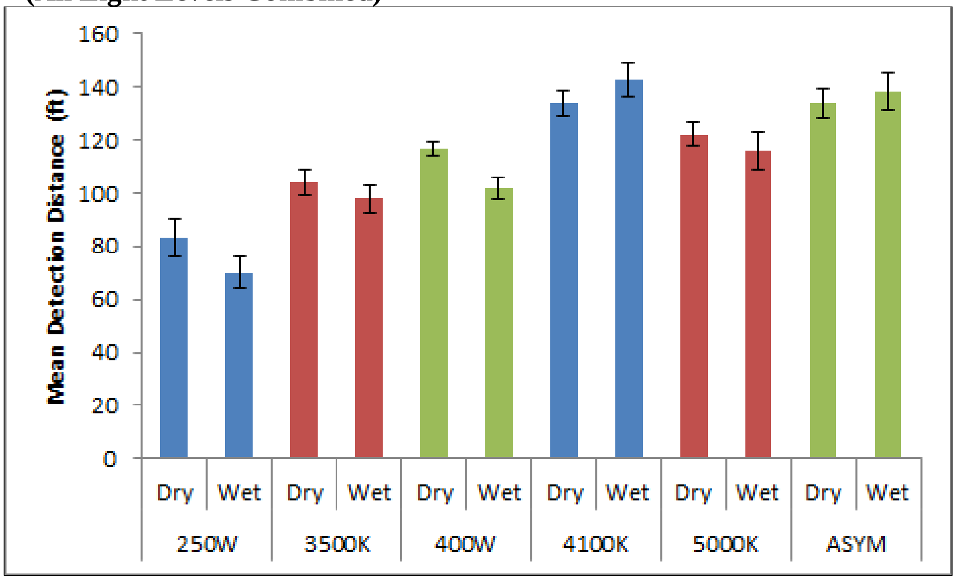
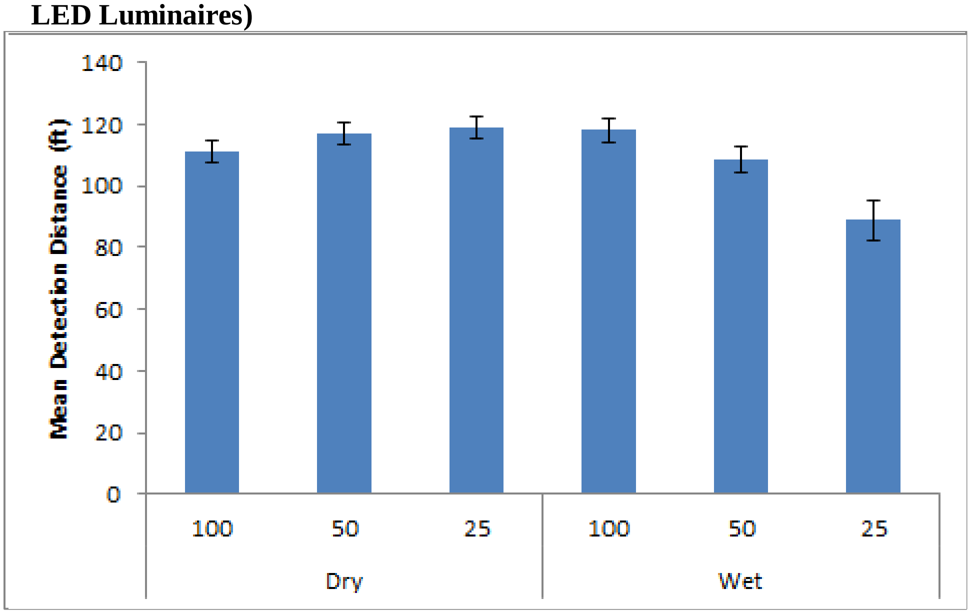


Figure 17 shows a comparison of wet and dry conditions by light level. Again, dry and wet comparisons alone yielded no statistically significant difference for the LED luminaires; however, in this case the wet twenty-five percent condition is noticeably lower than the other combinations. The fact that the twenty-five percent of full light output scenario for the wet condition had significantly fewer trials than did the fifty and one hundred percent scenarios may have contributed to its lower average, due to a larger margin of error.

Figure 17. Pavement Condition and Light Level by Detection Distance (All LED Luminaires)



The other contributing factor is the potential for an overall reduction in glare from the dry road. Wet pavement has a significantly higher specularity than dry pavement, thus causing greater impacts of glare of the light source.

A Student Newman-Keuls (SNK) Test for both nested error terms (pavement condition and light level) found target colors to be significantly different from one another. Participants detected blue and red targets approximately twenty to thirty feet sooner than either gray or green targets. Participants detected green targets with the shortest average distance of any of the four colors, meaning participants took longer to identify the green targets than any of the other target colors.

Figure 18 illustrates the differences in the comparisons between luminaire type and target color by detection distance. The varying spectral distributions due to the different CCTs of the LED luminaires contributed to the range of detection distances by target color.

The 3500K luminaires have more red and green color content than do the other sources; this explains the substantial drop-offs in blue detection for this light source, as the blue targets are less activated than the other target colors. While the 5000K luminaires have the highest CCT and have more blue content than the other sources, they did not outperform the 4100K luminaire in blue target detection distance, suggesting either a difference in contrast or a wash-out of color. The 5000K luminaires maintain a relationship similar to the 4100K luminaires across all target colors except for the neutral gray, where the two performed nearly equally. The asymmetrical LED luminaires performed on par with the 4100K luminaires with no statistical difference across the target types.

The HPS luminaires performed well for the colors red and blue while dropping significantly for gray and green. Neither HPS luminaire outperformed the 4100K luminaires or the asymmetrical LED luminaires for any target color.

Colors gray and green exhibited significantly lower detection distances for the 250 W compared to other luminaire types. The researchers interchanged gray and green targets by location, as they did for red and blue targets. The location of some of the targets may have played a role in these low averages, given researchers placed these targets at the start of the uphill portion. The distance of approach to the targets may have been less than that of other test areas with targets of the same color after the test vehicle changed direction. The 400 W HPS test area resulted in lower gray and green detection distances suggesting that the yellowish hue provided by HPS lamps negatively affects the visibility of green and neutral gray.

The results show that on average, the 4100K test area performed among the best for each target color. Based on these results, the 4100K luminaire appears to provide a sufficient balance between the red and blue extremes in the target color and is the most appropriate color temperature for color detection for all of the targets.

Figure 18. Luminaire Type and Target Color by Detection Distance (All Light Levels)

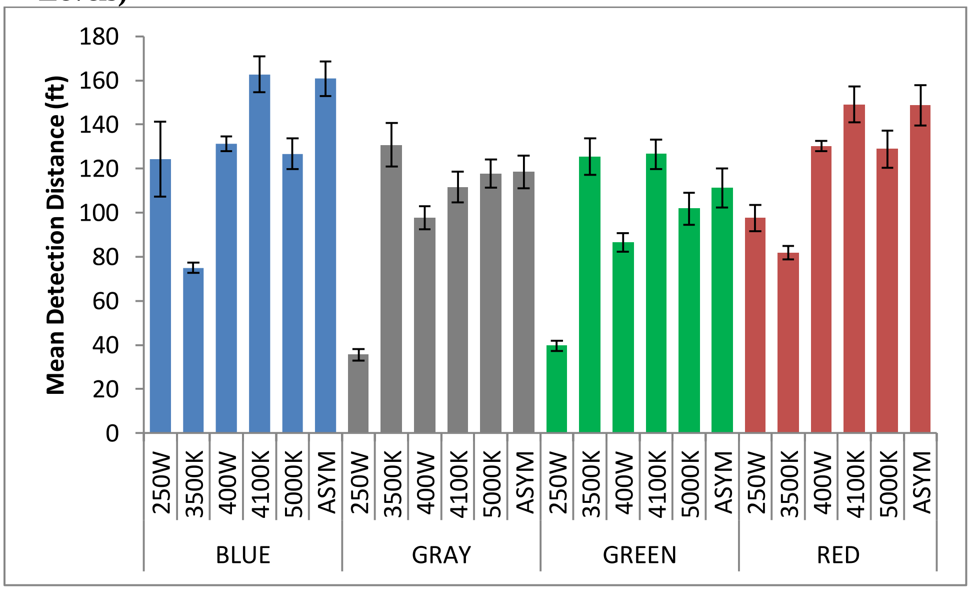
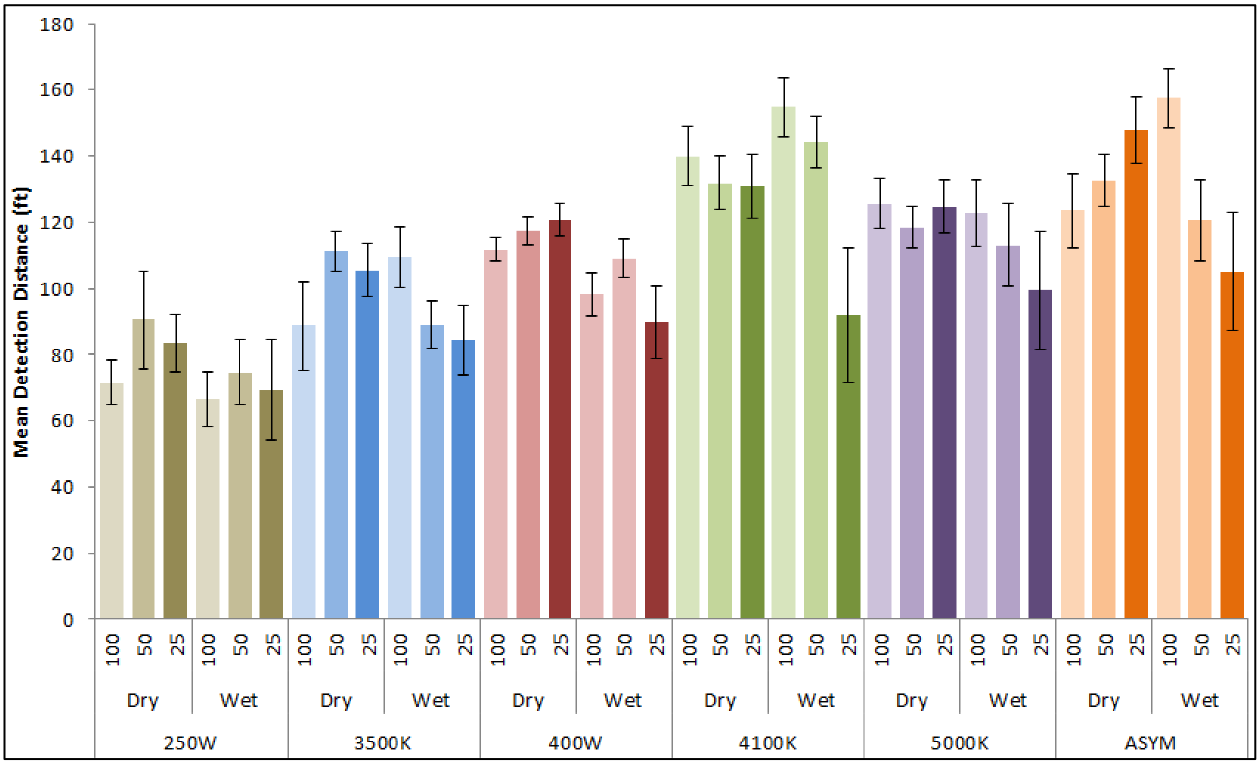


Figure 19 illustrates the differences between test areas by pavement condition and light level. The 4100K test area and the LED asymmetrical test area performed best overall with regard to color detection distance. While Clanton & Associates did not dim the 400 W and 250 W HPS luminaires for the twenty-five and fifty percent conditions, the HPS detection distances varied for those conditions; the contrast of neighboring luminaires may have been a factor.

Interestingly, the one hundred percent light output condition did not always result in the best detection distances; in scenarios such as LED asymmetrical dry conditions, detection distances were higher at the dimmed state. As light level tends to affect detection distance in an unpredictable way, researchers cannot form conclusions here; however, the results suggest a possibility that dimming a luminaire as low as twenty-five percent of full light output and reducing its energy use may not have a negative impact on detection distance. Notably, even though researchers did not dim the HPS luminaires, the dimming of the surrounding luminaires may have slightly affected the light levels in these test areas. Extraneous light sources such as lights from businesses or neighboring parking lots may have slightly affected these results as well.

The lack of a predictable trend between dry and wet conditions constitutes another noteworthy finding. This suggests that the presence of a wet road surface does affect detection distance in some form, perhaps due to higher spectral reflectance off of the roadway.

Figure 19. Luminaire Type, Pavement, and Light Level by Detection Distance



Note: 250 W and 400 W operated at one hundred percent light level and were not dimmed

5.3 Contrast

Contrast is defined as the difference in luminance that renders an object visible. The contrast metric used for these analyses is a formulation called Weber contrast, which is advantageous for these types of analyses due to its consideration of negative contrast. Values above zero are positive contrast, or the point at which an object is made visible by a dark background. Values below zero are negative contrast, or the point at which an object is made visible by a lighter background. Both negative and positive contrasts are represented here.

Equation 1. Weber Contrast Equation

$$r\ Contrast = \frac{Luminc\cdots rget - Luminance_{Background}}{\cdots ninance_{Background}}$$

The researchers assessed the contrast and luminance of the targets using a program created in MATLAB® as part of a National Surface Transportation Safety Center of Excellence (NSTSCE) endeavor. This data reduction used the still images, as shown in Figure 20, recorded by the luminance cameras of the RLMMS. Data reductionists verified the validity of each image and traced the outline of the visible target using a tool within the software. The luminance and contrast of the outlined target are calculated by the program while considering the inside of the trace and its surrounding elements.

Figure 20. Example Luminance Image

Figures 21 through 23 show the results of target contrast for each target color across all light types for the dry pavement condition. Because these data came from the second data collection effort, now wet pavement condition was available to be recorded for this analysis. A comparison of the contrast results for each dim level shows a slight trend from negative contrast to positive contrast as the illuminance is decreased (one hundred percent output versus twenty-five percent output). VTTI did not expect this finding, because as the illuminance on the roadway decreases, the roadway luminance and the target luminance would also decrease and therefore the contrast would remain the same. This increasing trend toward positive contrast indicates that the luminance of the face of the target does not drop as significantly as the luminance of the roadway surface. This implies that the ambient lighting from the areas off of the roadway provides some illumination on the target face and as the roadway dims, the ambient lighting becomes a more significant component of the target luminance.

These results notably demonstrate that although the contrast changes, the detection distance from the one hundred percent light level to the twenty-five percent light level did not change. Researchers expected to see this finding, given that as the driver adaptation is reduced, the threshold luminance difference required for visibility is also reduced, resulting in an equivalent visibility distance.

In order to remove the impact of headlamps, VTTI recorded the contrast in these figures at least 200 feet from the target locations, while they recorded the average detection distances for the targets all within 200 feet.

Figure 21. Target Contrast of One Hundred percent Lighting Level, Dry Pavement Condition, per Target Color across All Light Sources

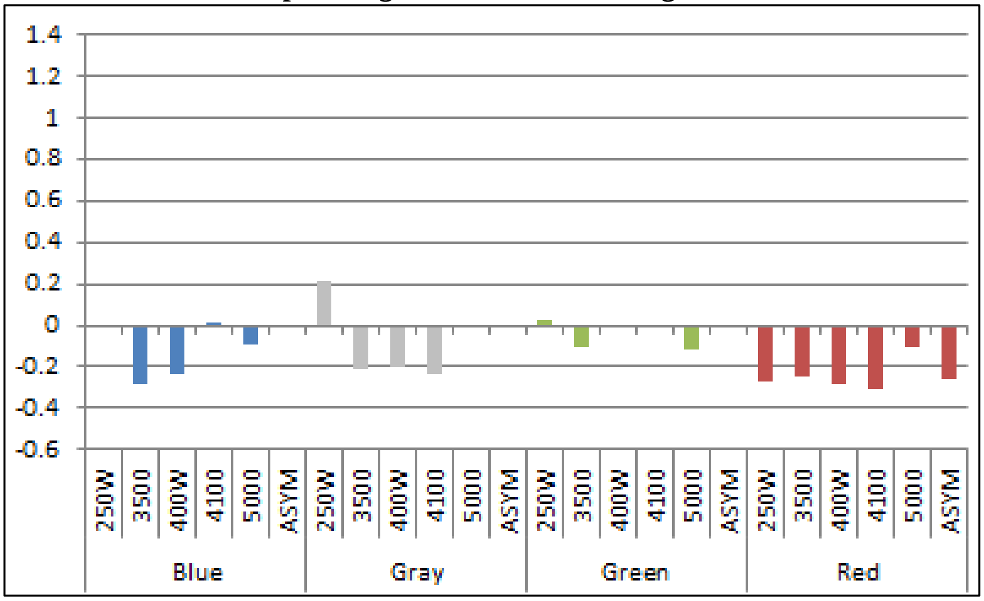
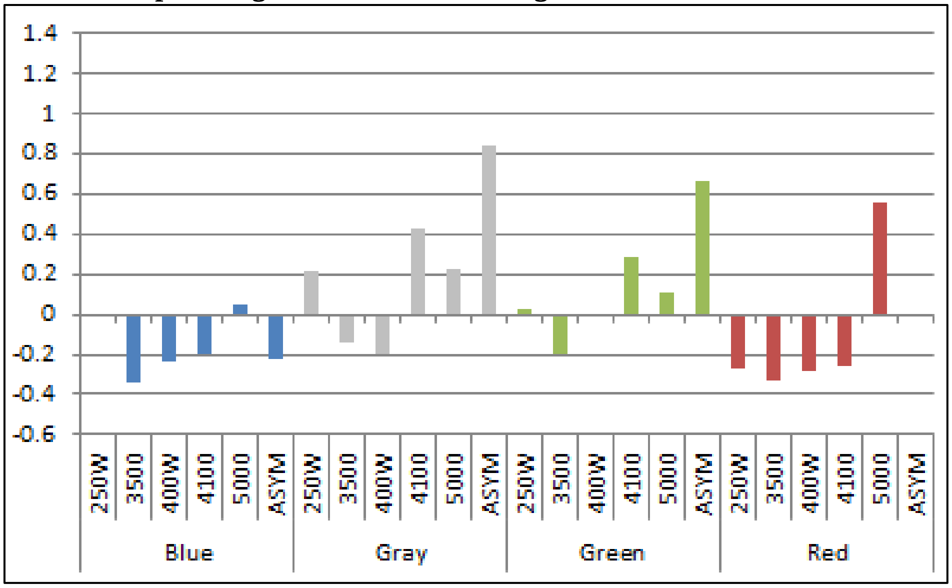
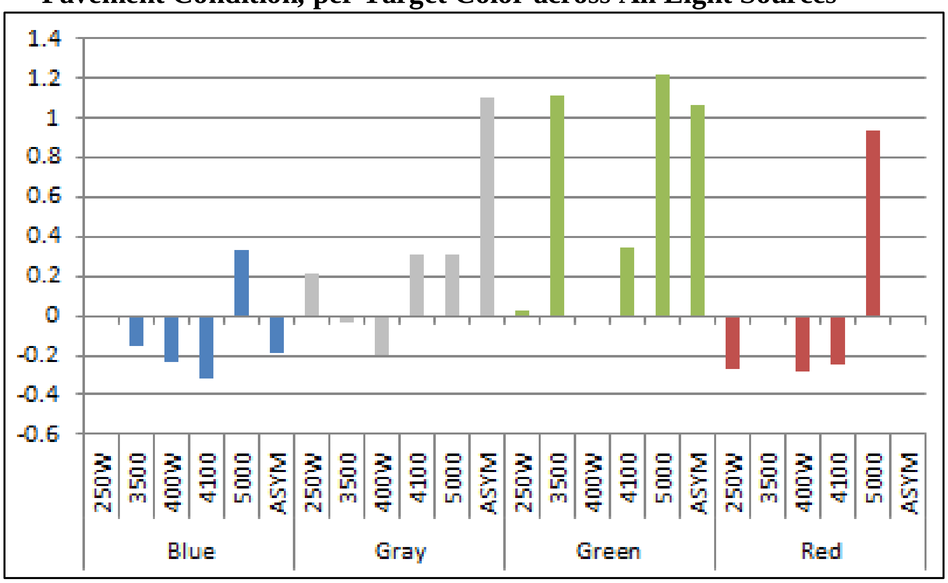


Figure 22. Target Contrast of Fifty percent Lighting Level, Dry Pavement Condition, per Target Color across All Light Sources



Note: 250 W and 400 W remained at one hundred percent

Figure 23. Target Contrast of Twenty-Five percent Lighting Level, Dry Pavement Condition, per Target Color across All Light Sources

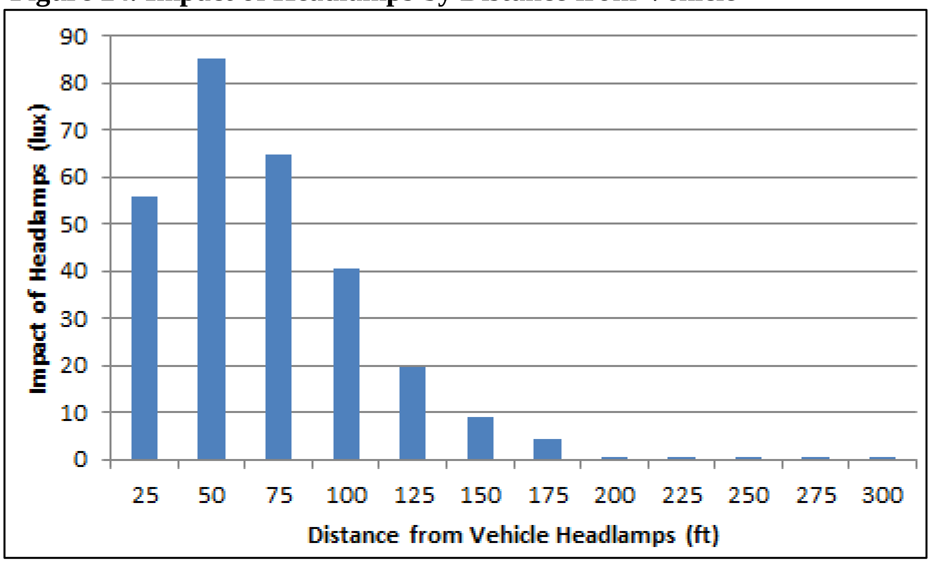


Note: 250 W and 400 W remained at one hundred percent

Figure 24 illustrates the impact of headlamps from the test vehicle. VTTI took a vertical illuminance measurement at target height every twenty-five feet, beginning at twenty-five feet from the vehicle to 300 feet ahead of the vehicle. The figure shows the calculated difference of the measurements with headlamps on versus off. The greatest headlamp impact occurs at a distance of fifty feet from the vehicle, where headlamps contribute up to eighty-five lux of light. The impact is reduced at twenty-five feet from the vehicle, where the light of the headlamps goes over top of the target. At 200 feet from the vehicle to the target, the test vehicle headlamps have little-to-no impact on small target visibility.

For detection distances of one hundred feet or less, assuming that headlamps provide a substantial contribution to visibility would be accurate. As dimming occurs, the headlamp becomes the dominant cause of the detection. As a headlight becomes the dominant detection mechanism, the vertical illuminance on the face of the target increases and the contrast of the target increases. As the roadway becomes dimmer, detection is limited by headlamp distance rather than by illuminance provided by overhead lighting. Managing this effect is crucial as the potential exists for a target to go through an invisibility period during the transition from negative to positive contrast.

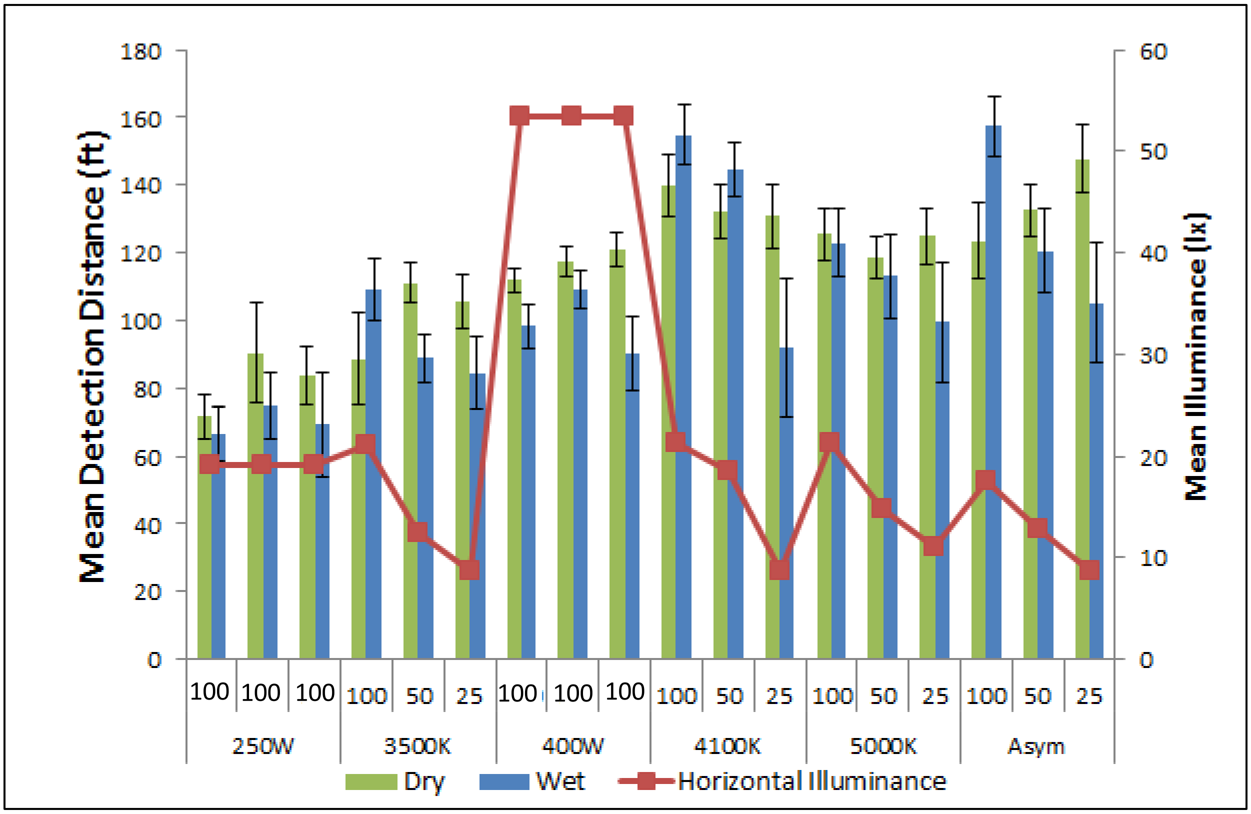
Figure 24. Impact of Headlamps by Distance from Vehicle



5.4 Illuminance and Detection Distance

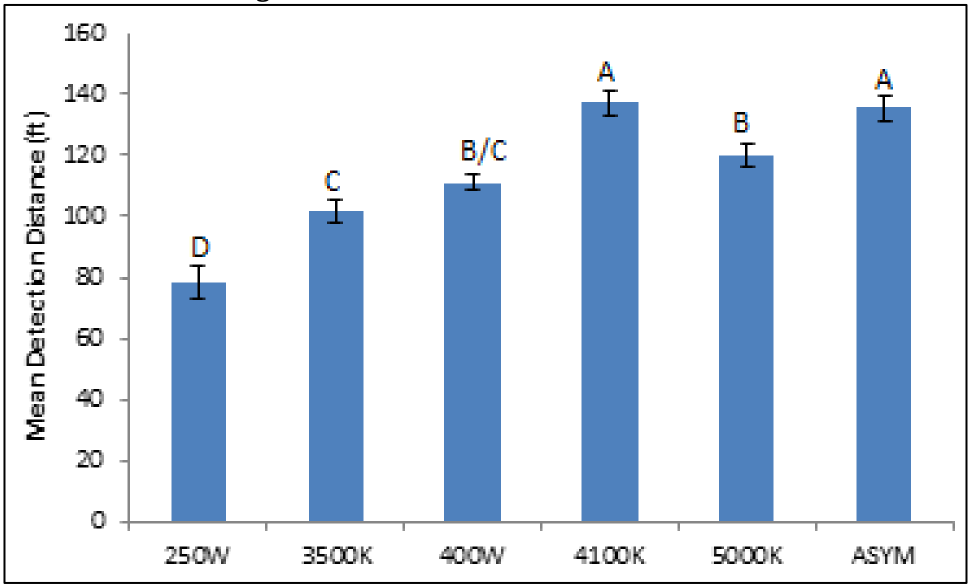
Figure 25 illustrates the relationship between the average horizontal illuminance of each test area and the corresponding differences in detection distance for each pavement condition. The red line represents the average horizontal illuminance for the luminaire's test area; the bars represent the average detection distance. Analyses found no significant differences among the light levels for detection distance. No other relative trends with light level existed for dry pavement; however, the average detection distances on wet pavement do trend similarly to the horizontal illuminance. This suggests that horizontal illuminance has a greater impact on wet pavement than dry, again likely due to the specularity of the pavement surfaces and the potential for increased glare. Note that the illuminance figures are representative of the horizontal illuminance within the entire luminaire's test area and not just at the target's location.

Figure 25. Luminaire Type and Light Level by Detection Distance for Both Wet and Dry Conditions



Results indicate significant advantages to the LED 4100K test area and to the LED asymmetrical test area when crossed with light level and pavement condition. Light levels and pavement conditions resulted in no significant differences; however, significant differences did exist by luminaire type, as illustrated by the SNK results in Figure 26 (between each luminaire by groups). Each column labeled with a different letter (such as A or B) signifies significance between the test areas. The 4100K test area and the LED asymmetric test areas are both in group A and thus provided a significantly better detection distance than the other groups. The 400 W HPS is within both groups B and C, suggesting it does not significantly differ from either B or C but is significantly different from groups A and D.

Figure 26. Luminaire Type by Detection Distance across Both Pavement Conditions and Light Levels



5.5 Lighting Metrics

The following six figures (Figures 27 through 32) represent the average horizontal illuminance gathered as the experimental vehicle traveled northbound and southbound with the RLMMS equipment. These data average the readings from each sensor (left, right, rear and front) of the spider apparatus mounted atop the vehicle. The spikes represent the peak output of an individual luminaire. Each test area is divided and labeled in the figures below.

Northbound and southbound readings are similar within each luminaire's light level, except for the 250 W HPS, which produced a higher illuminance on the northbound side.

Figure 27. Illuminance per Section at One Hundred percent, Northbound

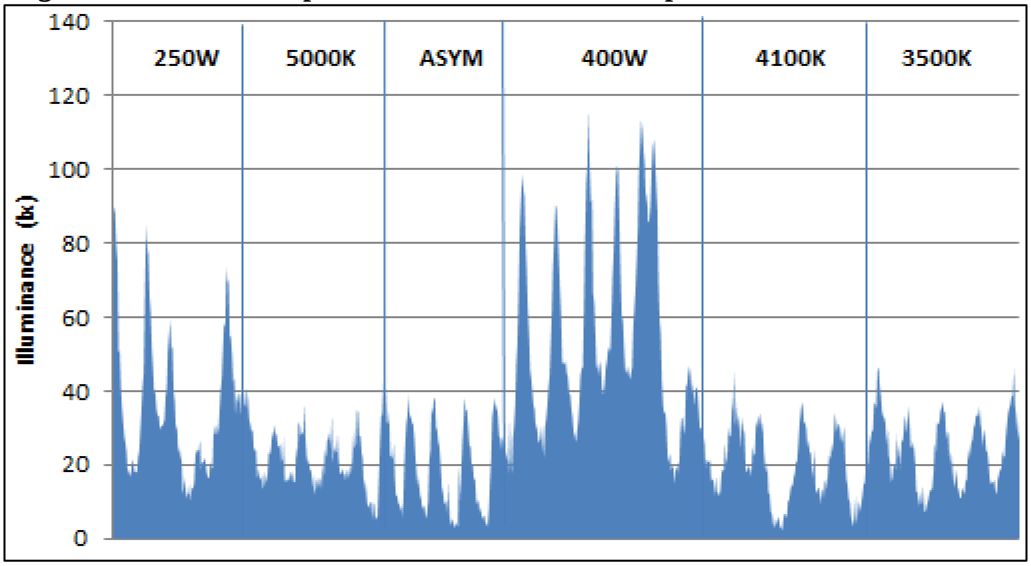


Figure 28. Illuminance per Section at One Hundred percent, Southbound

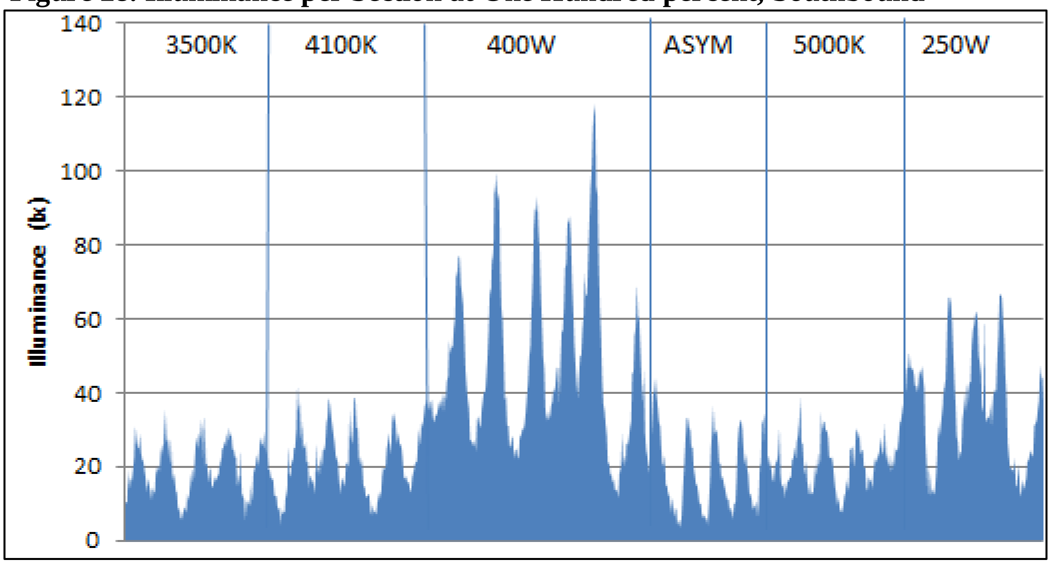


Figure 29. Illuminance per Section at Fifty percent, Northbound

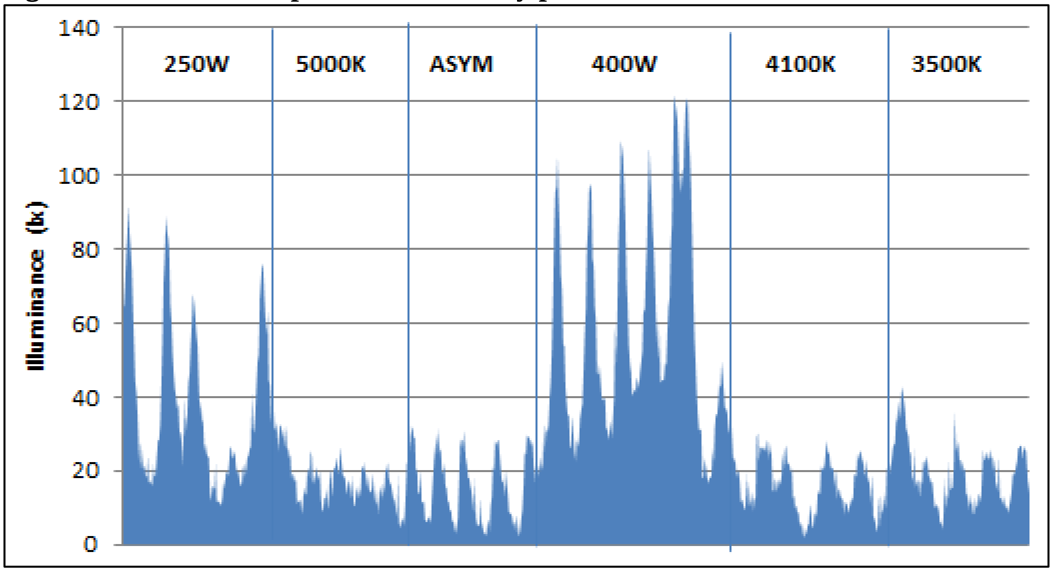


Figure 30. Illuminance per Section at Fifty percent, Southbound

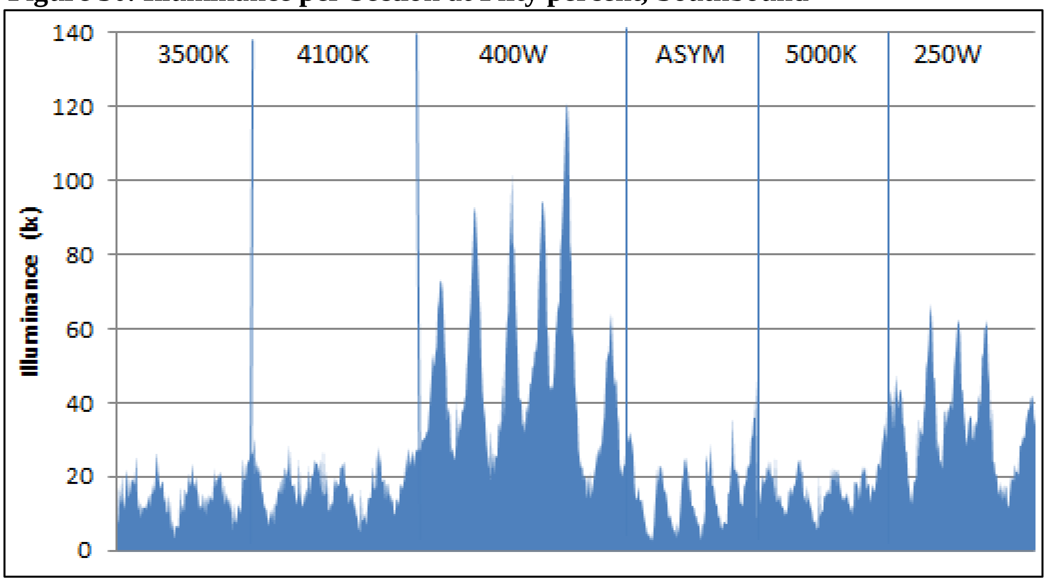


Figure 31. Illuminance per Section at Twenty-Five percent, Northbound

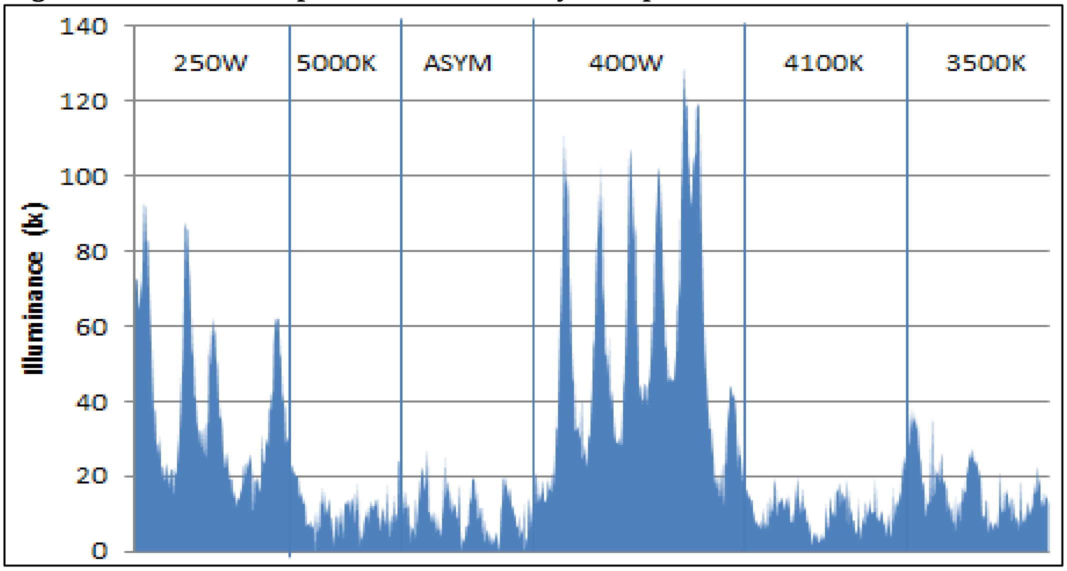
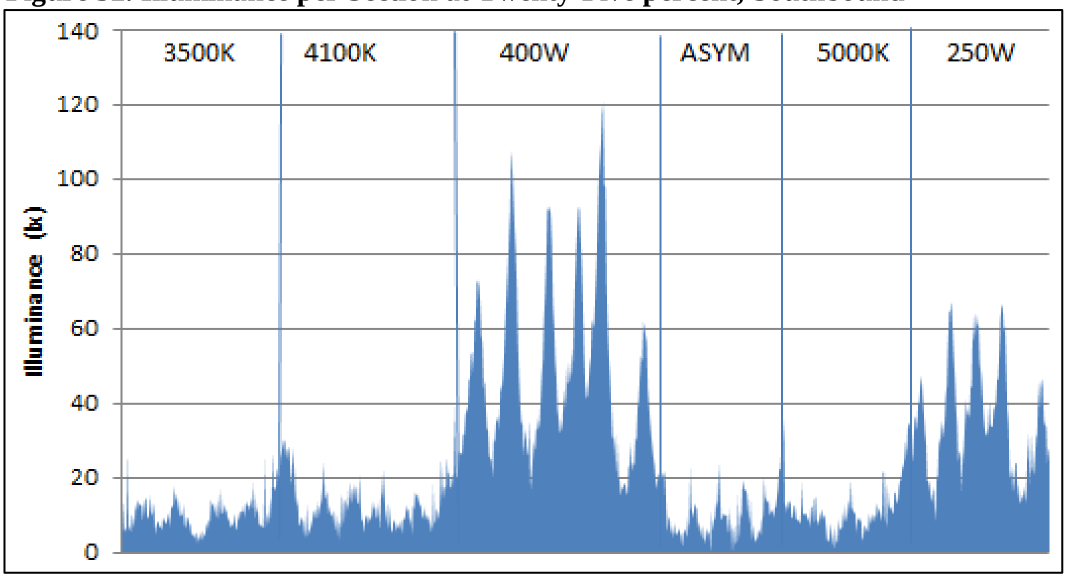


Figure 32. Illuminance per Section at Twenty-Five percent, Southbound



The profile of the asymmetric test area is noteworthy as it does not provide the evenly balanced light distribution. Again, the 400 W HPS and 250 W HPS test areas were not dimmed.

Tables 13 through 15 show metrics for all of the test areas. The relationship between each luminaire's horizontal illuminance and pavement luminance is shown in the following tables for each light level. Uniformity ratios are also included and are noted in the tables as "Avg/Min" and "Max/Min." The illuminance method uses only the "Avg/Min" value, while the luminance method uses both.

The maximum "Avg/Min" uniformity ratio for the horizontal illuminance in RP-8 is 4.0 for a collector roadway with a medium pedestrian conflict, but because of the elevated plane of the RLMMS (approximately seventy-six inches), VTTI did not expect the values here to meet those criteria.

The maximum uniformity ratio for pavement luminance in RP-8 is 3.5 for "Avg/Min" and 6.0 for "Max/Min." The asymmetrical luminaire exceeded the maximum "Max/Min" uniformity ratio of 6.0 only at 50 percent of full light output level.

The RP-8 recommended average luminance for a collector roadway with a medium pedestrian conflict is 0.6 cd/m^2. At the one hundred percent lighting level, only the 400 W HPS was able to achieve this recommended value. Although simulated values indicated that all of the Type II distribution LED luminaires exceed 0.6 cd/m^2, environmental conditions resulted in lower actual average luminance levels. This kind of variance between simulated values and measured values is not uncommon.

These data also demonstrate the inaccuracy of the current uniformity metric to adequately represent the lighting distribution. The asymmetrical design has an average uniformity ratio that is similar to the full distribution luminaires. However, the characterization measurements and the known distribution both indicate that uniformity is lower with the asymmetrical luminaire. These findings suggest a need for additional consideration to fully characterize the roadway appearance with special luminaire types.

Uniformity is also important in target detection. The 4100K luminaire exhibited the highest "Avg/Min" uniformity ratio for horizontal illuminance at both one hundred percent and fifty percent, indicating the most non-uniform appearance; it also had the highest visual performance. The non-uniformity of the lighting on the roadway surface seems to provide a visibility enhancement and greater contrast for visibility; however, further efforts to more fully define uniformity requirements and their importance in visibility are necessary.

Table 13. Light System Calculations, One Hundred percent Light Level

100%	Horizontal Illuminance at Grade (lux)		Dry Pavement Luminance (cd/m^2)		
Test Area	**Avg**	**Avg/Min**	**Avg**	**Avg/Min**	**Max/Min**
250 W	36.93	3.98	0.54	1.66	2.39
3500K	21.83	3.80	0.45	1.55	3.03
400 W	54.88	4.45	0.67	1.53	2.36
4100K	20.44	8.63	0.43	1.95	4.46
5000K	21.97	2.87	0.49	1.48	3.47
ASYM	18.89	6.79	0.40	1.97	5.66

Table 14. Light System Calculations, Fifty percent Light Level

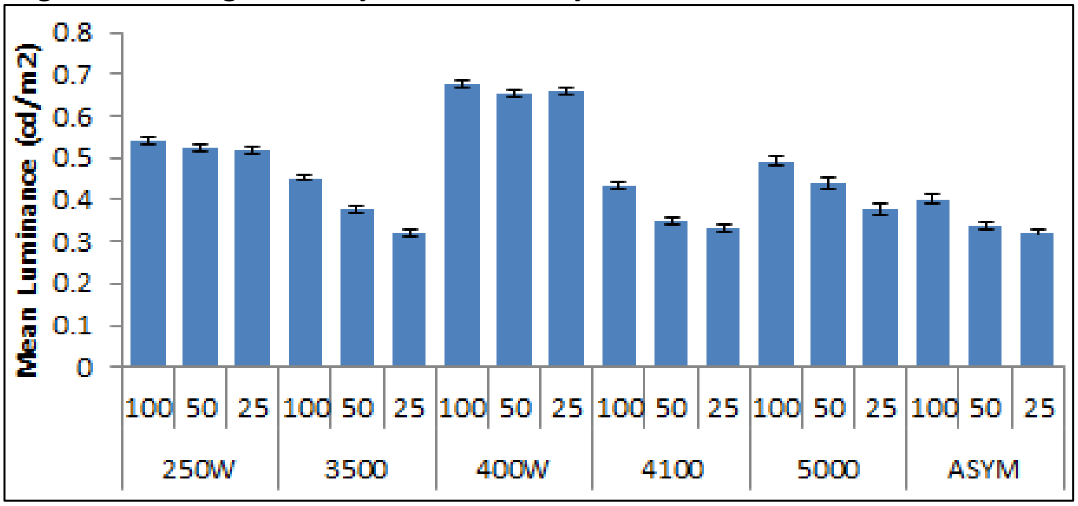
50%	Horizontal Illuminance at Grade (lux)		Dry Pavement Luminance (cd/m^2)		
Test Area	**Avg**	**Avg/Min**	**Avg**	**Avg/Min**	**Max/Min**
250 W	36.93	3.98	0.53	1.81	2.62
3500K	17.45	5.68	0.38	1.50	3.08
400 W	54.88	4.45	0.65	1.54	2.49
4100K	16.27	8.41	0.35	1.78	4.60
5000K	17.00	2.97	0.44	1.59	3.62
ASYM	14.85	6.88	0.34	2.12	6.46

Table 15. Light System Calculations, Twenty-Five percent Light Level

25%	Horizontal Illuminance at Grade (lux)		Dry Pavement Luminance (cd/m^2)		
Test Area	**Avg**	**Avg/Min**	**Avg**	**Avg/Min**	**Max/Min**
250 W	36.93	3.98	0.52	1.61	2.39
3500K	13.60	5.78	0.32	1.79	4.19
400 W	54.88	4.45	0.66	1.56	2.43
4100K	11.01	8.08	0.33	1.55	4.09
5000K	10.54	8.25	0.38	1.71	4.21
ASYM	9.83	7.21	0.32	1.96	5.25

Figure 33 illustrates the data from the preceding three tables: dry pavement luminance per luminaire section. However, because the follow-up data collection did not collect wet pavement data, that difference is not illustrated here.

Figure 33. Average Roadway Luminance: Dry Pavement Condition

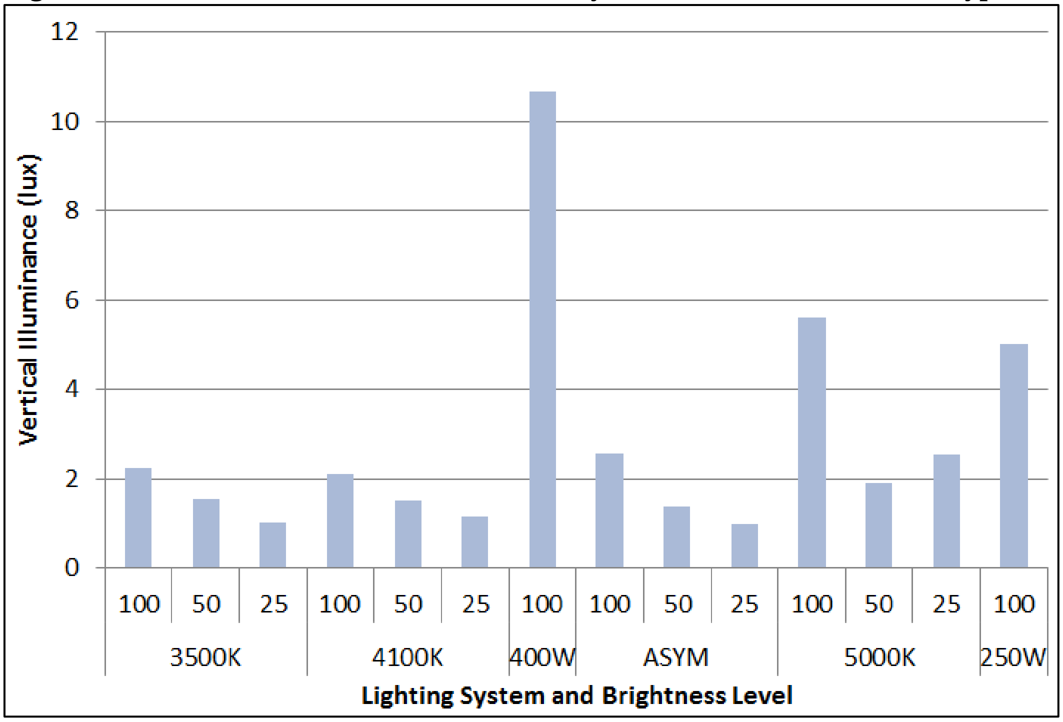


5.7 Sidewalk Lighting Characteristics

The second luminance data collection effort also considered sidewalks as part of the investigation. Researchers used a Minolta T-10 illuminance meter and a hand-held Minolta LS-110 luminance meter to measure the vertical illuminance on a pedestrian, the sidewalk luminance, and the light trespass from the roadway. VTTI used the meters to recorded vertical illuminance at pedestrian height, or five feet from the ground.

Figure 34 shows that at the one hundred percent light level, the 400 W HPS exhibited by far the greatest vertical illuminance, almost two times that of the next-brightest measurement. The 5000K luminaire demonstrated unpredictable results, as it showed a vertical illuminance at the fifty percent lighting level less than that observed at twenty-five percent. However, the 5000K's vertical illuminance at the one hundred percent light level is surprisingly more than two times greater than that of the other LED luminaires; however, this anomaly may be attributable to contributions of businesses and other off-roadway lighting in the area of the 5000K installation. The 3500K, 4100K, and asymmetrical LED luminaires demonstrated similar sidewalk vertical illuminance for each light level.

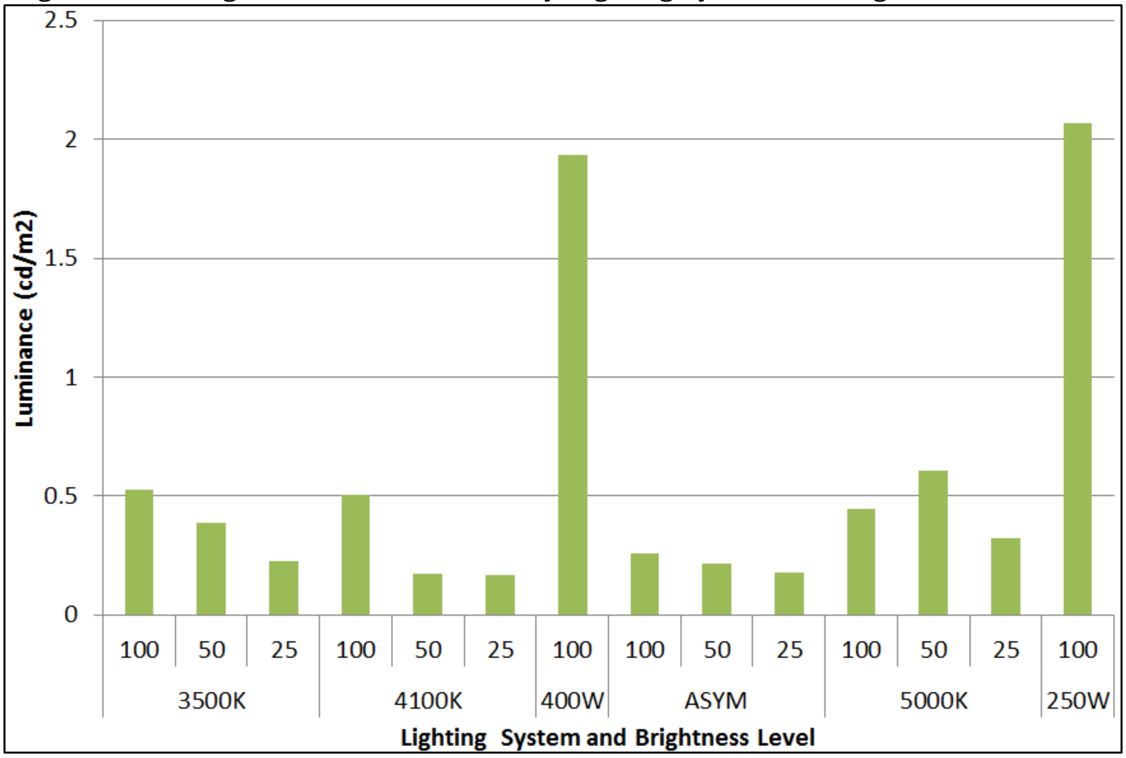
Figure 34. Vertical Illuminance on Sidewalks by Dim Level and Luminaire Type



An IES publication, "Lighting for Exterior Environments," recommends a vertical illuminance level of five to twenty lux based on the type of area surrounding the installation (IES RP-33 1999). Among the new technologies considered, notably only a single LED (5000K at one hundred percent light level) met this criterion, with a vertical illuminance of 5.5 lux.

As shown in the recorded average sidewalk luminance results in Figure 35, the HPS light sources produced the highest luminance at approximately 2.0 cd/m^2 each. The 5000K luminaire produced unexpected results as it achieved greater luminance at the fifty percent light level than at the one hundred percent light level. Off-site lighting from fuel stations, restaurants, and nightclub signage may have contributed to some of the higher values in certain areas. The 3500K, 4100K, and asymmetric LED luminaire results behave predictably, as the luminance increases with light level. No luminance level among these three types of luminaires exceeded 0.5 cd/m^2.

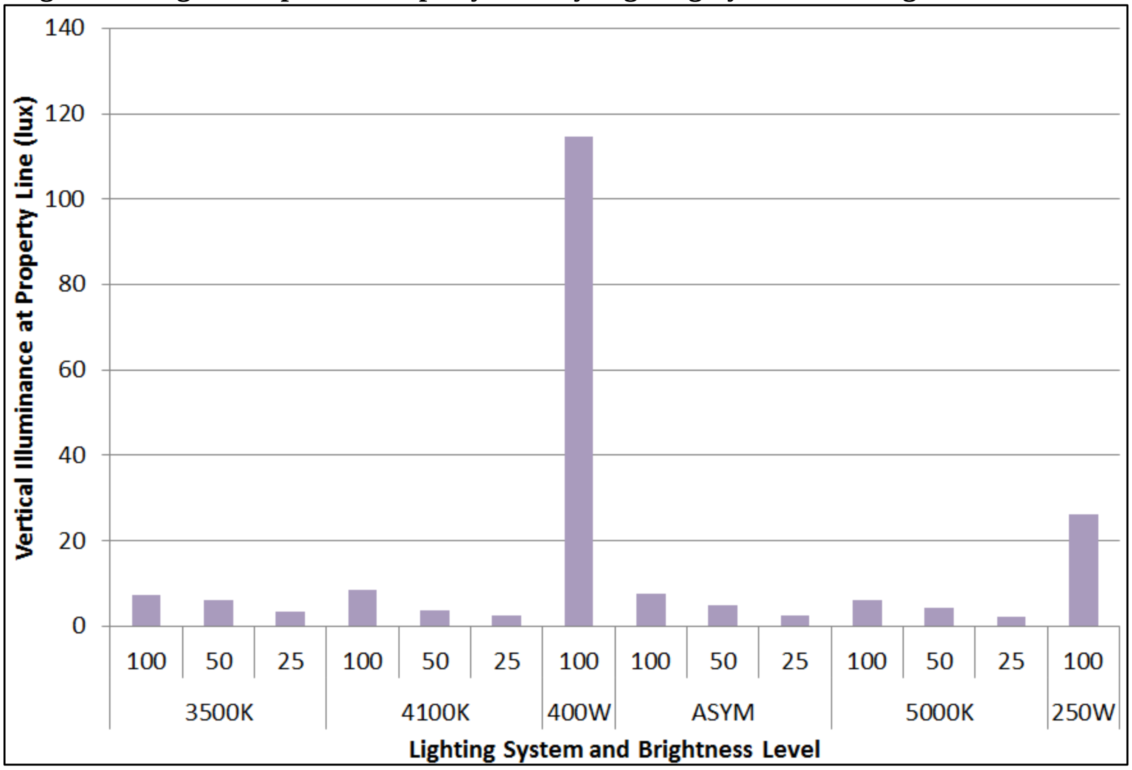
Figure 35. Average Sidewalk Luminance by Lighting System and Brightness Level



5.8 Light Trespass

Researchers used a hand-held illuminance meter to record light trespass at the property line. They took this measurement along the side of the roadway with the illuminance meter facing into the road; measurements represent the amount of light leaving the roadway onto the adjacent properties, as Figure 36 shows. The 400 W HPS produced nearly 120 lux of light trespass, while the 250 W HPS provided approximately thirty lux. All LED luminaires provided light trespass of ten lux or below, which meets the IES criteria from TM-11 as shown in Table 25 in Appendix E. Clanton & Associates selected these luminaires specifically for this application. The light trespass is a characteristic of the luminaire and is not a reflection of the light source technology. It does, however, highlight the potential for improved lighting designs based on the optical design controllability of the LED light sources.

Figure 36. Light Trespass at Property Line by Lighting System and Brightness Level



5.9 Glare

Glare comes in two forms: discomfort and disability. Discomfort glare is measured using a subjective rating scale; disability glare, or veiling luminance, can be measured in the field. IES RP-8 offers a formula for calculating veiling luminance (IES RP-8 2005):

Equation 2. Veiling Luminance

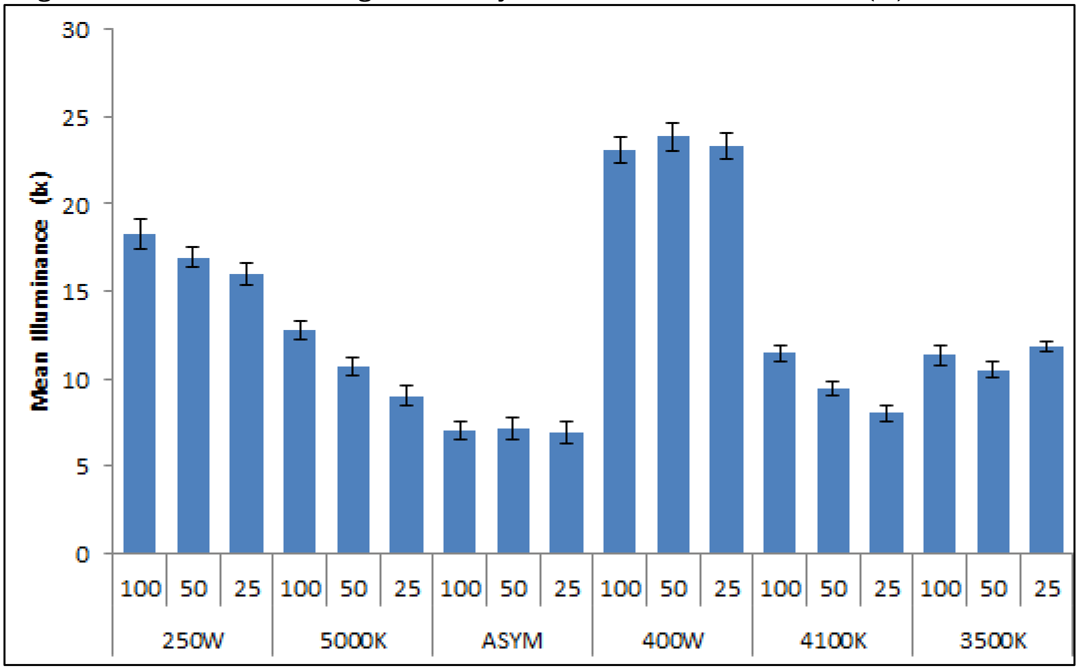
$$L_v = \frac{K}{\theta^n}, n = 2.3 - 0.7 \times log_{10}(\theta) \; for \; \theta < 2, n = 2 \; for \; 2 \leq \theta$$

Where:
L_v = Veiling Luminance from one individual luminaire
$K = 10 \times$ (Vertical illuminance at the plane of a 25 − year − old observer's eye)
θ = Angle in degrees

Using a glare meter placed vertically at eye level, a researcher can calculate the amount of veiling luminance and assess the quantity of glare. Higher lux values reaching the meter typically result in more glare or veiling luminance.

Figure 37 shows the average vertical illuminance recorded by the glare meter placed inside the windshield of the experimental vehicle for each test area and light level. The results indicate that the HPS test areas produce more glare than do the LED test areas, as evidenced by their higher average vertical illuminance values. The glare meter's vertical illuminance output values can be affected by neighboring luminaires, billboard lights, or business lights.

Figure 37. Test Area and Light Level by Mean Vertical Illuminance (lx) of Glare



The asymmetrical design generates particular interest here; this luminaire was designed to project the light in the direction away from the driver. It appears that the glare level experienced in the asymmetrical test area represents the glare from the environment around the roadway and not from the luminaires themselves. Environmental glare is location-dependent and can vary based on proximity to lighted businesses, stadiums, billboards, and campuses. Road geometry also plays an important role as vehicle orientation can determine the angle at which light enters the windshield. Environmental glare is defined as the overall impression of the ambient light in and around the street.

The overall results suggest that since the LED luminaires tested here have a maximum glare rating of IES G2, these luminaires have less glare consequences than current lighting technologies. Again, given that researchers selected these luminaires for their low glare characteristics, this statement relates more to the luminaires, rather than to the LED lighting technology.

Table 16 and Table 17 detail the average veiling luminance for each luminaire by direction of travel. These values are typically compared to the IES RP-8 recommended maximum veiling luminance ratio of 0.4 for a collector roadway grade. However, because RP-8 requires consideration only of the roadway luminaires, these results are not directly comparable to the

RP-8 guidelines. The glare meter placed in the experimental vehicle records vertical illuminance from multiple sources of light, including those not placed on the roadway and reflections, thus resulting in a ratio much greater than the 0.4 guideline. Luminaires placed at intersections not included in the study, lights from maintenance vehicles, and business signs factor into the large L_v values. However, the LED designs have lower glare ratios than those of the HPS luminaires.

Inter-comparisons of the technologies are important. In this demonstration, the HPS luminaires both had glare ratings higher than the LED replacements, particularly compared to the asymmetrical system. These values show the superior beam control of the LED systems. This lower ratio to the average luminance also indicates that streetlight designers and engineers can use a lower overall average while still providing the same visual performance, as the lighting system does not need to overcome the detrimental impact of the glare.

Table 16. Veiling Luminance, Dry Pavement

Veiling Luminance, Dry Pavement					
Light Type	**Light Level**	**Northbound L_v**	**Southbound L_v**	**L_{vmax}/L_{avg} Veiling Luminance Ratio**	
				North	**South**
250 W HPS	100%	4.491	3.387	1.850	1.399
	100%	4.415	3.911	1.954	1.499
	100%	3.969	3.898	2.242	2.202
LED 5000K	100%	3.016	3.391	1.268	1.429
	50%	2.467	2.893	1.115	1.307
	25%	1.859	2.531	1.158	1.458
LED ASYM	100%	1.567	1.939	0.713	0.905
	50%	1.526	1.988	0.746	0.972
	25%	1.349	2.034	0.841	1.268
400 W HPS	100%	6.232	5.402	2.701	2.341
	100%	6.561	5.378	3.056	2.505
	100%	6.131	5.583	3.641	3.316
LED 4100K	100%	2.493	3.299	1.099	1.455
	50%	2.145	2.630	1.017	1.247
	25%	1.737	2.261	1.049	1.366
LED 3500K	100%	3.006	2.616	1.385	1.206
	50%	2.677	2.587	1.332	1.287
	25%	1.986	1.525	1.256	0.965

Table 17. Veiling Luminance, Wet Pavement

Veiling Luminance, Wet Pavement					
Light Type	**Light Level**	**Northbound L_v**	**Southbound L_v**	**L_{vmax}/L_{avg} Veiling Luminance Ratio**	
				North	**South**
250 W HPS	100%	5.339	5.717	2.518	2.696
	100%	5.265	5.261	2.842	2.658
	100%	5.155	4.879	3.325	3.147
LED 5000K	100%	3.281	3.861	1.575	1.853
	50%	4.031	3.434	2.079	1.772
	25%	2.890	2.952	1.901	1.942
LED ASYM	100%	4.416	4.421	2.294	2.296
	50%	4.453	4.670	2.487	2.607
	25%	3.221	3.993	2.292	2.841
400 W HPS	100%	4.901	4.998	2.426	2.474
	100%	4.965	5.300	2.641	2.819
	100%	4.818	5.173	3.266	3.507
LED 4100K	100%	4.684	4.751	2.358	2.392
	50%	4.462	4.244	2.414	2.296
	25%	4.203	3.552	2.898	2.449
LED 3500K	100%	3.460	3.786	1.821	1.992
	50%	3.079	2.999	1.741	1.696
	25%	3.196	2.351	2.304	1.695

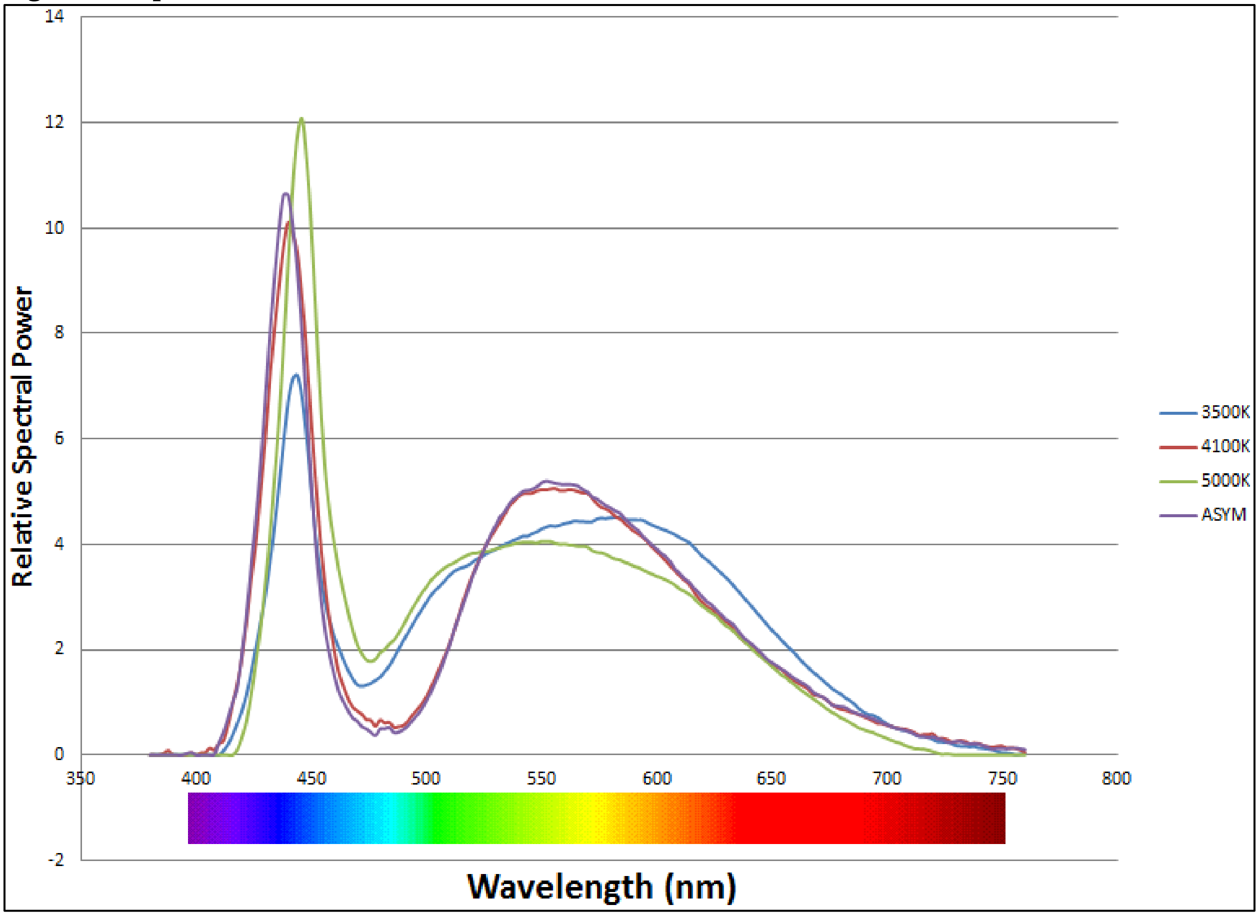
The results indicate that glare is higher in the wet environment for all luminaires except for the 400 W HPS. Light from businesses along the side of the roadway likely contributed to the differences in glare directionality. The southbound side of the road beyond the shoulder consisted mainly of residential blocks or closed businesses, while the northbound side consisted of multiple open or well-lighted business locations.

5.10 Spectral Power Distribution

The spectral distribution of the available light constitutes an important factor in color detection. The spectral power distributions (SPDs) for each luminaire are shown below in Figure 38. All of the luminaires show the typical sharp spike at 440 nm, which represents the amount of blue power needed to drive the other light production through the LED phosphor. The 5000K CCT shows comparatively little output in the higher wavelength regions. The 3500K produces less blue than the other luminaires but more yellow-orange spectral power. On the CCT spectrum, the

3500K luminaire is in the yellow-to-white transition and is the closest relation to the HPS luminaires in terms of CCT among the LED luminaires tested. The asymmetric LED and 4100K LED are very similar in spectral power distribution due to their comparable color temperatures. The 4000K-4500K CCT range is considered “neutral white light.”

Figure 38. Spectral Power Distributions of LED Luminaires



6 Discussion

6.1 Comparison to Previous Studies

The previous streetlight studies performed by Clanton & Associates in Anchorage, San Diego, and San Jose all had different study parameters, luminaire wattages, color temperatures, light sources, and existing pole layouts. Therefore, making direct comparisons to these findings would be difficult and likely valueless. For example, the City of San Diego had already decided to implement relatively low color temperature street lighting and did not test a large range of CCTs. Test conditions in Anchorage included snow (dramatically different contrast than the other cities) and car headlights, because that study did not include a road closure. San Jose street lighting forms a staggered pole arrangement, while Seattle's forms an opposite pattern.

However, a few trends do appear among the studies in terms of preference for color and light source. In both San Jose and San Diego, the participants preferred the 3500K LED luminaire when responding to the overall style of the lighting. In Anchorage and Seattle, respondents preferred the white light LEDs over the existing high pressure sodium lights, but no specific color temperature stood out as most preferable. In all studies, survey participants considered white light LED and induction sources to be acceptable.

Findings from the user field test data contain similarities to other streetlight studies. For example, in San Jose the 4000K LED performed better compared to the HPS and 3500K LED tested in the study. However, in that study, the 5000K luminaire performed the best – which was not the case in Seattle. Researchers cannot compare the relative detection distances between the two studies due to differences in road geometry, but the studies did show that the 3500K luminaire is not optimal for visibility among the LEDs tested in these two locations.

Three LED luminaires tested in Anchorage had color temperatures of 3500K, 4100K, and 4300K. All three luminaires came from different manufacturers; however, when comparing the performance of their CCTs, the 4100K outperformed the 3500K by approximately seven meters (twenty-three feet). Although target color, pavement type, and the presence of snow distinguish the Anchorage study from the Seattle study, the twenty-three foot detection distance difference is similar to that observed in Seattle. The Anchorage testing included no LEDs with CCTs above 4300K; however, the 4100K outperformed the 4300K, which exhibited performance results similar to that of the 3500K. These differences could be attributed to road geometry at the test site, pavement type, or the differences in manufacturers.

In San Diego, the test included two LED luminaires in the roadway portion of the study. Both luminaires had manufacturer-stated color temperatures of 3500K, although on-site measurements showed them to be different; one measured at 3475K and the other at 4560K. Counter to findings in the other three test locations, the luminaire with a CCT closer to 3500K significantly outperformed the one measured at 4560K, by approximately thirty feet.

Based on the findings of the previous streetlight studies together with the data collected in Seattle, CCT clearly affects visibility. These results indicate that 4000K and 4100K luminaires regularly outperform CCTs of 3500K and below, and perform just as well (San Jose) or better (Seattle) than CCTs of 4300K and above.

This research also illuminates inaccuracies in current uniformity rates. Uniformity is important in target detection, as a greater uniformity ratio indicates a non-uniform appearance. The 4100K luminaire provided the highest visual performance and the highest uniformity ratio. The uniformity ratio of the asymmetric design is lower than that seen with the full distribution designs, warranting consideration of how to fully characterize roadway appearance with special luminaire types. These results call for future efforts to fully define uniformity requirements as they relate to visibility.

Light trespass constitutes another interesting result. Only the LED luminaires met the IES criteria from TM-11. Although Clanton & Associates selected these luminaires specifically for this application, the results indicate that the light trespass is a characteristic of the luminaire and is not indicative of the light source technology. It does, however, highlight the potential for improved lighting designs based on the optical design controllability of the LED light sources.

6.2 Adaptive Lighting Opportunities

Traditionally, engineers design street lighting around the worst set of conditions that can exist for a particular street based upon vehicular volume, pedestrian volume, and ambient luminance. In reality, these worst-case conditions occur only part of the time. The rest of the time, traffic and pedestrian volumes are reduced. With the advancement of network controls for exterior lighting, streetlight designers and engineers can tune light output via adaptive lighting to deliver the appropriate amount of light based upon the corresponding vehicular and pedestrian volume present at a particular time. The implementation of adaptive lighting not only reduces the overall energy consumption of the streetlights, it also prevents over-lighting, reduces glare, and minimizes light pollution. Both the IES and the International Commission on Illumination (CIE) provide for implementation of adaptive lighting in different forms.

The user field test results from this study indicate that the implementation of adaptive lighting does not significantly affect object detection distance under dry conditions. However, when coupled with the written evaluation results, pedestrians consider reducing the light level to twenty-five percent of full light output for all hours of the night to be unacceptable. This result is not surprising. Tuning the light to a point such as twenty-five percent of full light output (when roads are dry) is justified at low vehicular and pedestrian volumes, but not for all hours of the night. While some industry metrics allow the implementation of adaptive lighting, each city can determine how to best apply adaptive lighting to its particular traffic conditions and community.

6.3 Future Design Standards

Traditional streetlights have long been a primary cause of light trespass. While sometimes the light leaving the back of the luminaire illuminates the sidewalk behind the luminaire, frequently the light leaving the back of the luminaire trespasses into residential windows, causing discomfort to the occupants. To combat the latter issue, luminaire manufacturers began offering house side shields for specification. These shields, which can be mounted either internally or externally, allow better optical control and reduce the amount of backlight leaving the luminaire. LEDs by nature are directional sources and do not disperse light toward the back of the luminaire unless purposely designed to do so. This technology advancement decreases the amount of light trespass potential, but consequently leaves the sidewalks behind the luminaires with less light.

Controls coupled with LED streetlights provide valuable energy savings for end users. The integration of these two products also provides a unique opportunity for innovative design. While reducing the light level by seventy-five percent minimally affected detection distances, some participants expressed concern that the sidewalks were difficult to navigate through the written evaluation comments. Although this study was not designed for participants to evaluate the sidewalk separately from the roadway, conducting such a study in the future may be beneficial.

Higher-wattage LED luminaires often contain two LED boards and two drivers. Right now, the luminaire controllers send signals to which both drivers respond, and dim accordingly. However, manufacturers could design controllers to send unique signals to each driver, in which case one LED board could dim to a different light level than the other. This dual control capability might alleviate residents’ apprehensions about reducing light levels on the roadway but maintaining the light level on the sidewalks simultaneously. Municipalities could still realize energy savings because half or more of the lights that contribute to the roadway could be dimmed.

6.4 Economic Analysis

The economic analysis below illustrates the economic viability of replacing the 400 W HPS luminaires with 105 W LED luminaires with adaptive controls. This analysis included sixty luminaires, similar to that of the demonstration test site.

Assumptions include real costs from the City of Seattle for the existing light sources, wattages, hardware, and maintenance. The LED luminaire prices are based on Lumec RoadStar luminaires used in the actual demonstration. The analysis used the Municipal Solid State Street Lighting Consortium’s (MSSLC) calculator, released in 2011 by the Department of Energy and the Pacific Northwest National Laboratory (PNNL).

Since this economic analysis included only a limited quantity of luminaires and only one manufacturer, actual pricing for larger quantities and multiple manufacturers would be lower.

Scenarios

The six economic analysis scenarios listed below illustrate a variety of opportunities, including different luminaires and the use of adaptive lighting. This analysis examines the economics of sixty LED luminaires installed in Seattle, Washington with technologies available as of March 2012.

- 400 W HPS – no adaptive lighting
  - This is typical street lighting for many cities.
- 250 W HPS – no adaptive lighting
  - This is typical street lighting for many cities.
- 105 W LED – no adaptive lighting
  - This approach allows for immediate energy savings and the light level remains constant throughout the night.
- 105 W LED with adaptive lighting (*fifty percent* light output for *six hours* per night)
  - This approach allows for immediate energy savings. The light level changes throughout the evening when traffic and pedestrian volumes are reduced.
- 105 W LED with adaptive lighting (*fifty percent* light output for *three hours* per night, *twenty-five percent* light output for *three hours* per night)
  - This approach allows for immediate energy savings. The light level changes twice throughout the evening as traffic and pedestrian volumes are reduced.

Assumptions and Limitations

Each lighting scenario reveals the economic costs and potential benefits to utilities and cities in the Northwest for investing in LED street lighting and controls. Inputs such as rebates, cost of labor, cost of power, and greenhouse gas emissions are based on information provided by Seattle City Light and provide a representative magnitude of cost and returns when implementing LED street lighting in the Northwest region.

The MSSLC calculator gathers project inputs to generate scenarios that a project manager uses to understand implementation options such as size, period of installation, cash flows, and a project's overall return on investment. While each entity in the Northwest will have different costs (materials and labor) and rebate programs to consider, this analysis uses SCL's rebate incentives and cost information as a representation of what other utilities and consumer ratepayers may find within the region.

The different street lighting scenarios use the same quantity of poles and luminaires, wattages, and control systems scenarios, as described within this study. Even scenarios without dimming include the cost of the control system due to several other non-energy benefits of using the control system, such as asset management and maintenance alerts. The analysis considers the cost of maintenance and captures the financial benefit of the longer source life of LEDs over HPS. The fact that dimming LEDs extends the life of the source is well-understood; however, given the lack of a precise quantification of this change in life, the analysis did not include this benefit.

Application

Based on the results of the visual acuity study, the economic analysis assumes that smart-controlled LEDs can be used as viable replacements for standard HPS luminaires in the

Northwest region. Since the detection distances in the dimmed LED scenarios compare well to the baseline non-dimmed HPS scenarios, energy and maintenance savings can be achieved with lower-wattage LED luminaires controlled by adaptive lighting with reasonable payback periods.

Analysis

The following tables describe the luminaires and control system components used in the analysis.

Scenario 1A: 400 watt HPS (no dimming) replaced with 105 watt LED (no dimming)

Table 18. Scenario 1A Economic Analysis Summary

Economic Analysis Summary	
Luminaires Installed	60
Implementation Period (years)	1
Simple Payback (years)	3.3
Annual kWh Savings	94,802
Annual Energy Cost Savings ($)	$11,760
Baseline 400 W HPS (no dimming) Baseline Annual kWh Use	125,356
Baseline 400 W HPS (no dimming) Annual Energy Cost ($)	$15,669
105 W LED (no dimming) Annual kWh Use	31,273
105 W LED (no dimming) Annual Energy Cost ($)	$3,909

Scenario 1B: 400 watt HPS (no dimming) replaced with 105 watt LED (with fifty percent dimming for six hours per night)

Table 19. Scenario 1B Economic Analysis Summary

Economic Analysis Summary	
Luminaires Installed	60
Implementation Period (years)	1
Simple Payback (years)	3.1
Annual kWh Savings	101,901
Annual Energy Cost Savings ($)	$12,738
Baseline 400 W HPS (no dimming) Annual kWh Use	125,356
Baseline 400 W HPS (no dimming) Annual Energy Cost ($)	$15,669
105 W LED (fifty percent dimming) Annual kWh Use	23,455
105 W LED (fifty percent dimming) Annual Energy Cost ($)	$2,932

Scenario 1C: 400 watt HPS (no dimming) replaced with 105 watt LED (fifty percent dimming for three hours per night, and twenty-five percent output dimming for three hours per night)

Table 20. Scenario 1C Economic Analysis Summary

Economic Analysis Summary	
Luminaire Installed	60
Simple Payback (years)	2.9
Annual kWh Savings	105,810
Annual Energy Cost Savings ($)	$13,226
Baseline 400 W HPS (no dimming) Annual kWh Use	125,356
Baseline 400 W HPS (no dimming) Annual Energy Cost ($)	$15,669
105 W LED (fifty percent dim for three hours; twenty-five percent output dim for three hours) Annual kWh Use	19,546
New Baseline Annual Energy Cost ($)	$2,443

Scenario 2A: 250 watt HPS (no dimming) replaced with LED 105 watt (no dimming)

Table 21. Scenario 2A Economic Analysis Summary

Economic Analysis Summary	
Luminaires Installed	60
Simple Payback (years)	6.7
Annual kWh Savings	46,778
Annual Energy Cost Savings ($)	$5,847
250 W (no dimming) Annual kWh Use	77,526
250 W (no dimming) Annual Energy Cost ($)	$9,691
105 W LED (no dimming) Annual kWh Use	30,748
105 W LED (no dimming) Annual Energy Cost ($)	$3,843

Scenario 2B: 250 watt HPS (no dimming) replaced with 105 watt LED (fifty percent dimming for six hours)

Table 22. Scenario 2B Economic Analysis Summary

Economic Analysis Summary	
Luminaire Installed	60
Simple Payback (years)	5.8
Annual kWh Savings	54,465
Annual Energy Cost Savings ($)	$6,808
250 W HPS (no dimming) Annual kWh Use	77,526
250 W HPS (no dimming) Annual Energy Cost ($)	$9,691
105 W LED (fifty percent dimming) Annual kWh Use	23,061
105 W LED (fifty percent dimming) Annual Energy Cost ($)	$2,883

Scenario 2C: 250 watt HPS (no dimming) replaced with 105 watt LED dimmed to fifty percent for three hours per night and twenty-five percent dim output for three hours per night

Table 23. Scenario 2C Economic Analysis Summary

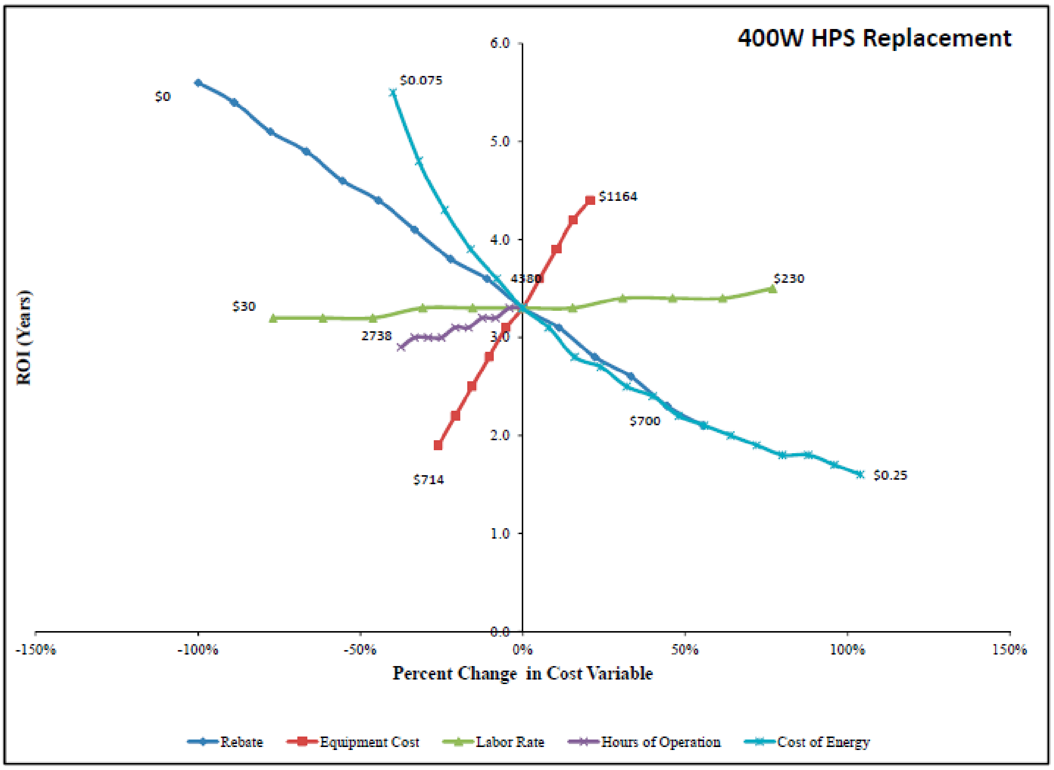
Economic Analysis Summary	
Luminaire Installed	60
Simple Payback (years)	5.3
Annual kWh Savings	58,309
Annual Energy Cost Savings ($)	$7,289
250 W HPS (no dimming) Annual kWh Use	77,526
250 W HPS (no dimming) Annual Energy Cost ($)	$9,691
105 W LED (fifty percent dimming) Annual kWh Use	19,217
105 W LED (fifty percent dimming) Annual Energy Cost ($)	$2,402

The sensitivity tables below show the effects on an LED project's payback when certain cost factors are changed. The central point of convergence on the graphs represents the baseline payback for the HPS baseline scenarios converted to LED luminaires: one graph for a 400 watt HPS to 105 watt LED conversion (Scenario 1C) and the other for a 250 watt HPS to 105 watt LED conversion (Scenario 2C). The graphs show different potential project costs, altering the project's payback, so each cost sensitivity curve shows its impact on the payback.

The central point of intersection, or the baseline scenario, is at a 3.3-year payback for a 400 watt HPS conversion to 105 watt LED with adaptive dimming controls. The cost factors varied from this baseline for each scenario are:

- Rebate value
- Equipment cost
- Labor rate
- Effective hours of operation (based upon dimming levels)
- Cost of energy

Figure 39. 400 W HPS Replaced with 105 W LED (Scenario 1A)

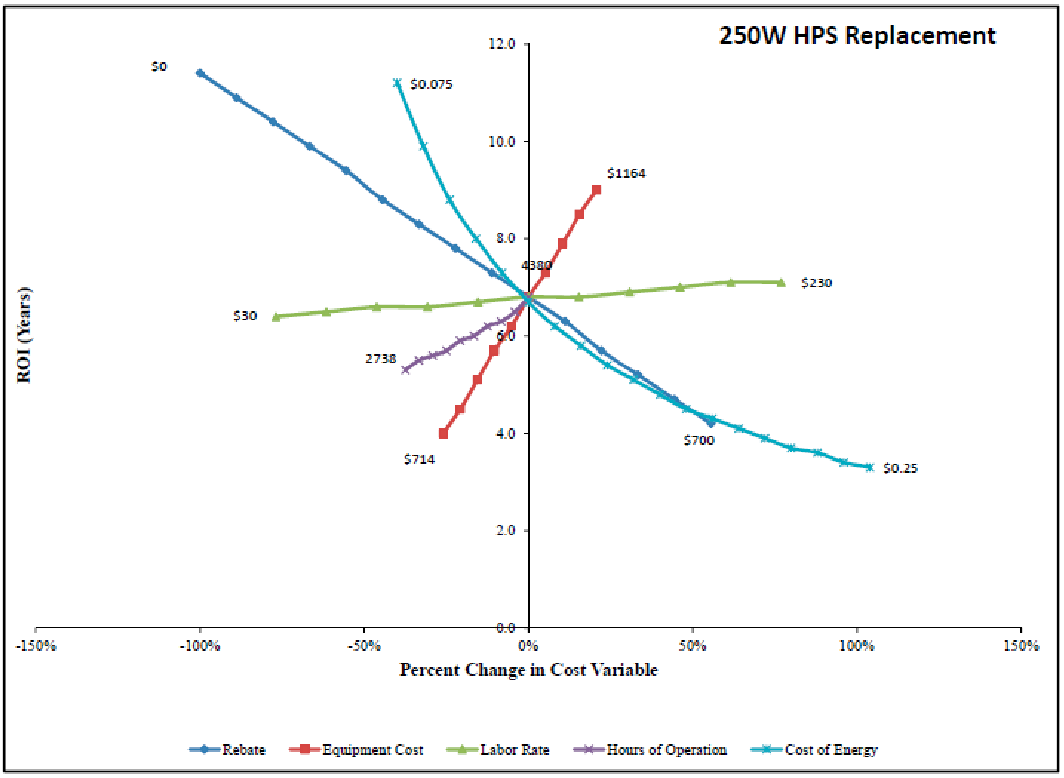


The spider graphs show how the base case changes when a single cost variable changes. Points on the graph represent an MSSLC calculation with the single variable either increasing or decreasing. The X-axis represents a percent change in the cost variables; the Y-axis shows the resulting change in the payback time in years. For example, looking at the cost of power curve, a fifty percent increase in the cost of power causes the base case payback to drop from 3.3 years to roughly 2.1 years. As another example, a fifty percent decrease in the labor rate (of maintenance) has very little impact on the payback, reducing payback only about 0.1 years to roughly 3.2 years. A variable with a steep curve, such as the cost of power, shows that a small change in this variable has a large impact on the payback. A shallow curve, such as the labor rate, reveals that even a large change in this variable creates very little impact on the payback.

Interestingly, control systems that allow for dimming lumen output may not have as substantial an impact on payback as other costs do. “Hours of Operation” represents the use of dimming with adaptive lighting and its impact on payback period. Note that this curve remains relatively flat compared to the curves representing “Cost of Power,” “Rebates,” and “Equipment Costs.” The single largest economic benefit comes from converting the 400 watt HPS to 105 watt LED. Rebating the initial cost of the LED luminaire has a larger impact than dimming the LEDs. Dimming may offer other benefits such as lower energy use (carbon footprint) and less light pollution.

The 250 watt HPS replacement scenario has a steeper and more sensitive curve than the 400 watt HPS “Hours of Operation” curve. The dimming savings represent a larger percentage of the overall cost savings than that for the 400 watt HPS replacement scenario.

Figure 40. 250 W HPS Replaced with 105 W LED (Scenario 2A)



The more dramatic slopes defining the curves for “Cost of Energy,” “Rebates,” and “Equipment Costs” have some notable similarities. Rebates act to effectively reduce the cost of equipment, reducing the payback period, as reflected in the slope steepness. Likewise, if the cost of equipment decreases, the payback also occurs in fewer years. Ideally, lower equipment costs and rebates will greatly reduce the payback period.

The “Cost of Power” curve acts as expected. As cost of power increases, kWh savings are more valuable, reducing the payback period. Again, rebates are a valuable incentive, especially in regions with low energy costs.

However, the “Cost of Power” curve is also unique among the cost curves because it is ongoing and typically rising (typically a three percent increase per year). If a manager implements an LED project and a year later an unexpected jump in the cost of power occurs, the project will pay back sooner than originally forecasted. The chart below shows that a forty percent change in the cost of power reduces the project’s payback by one year.

Another way to understand the current situation regarding control systems is that they increase the “Cost of Equipment” curve (a very sensitive curve) while not increasing the kWh savings enough to justify their current expense in all cases. Control systems need not be valued only as energy-saving tools; streetlight designers and engineers should also consider their other value-added services that go well beyond energy benefits.

7 Conclusions

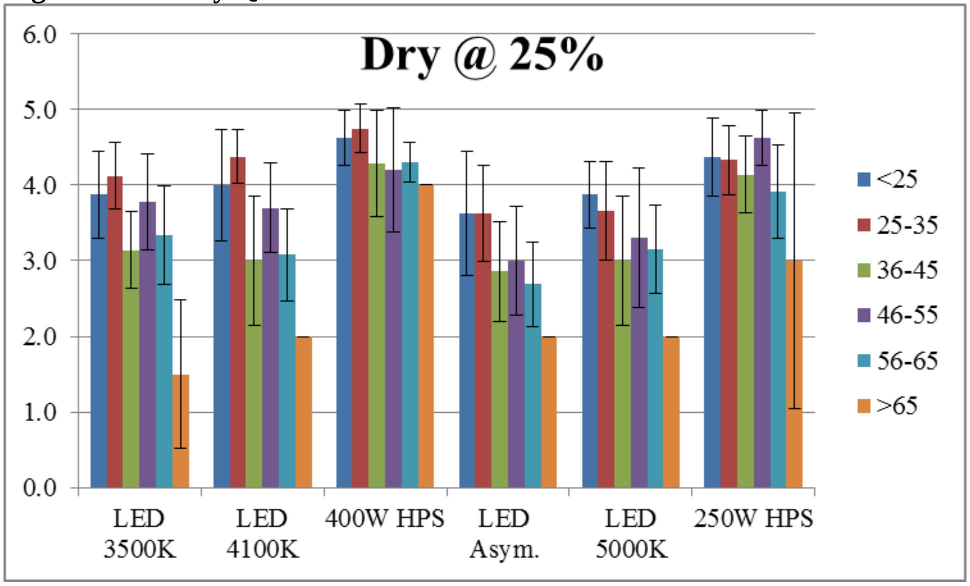
7.1 Written Evaluation

The written evaluation results provide valuable feedback on how well the different lighting systems meet community expectations. The results of the written evaluation indicate a preference for the incumbent HPS streetlights, while still showing acceptance of the LED luminaires. At the lower light levels, some participants considered the lighting too dark on the sidewalks. As seen in the sidewalk evaluations, vertical illuminance falls significantly below the requirements for all of the LED-based conditions, a condition further exacerbated by the impact of dimming.

Additionally, the lower light trespass from the LED luminaires, while desirable, fails to create the same bright surroundings found under the wider distribution of the HPS luminaires. This is valuable information that suggests separating the sidewalk and roadway lighting systems; however, many designs across the country intend that sidewalk lighting to be covered by the roadway lighting. The results of this demonstration suggest that separate dimming control, under which the backlight illuminating the sidewalk is dimmed separately from the roadway, may be valuable.

As mentioned previously, researchers assigned the participants to specific evaluation groups in part based on age to ensure the sample adequately encompassed a wide range of ages. Older individuals (those over sixty-six) often experience yellowing of the lenses of their eyes, which can make it more difficult for them to see. In fact, the IES 10th Edition Handbook has developed lighting criteria based upon three age groups for each application: twenty-four years of age and younger, twenty-five to sixty-five, and sixty-six years of age and older. The criteria (for light level) increases with the increasing age groups. Not surprisingly, participants sixty-six and older rated all of the LED test areas low for the survey question *"It would be safe to walk on the sidewalk here at night*" with the lights dimmed to twenty-five percent output.

Figure 41. Survey Question 8: "It would be safe to walk on the sidewalk here at night."



Note: Mean ratings on a scale from 1 (Strongly Disagree) to 5 (Strongly Agree)

The complete list of open-ended participant comments is available in Appendix C: Written Evaluation Comments.

7.2 User Field Test

The results of the user field test indicate that the 4100K LED luminaire provides the greatest balance in the visibility of all of the target colors, which indicates that the 4100K may be the best choice with regard to luminaire CCT. The 4100K and the asymmetric LED luminaires performed more impressively than the 3500K and 5000K LED luminaires. However, the other light sources also demonstrated benefits; thus regional preferences may still play a key role in CCT selection. Careful consideration should be given to the CCT of a given luminaire upon selection.

The asymmetrical design demonstrated a reduction in glare combined to other distribution luminaires, but no increased performance on visibility; thus its anticipated higher performance failed to be substantiated, although drivers under this design may be more comfortable.

In the past, standard making bodies have generally determined lighting levels based on consensus values and some crash analyses. Previous investigations, including those performed by Clanton & Associates' research team in San Jose and San Diego, failed to show significant impacts on the dimming levels of the lighting system for the object detection task. This is likely a result of the human response to lighting, which usually follows an exponential function called Stevens' Law. In general, this law indicates that the response of a human to a physical stimulus is as follows:

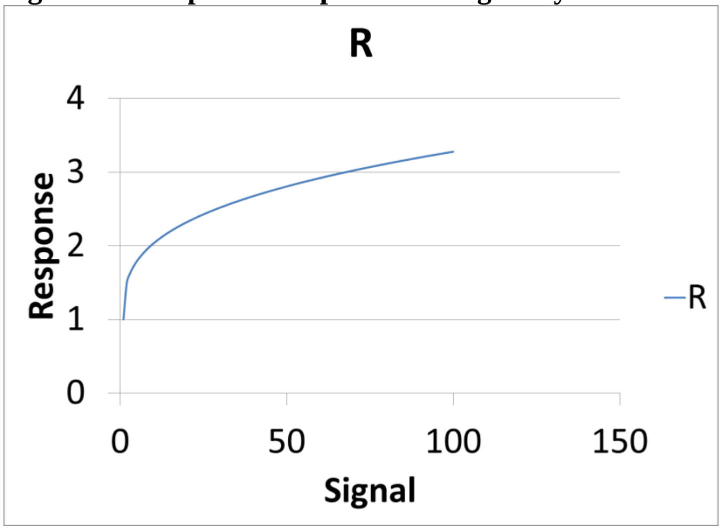
Equation 3. Stevens' Law

$$R = k\,(S-S_0)^{\alpha}$$

Where R is the response, S is the stimulus, S_0 is a base condition to which the stimulus is compared, and α is the response exponent.

The exponent for light ranges between 0.33 and 0.5, depending on the lighting parameters (flash versus steady state). Figure42 illustrates a simplified response to a light signal.

Figure 42: Simplified Response to a Signal by a Human



As a lighting system is dimmed, the non-linear response of the human eye has limited impact on the detection performance. This means that the dimming might remain on the plateau of the function and that it has not yet reached the knee in the function, where performance significantly falls off. The researchers in this investigation took an additional step to attempt to affect the vision system by dimming to twenty-five percent of full light output. The visual detection performance in the dry pavement condition appears unaffected; however, in the wet pavement condition, the light level did significantly affect detection at fifty percent and twenty-five percent of full light output. This result indicates that while streetlight designers and engineers have an opportunity for dimming under dry conditions, they must exercise caution in wet conditions.

The impact of headlamps constitutes another noteworthy consideration in dimming. As a lighting system is dimmed, the use of vehicle headlamps may limit the reduction in visibility. While this is a realistic condition, researchers doubt it affected this investigation as the results indicate a performance decrement in the wet condition that would likely not be evident had the headlamp limit been reached.

The three LED luminaires with standard Type II distribution met IES luminance criteria for a collector road with medium pedestrian conflict using the standard industry practice of lighting calculation software with light loss factors. Researchers completed the calculations using the industry standard software AGi32 and found actual measured average luminance values lower than the simulated values. Such variation is typical and expected given that simulations assume ideal conditions, while in reality, pavement type and road conditions play important roles in the resulting lighting system performance.

The wet pavement condition presents a dynamic environmental change in which the roadway reflection is reduced and becomes much more specular. These results indicate the importance of maintaining the lighting level in adverse weather conditions.

7.3 Color Temperature

Industry representatives have long debated the ideal white light color temperature of exterior luminaires. Some entities claim that exterior luminaires should not exceed the color of the moon, or 4100K. Some believe that warmer color temperatures are more ideal (3500K or less). Several factors influence these debates, including color rendition, quantity of wavelengths below 500 nm (particularly near observatories), and energy efficiency. Many white light LED luminaires originate from a blue diode; energy is required to make that blue diode into warm white light. The more efficient white light LED luminaires have cooler color temperatures (5000K and above).

The user field test demonstrated that the 4100K test areas, including the asymmetric test area, outperformed all of the other test areas in terms of detection distance. This finding is not surprising, given the industry-wide recognition of white light multipliers (IES 2012, CIE 2010). White light sources receive a calculated benefit based upon the luminaire's scotopic to photopic (S/P) ratio, then the calculated multiplier increases the effective luminance values. The 4100K color temperature effectively represents all colors in the spectrum as a neutral color; it is warm enough that reds are rendered well and cool enough that blues are rendered well.

From the written evaluation, participants showed no preference for any particular color temperature among the four tested: 2100K, 3500K, 4100K, and 5000K. With dry pavement, agreement with the survey question "*I like the color of the lighting*" is statistically on par across all test areas (see Figure 43). With wet pavement, participants rated the asymmetric test area lower than all of the other test areas for this same survey question (see Figure 44). Given the asymmetric luminaire's color temperature of 4100K, participants may have rated it lower than the other test areas due to another factor such as contrast or glare.

Figure 43. Survey Question 11: "I like the color of the light" – Dry Pavement

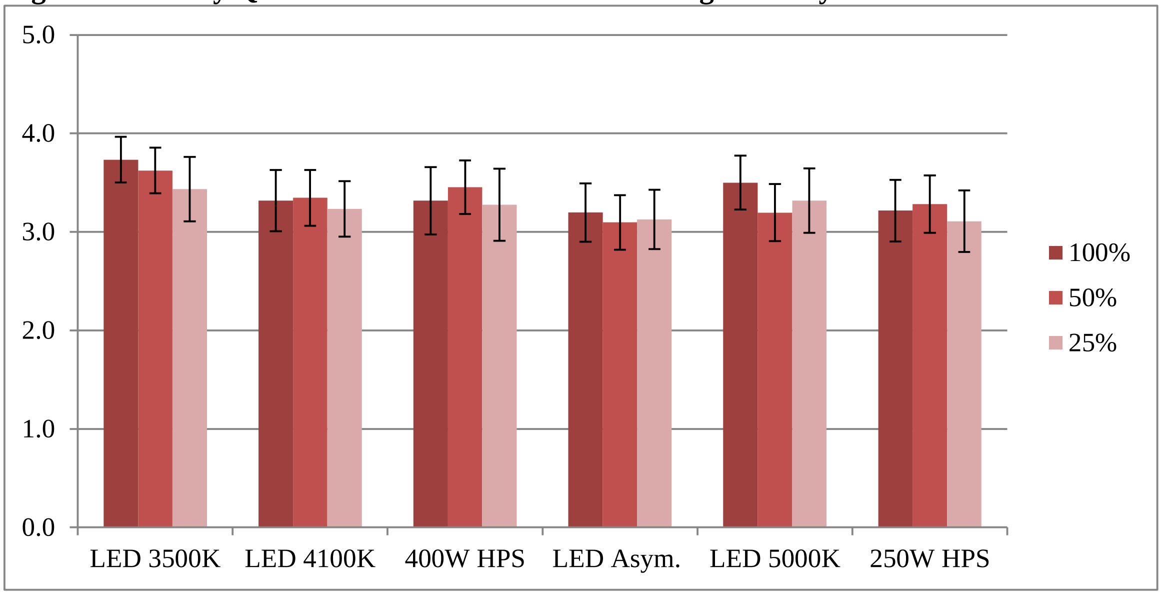
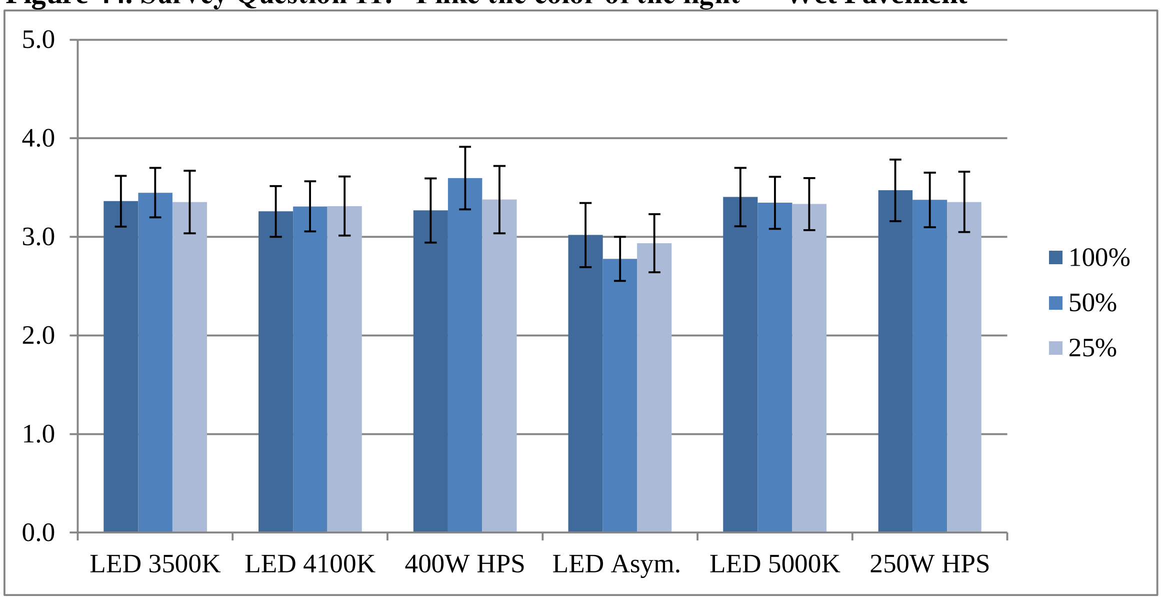


Figure 44. Survey Question 11: "I like the color of the light" – Wet Pavement



7.4 Pavement Conditions

This study used both wet and dry pavement in its evaluations to determine the existence of any luminaire or light source advantages for one condition over another. The detection distance results from the wet and dry pavement tests yielded no predictable trend. While detection distance is somewhat affected by the higher specular reflectance off of the wet roadway, the two conditions are not significantly different from one another. This study indicates that light levels should be not be dimmed at all during adverse weather conditions.

7.5 Asymmetric Design

The research team hypothesized a performance advantage for the asymmetric luminaire over the other standard Type II distribution LED luminaires. With regard to detection distance, the asymmetric luminaires actually provided the second-highest detection distances, behind the standard Type II distribution 4100K LED luminaires. The fact that the asymmetric luminaires are also at 4100K may suggest that CCT is more important than distribution with regard to detection distance.

The asymmetric luminaires recorded the lowest glare values of all of the test areas, as the light was intended to be directed away from the driver. While the asymmetric luminaires performed well in the user field test, participants did not rate the asymmetric test area very high, especially at the lower light levels. Participants found its distribution patchy and signage difficult to view.

7.6 Control Systems

End users (such as cities, utilities, and departments of transportation) could use a control system with nodes in every streetlight for reading home energy meters, identifying emergency locations from 9-1-1 calls, or even for supporting police actions by turning off lights to allow for night vision goggles. Adding such features to a demand response control system that exists in a network every 160 to 250 feet across a metropolitan area could fulfill many purposes beyond dimming for energy savings. Cities should consider such changes and potentially justify them in a broader context, more like a typical capital expenditure with an energy savings benefit, and less as a cost-saving project that must justify itself with an acceptable payback. Some non-energy benefits include lumen depreciation dimming, health and well-being in a darker nighttime environment, inventory maintenance, and asset management.

Some end users are looking at control systems to keep their lighting levels uniform to reduce liability over the life of the luminaire. Historically, some end users have purposefully over-lighted their streets beyond IES recommendations to account for the lumen depreciation. LED luminaires operated with a control system could maintain lighting levels and their spectral distribution. Lumen depreciation dimming (not considered in this economic analysis) would offer additional energy and maintenance savings.

Dimming capability also addresses the potential health and wellness components of exterior lighting. Much lighting research now explores the impact of exterior lighting on people, plants, and animals. With design problems such as light trespass, over-lighting, and the new spectrum of blue light that LED luminaires add to the nighttime world, dimming the lighting can decrease these potential and currently unknown impacts. For example, controls add the ability to dim or turn off outdoor beach lighting that draws hatching sea turtles away from the ocean and toward hotels or housing units. Nighttime neighborhoods with minimal traffic after 9:00 p.m. but large amounts of light coming through windows and bedrooms would see a marked decrease in the amount of nighttime light trespass into bedrooms.

Control systems also manage the maintenance of streetlights. With two-way communication, the control node within the luminaire can send a signal to report a maintenance problem. These signals can then be aggregated into one email sent daily to the streetlight manager. This feature reduces maintenance needs by allowing staff to target maintenance efforts to the exact luminaire that needs to be repaired without sending out crews to identify “day-burners.”

Control systems also provide the valuable benefit of an electronic asset management system.. Traditional street lighting databases are often antiquated and may contain conflicting information. A control system electronically collects the GPS coordinates of the luminaire along with its wattage consumption, hours of operation, and other characteristics. The configuration of the system can permit streets or geographical areas to be grouped together. This comprehensive database then provides the user with immediate control over a large load. Street lighting could potentially be used to shed load very quickly.

7.7 Lessons Learned

The research team identified a few lessons learned to apply to similar future studies.

- Move the traditional technology sources to the ends of the demonstration site. The layout of this study located the 400 W HPS test area in the middle of the demonstration site. With the LED luminaires dimmed to twenty-five percent of full light output, adaptation between the test areas proved to be difficult.
- Allow more time for user field test measurements. The tight coordination of bus and participant schedules limited time for additional user field test measurements. An extra thirty to sixty minutes each night for user field testing would have been ideal.
- Allow more time for user field tests to increase the sample size and thus decrease the variance in the results of the study. Keeping written evaluations going on at the same time as the user field tests requires coordination.
- Track duplicate participants through user field test data. If the study necessitates duplicate participants, analyze their responses separately from the non-duplicate participants.

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Appendix A: Prior Work

A significant number of studies and pilot projects have preceded this work; a partial list follows.

- NEEA Study: LED Lighting Technologies and Potential for Near-Term Applications. This assessment evaluated LED technology and its *likely uses in lighting applications.*
- *NEEA Study: Technology and Market Assessment of Networked Outdoor Lighting Controls. This study evaluated and compared the many manufacturers of outdoor lighting controls available for street lighting.*
- *Seattle Belltown: For this installation, the City of Seattle will respond to a high crime area by dimming the lights to* seventy percent *of full output for general* nighttime *use. At 1:00* a.m. *the lighting* will be *raised to full output in an effort to increase a sense of security.*
- *Seattle Residential: The city is halfway through an LED conversion of 41,000 residential* streetlights.
- *Anchorage: The consulting team for this project performed the first of these studies in Anchorage, Alaska. With high electricity prices,* Anchorage *sought to reduce luminaire wattage and power consumption. Written evaluation test results in both residential and commercial areas and user field test results in commercial areas provided enough confidence in LED lighting from HPS to move to a full change-out, city-wide.*
- *San Diego: After a similar test in San Diego, the city adopted induction technology (another white light source) for its standard luminaire. Its decision was based on better visibility, a more maintenance-friendly light source compared to low pressure sodium – LPS and high pressure sodium – HPS, lower energy use and accepted light source spectral distribution range for the observatory at Mount Palomar.*
- *San Jose: In San Jose, the team expanded the test to include the dimming capabilities of LEDs and controls. After showing comparative visibility and community acceptance of LED sources and reduced light levels, the City developed an Adaptive Lighting Guide and Luminaire Replacement Guide for use in* both *retrofits and new installations of street lighting systems. These documents provide guidance for dimming streetlights to a lower level at night, when traffic and pedestrian conditions have changed significantly from the high levels during rush hour, and for replacing existing LPS lighting with new LED luminaires.*
- *The DOE gateway projects demonstrated LED street lighting in New York, Portland, Sacramento, Palo Alto, Minneapolis, San Francisco, and Oakland. Most of these monitored energy and light output performance compared to existing HPS lighting.*
- *California Lighting Technology Center: The CLTC has* conducted *research and demonstration projects that evaluate LED and induction white light sources with networked controls and bi-level dimming.* Its *research also includes an in-depth study of California's existing* streetlight *infrastructure.*
- *Los Angeles: A city-wide conversion program had replaced nearly 77,000 luminaires with LEDs as of May 2012.*
- *BC Hydro: Numerous Canadian cities have partnered with the utility for LED and adaptive control demonstrations and pilot projects including Vancouver, Port Coquitlam, and Prince George.*

- *BC Hydro: Adaptive Lighting Feasibility Studies performed for cities within British Columbia found average dimming ranges for each type of roadway (local, collector, and arterial).*
- *BC Hydro Power Smart Program: The Adaptive Lighting Guide outlines a process for municipalities to develop adaptive lighting standards based on IES criteria for pedestrian and vehicular conflict.*
- A 2005 study by t*he Illuminating Engineering Institute of Japan found very little effect on driver visibility with changes in light levels.* (Illuminating Engineering Institute of Japan 2005).

Appendix B: Written Evaluation Form

COVER PAGE

NEEA Nighttime Commercial Street Lighting Subjective Evaluation

First Name		Surveyor #
Last Name		

The Seattle Department of Transportation and Seattle City Light, in collaboration with the Northwest Energy Efficiency Alliance, thank you for participating in this important research! We are trying to understand the effect of different lighting systems for potential application throughout the City. The main goal is to understand public acceptance of various street lighting systems. Please respond to each of the questions with that goal in mind.

General Questions

G1. Do you live in Seattle?

Yes ________ No__________

G2. Do you live within two blocks of the 15^{th} Avenue test area?

Yes ________ No__________

G3. Do you work in the lighting industry? (design, manufacturer, specification, sales)

Yes ________ No__________

G4. Do you have LED streetlights in your neighborhood?

Yes ________ No__________

Demographic Questions

D1	*Gender*	M	F	*(circle one)*
D2	*Age*			*(in years)*
D3	*Zip Code*			

Site Questions

S1. Weather conditions --- Clear _____ Cloudy_____ Rain_____ Fog_____

S2. Ground conditions --- Streets Dry _____ Streets Wet_____ neea

TEST AREA 1

	Rate Statements	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	No Opinion
1	*It would be safe to walk here, alone,* ***during daylight hours****.*	O	O	O	O	O	O
2	*It would be safe to walk here, alone, during darkness hours.*	O	O	O	O	O	O
3	*The lighting is comfortable.*	O	O	O	O	O	O
4	*There is too much light on the street.*	O	O	O	O	O	O
5	*There is not enough light on the street.*	O	O	O	O	O	O
6	*The light is uneven (patchy).*	O	O	O	O	O	O
7	*The light sources are glaring.*	O	O	O	O	O	O
8	*It would be safe to walk on the sidewalk here at night.*	O	O	O	O	O	O
9	*I* ***cannot*** *tell the colors of things due to the lighting.*	O	O	O	O	O	O
10	*The lighting enables safe vehicular navigation.*	O	O	O	O	O	O
11	*I like the color of the light.*	O	O	O	O	O	O
12	*I would like this style lighting on my city streets.*	O	O	O	O	O	O

13. How does the lighting in this area compare with the lighting of similar Seattle city streets at night?

Much worse Worse About the same Better Much Better

14. Write additional comments below.

Appendix C: Written Evaluation Comments

Dry Pavement – 100% Light Level, Test Area 1

- This is OK. Does the job. Discovered one patch of dark sidewalk though.
- One streetlight is out on the opposite of the street.
- It is a yellow, but not too yellow. Not terrible.
- When trees have leaves, the light will be different. Light out at NW of 77th and 15th.
- As with some of the other test areas, I like this lighting a lot. Without referencing my other notes, this seems like the best combo of all.
- Dark Alleys
- I like this light. It is not patchy and provides sufficient light. It is warm, but bright at the same time. Lots of shadows though.
- Sidewalks are kind of dark. Road okay but could be a little brighter.
- More trees.
- One lamp isn't working. The lighting isn't overpowering. I like the color of the lights. Lots of shadows on sidewalks.
- Add light pollution covers.
- My fave so far.
- The lights are very bright and glarey, but not enough light reaches the street level. All 4 sets of bright glare lights would be distracting and annoying when driving at night.
- Budget Rent A Car has lot spot lights that effected the overall street lighting in a negative way to bright and too much glare.
- Appears lighter, but not too bright (although I like it bright). Sidewalk are better lit, more shops also have contributed to light source.
- Good light on street, sidewalk was a bit dim.
- There are some areas I would worry about due to darkness, but where the light covers it is nice.
- Too much time was allotted for the walk. We could have easily done it in half the time (and not gotten so cold).
- My street is residential and I would prefer less of the lights and less brightness. A little unsafe because of neighborhood, not lights.
- I like the white color of the lights vs. the standard orange tinted lights that are common.
- Lights could be brighter. Not enough for sidewalk.
- The moon is very full tonight.
- The nearly full moon should be accounted for. It is brighter tonight than usual for Seattle.
- Hard to judge because of the full moon.
- Glare when looking up at light.
- Light is just a little dim.
- Sidewalk park strip tree here.

Dry Pavement – 100% Light Level, Test Area 2

- Too dim on sidewalks.
- Sidewalks are darker.
- Cozy. Like being in the moonlight.
- Seems like sidewalks has better light on the West sidewalk.
- Seems patchy in some places, but not as bad as patchiness in test area south of here (3). I like the non-glaring "safe softness" of the light.
- The lighting is better than some of the other white lights but still patchy.
- Good for a side street, but light on road seems dim for Main Street. Sidewalk patchy and uneven. Road also patchy.
- Trees make light patchy on sidewalk.
- Lights do not light up sidewalk completely.
- This section has better lighting than the other of the same type of lighting source. I like the softness of the source. They really penetrate into the side yards well.
- Add light pollution covers.
- Sidewalk area okay.
- Again these are too bright and glaring at the light.
- It really is dark and does not light up sidewalk or parking lots or shops. It was an obvious change from previous street.
- Darker, less even light.
- Not too dim and not too glaring, a little patchy.
- Some dark areas but gray, not black. Feels easier to see in shadow then I used to.
- Lighting feels softer here – maybe because there aren't as many business signs/lights.
- The lighting would make it easy to see bicyclists/pedestrians while driving.
- Lights too bright to look at directly, but impact on street lighting is great – everything is illuminated.
- Much brighter and cleaner than area 1. Does sort of contrast with house lights – looks weird, but I like the brightness.
- Looking directly at the lights is too bright for my eyes. But otherwise, they are nice and bright.
- Better than area 1.
- I haven't really paid attention to other streets lighting.
- This amplitude of light is very strong. Even blinds would not stop a bedroom from being in perpetual daylight.
- Sidewalk feels safer because of porch lights.
- Glaring when looking up toward/at light.
- Good depth of coverage.
- Nice solid street lighting.
- Brightness of lighting varies depending upon distance and location between streetlights.

Dry Pavement – 100% Light Level, Test Area 3

- It is nice and bright. Good visibility on sidewalks and streets.
- Sidewalk and environs are well lit.

- Great for driving in. Would not want to live on a street with these lights.
- Just too much light. Plus it is yellow.
- Lighting is yellow. Really bright against the apartments. Bright on sidewalk.
- Seems bright, yet not glaring – I like it!
- Alleys and shrubs are lit.
- The lights were pleasant and gave enough light. I would feel safe driving and walking at night.
- A little orangey, but good coverage on both street and sidewalk.
- Aside from the lights leaving spots in your eyes when you stare too long, it is probably the best lit block so far. Less shadows on the sidewalk.
- Add light pollution covers.
- Very even lighting with few shadows.
- Very few shadows, especially at edges of sidewalks. Fully lighted building facades at street side.
- The lighting improves visibility tremendously; however, it is too bright. It seems that the LED lights provide much more comfortable lighting than the current *streetlights*.
- Too bright.
- A bit too bright, but way better than 4 or 5.
- Too orange.
- Sidewalks are better illuminated. I noticed more people talked too.
- That tree looks awful.
- Trees look awful.
- Good light on sidewalk, still a yellow light but not as bad.
- The brightness hurt my eyes a bit.
- Way too bright for residential. Seems overly bright for commercial too.
- Glaring! Have to squint. Very patchy. Hate it.
- Seems like the lighting is more even than the other test areas without areas of darkness.
- I definitely prefer these lights. Well lit and the lighting is warm. The sidewalk was very well lit.
- Too much light for people in houses along street.
- Nice bright glowy yellow light.
- The yellow light creates less lighting pollution in the sky.
- And by better, I mean brighter to a slight degree. I consider myself as a traditionalist, so favor the amber orange hue.
- Seems brighter than previous 2 sections.
- Brighter of all so far.
- I like the yellow tone vs. the blue.
- Old lights along this area.
- Looking right at lights is difficult. Light on street and sidewalk seems to have more coverage on street and sidewalk than test area 1 and 2.

<u>Dry Pavement – 100% Light Level, Test Area 4</u>

- Sidewalk has a lot of uneven places and settling and the light does [not] illuminate it at all in many places. Bad for pedestrians. Unsafe.

- Insurance agency really lights the sidewalk. Trees block light on uneven sidewalk surface. In places sidewalk is very dark.
- Low glare at light source is nice.
- REALLY dark on sidewalks. Dark spot at 7040, 7037, 7052
- Thinking about bike riders here, patchy lighting makes navigation much tougher!
- Retailers sign is brighter than street
- I did not feel safe on this road, especially if I was alone. Too many shadows. It seems if I was driving, I would have a hard time reading road signs.
- Too dark on sidewalk. Patchy on street, style of light is a lit distracting
- Significant dark areas before lights.
- I feel like the color is nice. But it's not intense/bright enough for me to see what I am writing.
- The LED lights here are good for driving, but visibility on sidewalk is not good.
- Large areas of shadow on sidewalks and between some lights. Hard to see to avoid uneven sidewalk in places. Can't read this form well in places.
- Darken edges/shadows-borderline almost too dark. Building facades are not illuminated very well. In the rain, this would be too dark. Sidewalk area too dark but this block has more residential - no much light from businesses.
- A little dimmer.
- Light is similar to Area 5, a bit more uneven, but way too much glare.
- Patchiness on sidewalks unacceptable.
- Can’t see people are tripping.
- Patchier, less light than 5.
- The owls scared me.
- Much too dim, not light reaches the sidewalk.
- Something about the light makes my eyes hurt and there are too many dark areas.
- This section is a little patchy, which makes the lighting noticeably worse. Compare to the really bright. section, a burnt out bulb here would be very noticeable. The road is bright, sidewalk is dark.
- Too little lighting on much of the sidewalk.
- Horrid. Can’t see a thing. Had to stand under a light to fill this out.
- The houses and sidewalks along the street are too dark. There are a lot of patchy areas.
- Absolutely not enough light. Tripped on the sidewalk because of the lack of lighting
- Patchier.
- Not nearly enough dispersion, the patches are quite stark.
- I wouldn't want my daughter driving here at night.
- Style would be okay if some consistent light.
- Light on the street is not continuous - but like spotlights with dark gaps between, uneven.
- Live in the section.
- I can now realize different lighting in test areas. This one seems very patchy.

<u>Dry Pavement – 100% Light Level, Test Area 5</u>

- Not as good as area 6.
- It seems darker especially on the sidewalk.

- Things look natural and crisp.
- Street trees will obscure lights.
- Seems more glaring and patchy, more so on sidewalks than on the street. Business signs and storefront lights are very bright in some areas, accentuating glare and contrast.
- Light is bluer than T6.
- I had trouble reading my paper with these lights. Although the street seems well lit for cars, the sidewalks are not as well lit. The color of light was kind of uncomfortable.
- Good light on street, but lights are a little distracting (and glaring) to look at. Good coverage on street but a little patchy on sidewalk.
- Trees made light patchy.
- Lights look very modern. Definitely felt like streets are evenly lit.
- I believe you should look into a wider angle for your back bar. There are a few darker areas toward the center line between lights.
- Add light pollution protectors.
- Did not light sidewalk area as well - darker edges, more shadows. In the rain, this would be too dark.
- I don't like these lights, way too much glare. Lots of light from shops on street (neon signs).
- The shop auto repair made a big difference on the sidewalk as far as lighting.
- It appears darker with more shadows - light is not as blotchy but seems dark unless directly under a lamp, more shop lights.
- Good, cleaner and even lights, lit up the sidewalk almost as much as the street.
- There were some more shadowy areas but there were no starkly black areas.
- I usually walk faster.
- The lighting seems really good here, but I think it is largely because of the lack of obstructions.
- Good distribution of light to sidewalks and street, including between lights.
- The light is bright enough and even (not patchy) to fully light the street and sidewalks.
- This was nice not as light as area 3 but good. Color was soft.
- This is a cold color and I don't like it much as a yellower light though it does provide good illumination.
- This test area strikes a fine balance of amplitude between the glaring of section 2 and the dangerous patch work of 4.
- Glare when look up at lights.
- A little dim, not quite bright enough.

<u>Dry Pavement – 100% Light Level, Test Area 6</u>

- I like the pinkish tone. I can see colors quite well.
- Street is evenly lit as is the sidewalk. Interval between the lights is good.
- Orange glow is annoying.
- With leaves, street trees will negatively impact light and visibility. Patchy light/hot spots are light and bright. Not light and dark.
- 1st stop. Hard to compare but this seems like very even light. Bright enough for safety, but not harsh or glaring.

- Stronger the light, the darker the shadows.
- The lighting is nice, not too harsh and I think it gives full coverage of the streets and sidewalks.
- Very orangey. Bright in some areas but less so in others.
- Color is yellow/orange.
- People were talking - kind of distracting. Lighting looks pretty average to me. Light fixtures do not bother my eyes. I felt like some lights were slightly dimmer.
- Add light pollution protectors.
- Sidewalk lighted, a few shadows at edges.
- My eyes have become more sensitive to light as I've aged.
- Similar to other bigger streets.
- All the lights are working correctly. No flickering on and off.
- Seems blotchy. Some areas darker than others.
- Light seems dim and yellow, didn't reach the sidewalks.
- There is some construction on the west sidewalk and a large dark spot immediately south of it. That would feel unsafe.
- The lights are way too bright for residential application. The sidewalks are well lit, but also overly lit.
- I like the yellow color better than white, but it seems like white lights things up more efficiently
- Same thing as we have now. Too yellow, too patchy.
- Lighting is very even (not patchy) but I prefer the white lights from other test areas.
- This is the best; color illumination, not patchy, not glarey. I like style best too.
- Best.
- Again, count me a purist, another sucker for the dusky orange glow. Find a way to incorporate this hue into LEDs and its arguable even from an aesthetic standpoint.
- Good consistency - no gaps with dark areas. I like the yellow town.

Dry Pavement – 50% Light Level, Test Area 1

- Like lower overall glare, lower level of light (less light pollution), slightly warm tint is nice.
- I would feel safer if there were more light directed at sidewalks.
- Some of LED lights are less brighter and kind of bothersome.
- Super dark here!
- Seems easy, like moonlight.
- I think it is important to test the lighting on the side streets - usually the neighborhood streets are darker, so the question could be: is light enough to see house numbers and to see street signs?
- Questions are in a font that is too light and too small to read easily. Binders are difficult to handle.
- Street lighting was good (though darker than normal), but sidewalk lighting was a little dark.
- Seems a bit dim, sparse. The full moon is bright.
- Different color.

- Like the lights - not enough of them. Glare uneven along the length of light.
- When I look down the street, it looks really dark.
- Trip hazard.
- This is pretty good.
- Very slight glaring when looking up at or very near the lights.
- Even though I feel the lighting is worse, I think the lighting is good enough.
- Sidewalk ok, street ok.
- One of the street lamps was out.
- Too dark, cold.
- Good color, but too dark for walking on sidewalk….would be perfect if it were brighter and not so patchy.
- I like the color of the light, but it is not bright enough.

<u>Dry Pavement – 50% Light Level, Test Area 2</u>

- A little brighter, good but a little glarey as you get closer or directly underneath. Still okay, though.
- In comparison to area 1, area 2 seems better illuminated.
- Test area 2 seems better lit than area 1. The lighting seems generally too dim overall.
- Darker on sidewalk, lighter in street.
- Seems more patchier that area 1.
- Would like a little brighter.
- Many sidewalks are darker than street.
- Sidewalk lighting was adequate.
- Adequate but a bit dim.
- Nice balance overall.
- Lighting across each lamp was very even.
- Dark shadowy. Seedy. Cold.
- I almost tripped three times.
- If it could be a little brighter and or if the lights could be shining out to the sides a bit as well, it would be safer and aesthetically pleasing.
- Good overall lighting, both sidewalk and street.
- Too dark.
- Way too dark on sidewalks. Lighting is extremely bad unless directly under lamp. Bad shadows.
- Too dim.

<u>Dry Pavement – 50% Light Level, Test Area 3</u>

- Same yellow color as other streets, not bright white.
- Warmer tone is nice, but lights are way too bright. Good to id pedestrians in black/dark clothing, though (see those in Seattle often).
- Felt too bright, too many strong shadows. Might be good for high pedestrian areas at certain times.
- These lights seem to be more intense and bright. I like it bright.

- Yellow/orange look. The LED lamps in area 1 and 2 had a daylight look. I like the daylight color better.
- A lot more ground coverage of the light and that ensures more safety in less road kills or any unseen danger threat.
- A little dark in between *streetlights* - the neighborhood bar brings out pedestrians late in the evening.
- I see no difference between thin and existing lights on 15^{th}.
- I really like this style of lighting. It is sufficient for seeing both street and sidewalk. Quality is warm.
- Too much unnecessary light pollution! Can't see the stars. If you consider more light better, however I don't like it as much even though more light.
- I like it bright on main streets but dimmer in neighborhoods.
- Seems more consistent that other Seattle streets.
- More coverage and less patchy. Sidewalks are illuminated.
- Felt more comfortable, more light.
- Look same as other arterials with older technology.
- Don't like color and glare. Level of lighting on street and sidewalk is great!
- Bright, warm.
- I like this, even and good.
- Bright sidewalk, bright street.
- This was the only one that made me think it might be safe to walk at night.
- Almost daylight!
- Bright enough, but poor coloration.
- The light is a bit too yellow but I like the even coverage and lights that are bright but not glaringly so.

<u>Dry Pavement – 50% Light Level, Test Area 4</u>

- The lighting seems low, they should be brighter for car visibility.
- A little too dim, big black/dark areas between pools of light. Just barely enough.
- Too many dark areas. Felt unsafe.
- These lights are set way too low. To clearly see this survey I must be directly under the light or within 10 ft.
- Seemed too dark and even the slightest shaded area felt super dark.
- Super dark! Gives me the creeps! Terrible.
- Darker on sidewalk, patchy on road.
- Too dark.
- Sidewalk lighting greatly compromised.
- Dim, patchy.
- Right color, too dim.
- Dark shadowy.
- Sidewalks need work.
- Have to search for a place to read.
- Dark sidewalk.
- Too dim/too spotty.

- Not bright enough on sidewalks.
- Dim light, though the color is better than in Area 5.

<u>Dry Pavement – 50% Light Level, Test Area 5</u>

- Residents should watch their language.
- A little brighter, and cooler than I would prefer, but some good.
- Lights are not bright enough.
- Too dark here. Doesn't feel safe.
- Seems normal, like moonlight, easy not obtrusive.
- Dim, but better.
- Nice color, nice balance.
- Glare toward middle of each light fixture.
- Lights from signs can affect perceptions of things.
- Pretty dark, sidewalks are shadowy.
- Sidewalks dark, streets even.
- There seems to be enough light on street but sidewalks are dark.
- Dark sidewalk.
- Cold.
- Not bright enough…
- Way too blue, not bright enough.

<u>Dry Pavement – 50% Light Level, Test Area 6</u>

- Somewhat dim, but not awful.
- Good brightness maybe a tad too much. Don't like the yellow look of source, washes color of things and sources are a little glarey.
- Borders on being too much light.
- IN the car you would have your headlights adding some light to the street.
- Once again, this looks like existing lighting on 15th.
- This feels nice and bright, safe. Best yet! I could read a book by this light.
- Kind of yellowish but comfortable.
- Better lighting but not enjoyable.
- Overall, the LEDs were adequate for vehicles but not for pedestrians. Sodium was more comfortable, better visibility (pedestrians).
- Looks similar to test Area 3, but seems more patchy in street.
- Kind of muted.
- Warm.
- Seems a little dim, but I like the color of the light.

<u>Dry Pavement – 25% Light Level, Test Area 1</u>

- Although this project would be good for energy saving purposes, I would really prefer yellow low-pressure sodium lighting for purposes of insect conservation.
- Moon glow casts more shadow.
- I felt like a black-out.

- The light seemed to reduce depth perception, made everything same flat gray. I noticed people all stopped. directly under the lights to white. Too dark? I would feel unsafe biking on a road lit like this.
- One of the lights actually flickered & went out during the test.
- Just dim enough to be annoying.
- Very washed out.
- Full moon helps!
- Seems a little dim.
- Lighting from looking off sidewalk to street seems minimal/lacking.
- But just not as bright but no glare.
- Red, orange & white was easy to differentiate, but blue/green was very hard to tell apart.
- Too much light to pee on sidewalk - good or bad? I'm not sure yet.
- Too green.
- This type of light is better for driving. It won't make people blind.
- Whites seemed a diff color.
- Too dark.
- Too dim.
- Adequate lighting for driving or walking.
- Looks a bit yellow.
- Like this best - not too bright, not too dark.
- Rate this in the middle.
- This is ok - lights are dim, but adequate for vehicular & pedestrian traffic. I think the color is 'warmer' than the other LED sections - I like that.
- Full moon seems to be the better of the LED areas.
- A bit too dark.
- Feels a lot like test area 2, but sidewalks feels better lit. I think this zone is my most preferred!
- I feel like the lecture provided some influence. Comments like "we hope you feel this way," etc.
- Best one even coverage of street cooler light.
- Lights better than 2 but still too dark, ok for driving but questionable for safety of walking. Couldn't fill out forms except for light for buildings.
- Best overall of the LED dot lights.

Dry Pavement – 25% Light Level, Test Area 2

- A light at the end/beginning of block between areas 1 & 2 would have been nice.
- Looking for light.
- Again, while slightly brighter, this light seems to make everything a flat gray. Very hard to distinguish colors. Would not feel safe biking here at night. Use fluorescent light to write this.
- This light hurt my eyes a little when I first looked at it.
- Nice dim light.
- These lights seem brighter than test 1 even with less commercial lighting.
- Seems more even than area 1.

- Less glare. Certain angles don't have sharp light that hurts my eyes.
- More glare, uneven light, does not light sidewalk.
- This area holds my local bars.
- Sidewalk seems more open than #1 - could be uniformity of lighting?
- Still too green.
- Brighter than #1 but not glaring, doesn't overwhelm.
- Seems a little brighter than test 1.
- I like the color of the light, blue-white vs. yellow-white. Cool.
- More glare than test S but nice.
- This area the light seemed more consistent across the test area, like the light is more even. No businesses with really bright lights - makes me think of spring. Moonlight from the full moon where you can see once eyes adjust if this was a sketchy area (crime) would want more light.
- To dark same as 5.
- This acceptable dimmer than 6 & 3, but ok - I would not use my flashlight in this section - no color visible, but even without bright structures, I can see far enough ahead.
- Full moon can barely read the survey.
- Way too dark.
- Feels like the perfect amount of light in the street, but sidewalk feels a bit shady.
- Looks a bit dark. Little contrast w/ambient light. Preserves true colors great.
- LED lights like design not as glary need slight amount more, dark areas on sidewalk.
- light very dark - too dark for safety, patchy - unacceptable poorest so for.
- 2nd best of the LED dot lights.

Dry Pavement – 25% Light Level, Test Area 3

- Awfully bright from the sides as well. Maybe too bright for a vehicle?
- Too bright.
- Now I can see clearly.
- This light makes it much easier to distinguish colors. I would feel visible to cars if I was biking here & more able to see obstacles in my own path. Compared to the softer, previous light it seems a little harsh.
- This test site seemed especially bright, at a much higher intensity than previous tests.
- The glaring is slight enough to tolerate.
- Way too bright.
- Quite bright - not too bright, but if more costly than #2, not necessary.
- Patchy eye sight if look up directly @ light.
- Good until I walk under light then there is a sharp/annoying source of light at the upper part of retina/glaring?
- Lighting feels safer than test area 1 & 2 nature of the block that makes it questionable. Shadows - more on test 1 & 2 much more visibility here.
- While the lighting is good for road travel, there is far too much light on the sidewalk.
- This area felt much brighter in comparison. Too much light for biking? - No. Too much light for graffiti?- Yes.
- Sodium lights FTW (If only they weren't so inefficient.)

- This kind of light is making blind during the rain.
- Seems like regular *streetlights*, maybe brighter. Can pick out details that I could not see in 1 or 2
- Much brighter. Is a glare when I look directly at lights.
- (for driving glare) Brighter than necessary.
- Color ok, but too bright.
- This lighting is excellent from a pedestrian's standpoint-warm, bright, everything is well-illuminated evenly.
- Too bright too yellow too glaring.
- Real difference with bright lights, wouldn't want to live next to lights this bright.
- Excellent!
- I thought I liked LED lighting, but alter sections 4 & 5 this feels great! Every color is hard to see and yes they burnout, but I like this light.
- Full moon.
- Well lit area, although a bit glaring.
- The street seems way too bright, but the sidewalk feels safe, but overall it feels like too much light.
- Washes out on the colors! I hate these lights.
- Good for road & sidewalk very yellow lots of glare and light pollution. Seems over lighted for residential
- Like the color quality and distribution of light my preference by far over 6 5 & 4.
- way too bright - like daylight which seems like overkill as vehicles should have head lights on.

<u>Dry Pavement – 25% Light Level, Test Area 4</u>

- Very directed light, not glaring to the sides.
- Brighter? Still a little hard to see colors. Less harsh, but would still feel less visible to motorists.
- This lighting seemed to make the sidewalk more shadowed than the others so far.
- Very dim there isn't a lot bleeding light from businesses.
- A little too little light.
- Sufficient light, could be a little brighter.
- Quite dim.
- Very patchy looking from sidewalk to street and on sidewalk, like the lack of glare though.
- These shaded lights don't hurt retinas.
- Sidewalk areas too dark.
- The light level up to 20 feet is good on both sidewalk & street, but sharply declines to not enough light after that.
- Sidewalk walking is fine, biking or running it may be too dark.
- Sidewalks overgrown and dark.
- Feels like #1 - too dim. Shadows encroach easily. Too dark, too long between lights.
- Not as bright but less glare.
- Way too dim.

- It is probably sufficient lighting for driving, but a bit dim for walking.
- Too dark.
- This was my 2nd area; found that my eyes adjusted better to lower levels of light would find it difficult to read small numbers, this block seemed more residential.
- This section worse than section 5.
- As dim as section 5, but more even (not patchy) - too dim! I would use my flashlight here at night.
- Full moon very dark between lights.
- Way too dark.
- Trees seem to close some patchiness.
- Lots of shadows difficult to see papers in this light.
- Not enough light. Patchy somewhat harsh. Not enough lite to feel safe to walk.
- Seems almost as dim as #5 area.

Dry Pavement – 25% Light Level, Test Area 5

- Better, still hard to distinguish shapes. Target in the road (for the car) was indistinguishable. In yellow light would immediately have ID'd it!
- This lighting is my favorite thus far.
- Great lighting.
- Like #3, lighting here might be insufficient in cloudy/rainy conditions.
- Even but a little dim.
- Less tree cover on this block light looked more natural, like super bright star light.
- Similar lighting to #4, but no vegetation overgrowth makes it feel safer.
- Too dim, too diffuse.
- A little dim.
- Was in car experiment & missed the 1st marker as I did not understand where they were.
- Lighting is even but there is not enough light. Had to fill out this page of the survey using light from the front of a business.
- Love, not too bright, no glare-covers the street amazingly well.
- Would be nervous about walking @ night without the additional lighting provided by storefronts - seems awfully dark, I would want to carry a flashlight.
- Had to find a lighted area to fill out this form.
- This must be a joke - this is way too dim - I notice all the testers huddling in front of city nails so we can see our surveys. I would get out my flashlight walking here at night.
- Full moon barely enough light to read this survey.
- Light is pleasant to look at but doesn't illuminate enough.
- Lights from buildings are brighter than the *streetlights*!
- Seems to blend with ambient light, which makes street area brighter is not bad or good. I love how it does not distort true colors!!!
- Good prevention of light pollution upward. Lots of business lights on this side of street makes difficult to properly evaluate.
- Very dark patchy.
- Seems dimmer than #4 areas.
- Little light.

Dry Pavement – 25% Light Level, Test Area 6

- Note the bright moonlight makes conditions somewhat difficult verses if it had been a moonless clear night.
- Quite bright.
- All right.
- Very bright glare.
- I felt the section was patchier and the lights glare more. Can tell colors & objects though, which is important and helpful.
- A little to yellow.
- Not uneven but less light in center lane.
- Unnatural color to the lights compared to past areas.
- Brighter better lighting & open sidewalks feel safer.
- Orange's lighter orange than 4 nice! My favorite. Chases away shadows without being glarey or too bright.
- Too bright!
- Should be better lit as it is a school area.
- The only patchiness I noticed was due to trees near light source.
- Glaring when looking up at one light but not overall.
- Na - I'm very familiar with this section & these lights - they are fine, when they work. I have reported many burned-out sodium lights here.
- Full moon.
- Lots of shadows.
- lots of shadows, dark spots on sidewalk.
- Too "warm" of color. Seems to wash out true colors.
- Yellow, glare.
- Comfortable degree of light & color appears fairly evenly distributed adequate.
- The glare from bulbs too much but light quality quite appealing, meaning its relative naturalness.

Wet Pavement – 100% Light Level, Test Area 1

- Could actually see the shade of green on building's sign.
- Lots of dark patches.
- Again, I think it would very informative to test o side streets where it's less illuminated & *streetlights* need to be bright enough to see house numbers & street signs.
- This light is pleasant and adequate - the wet street is well-illuminated the area right at 77's looks too dark (from up the block) - but it's because a whole fixture is non-operational.
- Full moon is a lighting factor in test.
- The pre explanation tonight was much more explicit than last night causing me to answer my questions w/ a different understanding. Last night I had variables such as broken cement causing falling & potential muggings.
- Cold/dull light also shadowing patchy light on sidewalk. Roadway lit ok.
- If you like shadows this is good. Nice for shady activity.

- Were some of the lights meant to be out?
- White light.
- Rolled my ankle on an uneven part of the sidewalk that I didn’t notice.
- Very white lighting, harsh on eyes bright.
- Light at the end was out, really noticeable. Glare only when looked up at directly.
- Full moon patches of dry & wet pavement, wet much reflection.
- Standing directly under the light is too glaring, but looking across the street to the other light is fine.
- It's actually hard to tell if the lamps are lighting the as much as the street signs it's pretty bright.
- Park gaps between light areas - too much contrast.
- Didn't look like enough light on street.
- The moonlight (full moon) may have enhanced the illumination along with the reflection off the wet street.
- More balanced than previous areas especially considering I do not favor the cooler light.
- Patchy but good overall coverage. Light all the way just some bright spots.
- Difficult to get full effect of lighting due to commercial signage.
- This was my 2nd fave.
- Can see oncoming car lights in this area. And goldilocks said, this is just right.
- Patchy.
- Not bright enough, shadows.
- The budget rental spotlight meant that I had to get to mid-block to really tell what the lighting looked like.
- I liked this area best in the LED style.
- Sidewalk is less patchy than area 2, but still a bit too patchy.
- Although not my favorite, it is not the worst. I prefer the warmer lights.
- This lighting is my favorite of the LED. It feels more natural than other LED lights.
- There was a street lamp out and in that area it was very dark. The other street lamps did not help in that area.
- The light is not harsh or uncomfortable; it sits in the middle for me. But it doesn't make me feel too comfortable.

Wet Pavement – 100% Light Level, Test Area 2

- Too much glare: I'm squinting in the dark.
- Really good lights.
- Are the lights performing any differently when it is raining? Of course there is reflection when the street surface is wet, but is the lights bright when they're shining through rain.
- Well-lighted, Adequate, 'color' of light feels sadder than section #1 - but it's ok, even the wet pavement is well-lighted.
- The lighting seemed better on this section than the first - lighting is more of a natural color.
- Full moon is so bright it is hard to tell.
- Much better (more) lighting on sidewalk.
- Funky tint to the light, shadowy. The sands red-light district still visible.

- We have these sort of lights where I live they work great.
- White light.
- Lights from buildings seemed to assist *streetlights*.
- Spacing better than unit one.
- Closer together Brighter.
- Has dark patches in parts.
- Felt more like more building light this section.
- More directed light whiter can see cracks on sidewalk better.
- I like test area 1 better, this light feels less friendly. Also still standing under *streetlight* is glaring but looking across at it is not.
- Due to less distracting lighted sign I can see the street lamps effects better.
- Better than 1.
- Even brightens up a depressing and shady strip club corner!
- Seems brighter than area #1.
- Uncomfortable.
- Sidewalk very dark, street patchy.
- Again, not enough light on sidewalk.
- Fine for residential areas. I have LED lights outside my house. This reminds me of them.
- Doesn't emit as much light as others.
- Spotty, too dark.
- These lights look glaring from afar but are not as bad when standing under them.
- Seemed really dark.
- Donut shop and corner store make for any sidewalk lighting.
- Very patchy with lots of dark spots.
- Lights are not bright enough and need more lights.
- Very poor visibility, definitely too dark.
- The light seems very sharp, but I feel like I can see well.
- My favorite so far - I really like it. A bit dimmer at night, this is much more comfortable.
- Seemed darker.
- The light seems too harsh which makes me feel uncomfortable.

Wet Pavement – 100% Light Level, Test Area 3

- Can't see colors; everything looks yellow.
- Very bright but also very glaring. No dark patches.
- I think this was well organized w/professional attitude & execution. Justin was especially, especially helpful & encouraging. Thanks You! Also the cookies & beverages were a nice touch!
- Good old sodium - compared with LED's in 1 & 2 this does seem 'glarey'- easier to see colors (even w/yellow light) I do like this lighting, but I know it starts flickering and flashing eventually, which is awful - I like it, but I don't doubt it being obsolete.
- This lighting lit up the sidewalks better giving a bright yellow here on sidewalk. Easy to see problems w/sidewalks - lighting better than test one.
- I can see a great distance under this light, good depth of field, good color.
- Great light for watching TV. Seems like light is dimmed need more watts.

- So far best lit sidewalks.
- Yellow light.
- Not the industrial blue.
- Full lighting, no dark patches.
- More yellow, spreads out more color.
- Seems lighter than I'm used to, I thought that the LED lights were glaring but actually these are more.
- This area is really light; there are a lot of lamps giving off a lot of light. I will not want to live on this street, but as a main arterial this is really lit.
- Bright, sort of glaring, but good.
- Light was brighter here.
- Very beige.
- Too much glare!
- There were some dark areas! Housing little scary.
- Warmer the light the better.
- Lighting reflects brightly off buildings strongly.
- Stark contrast in pedestrian lighting. Light actual hits sidewalk compared to area 4.
- Would be too bright outside my home windows.
- A little glaring but not distracting.
- Good light, sidewalk very good like the brightness in street.
- While bright, I think this light is too yellow and too bright.
- Better lighting - doesn't blend in with the stop lights.
- Harder to read than 5.
- Light was even on sidewalk.
- Plenty of light for all lanes. Full visibility and I like the warmth of the light color.
- The lighting really seems to distort color.
- Yellow light is casting a icky shade on all objects.
- It is bright enough where I can see people clearly far ahead of me and behind me which make me feel safer.

Wet Pavement – 100% Light Level, Test Area 4

- Way too dim; couldn't see the sidewalk.
- Way too dark unsafe to walk unsuitable.
- If not for the commercial lighting, this street would be unsuitably dark. I don't like it.
- Not enough light in this test section. Sidewalks dark & dangerous (cannot see cracked & uneven surfaces.)
- Light in street very patchy - shadowy dark, alternating banks of dark & light. Light is pooled under lamps.
- Nice & mellow able see with less shadow. I can see & smell green.
- Way to dark!
- White light.
- Trees and branches blocked some of the light in certain areas.
- Seems darker but you can still see to walk and drive.
- Lighting threw shadows on sidewalk, actually making visibility worse.

- Too many shadows, areas with no light very patchy.
- Dreary.
- This light seems less harsh, more natural colors & although it's darker there is less glare & my eyes do not need to adjust as much as the previous area test #3.
- Is this the same light as #1? So dim people gather in doorways to write comments!
- Easy on the eyes. Solar powered?
- Too dim.
- Very uneven light, sidewalk dark.
- Unacceptable amount of lighting on sidewalk. Street is barely lit. If I wasn't familiar with neighborhood, I would not walk here at night.
- Maybe this is darker?
- Too dark, spotty, sidewalk way too dark, Danger.
- Some of the *streetlights* seem brighter than others.
- Hard to see on sidewalk.
- It is a little hard to read things.
- It is a much softer glow.
- Street was well lit, but sidewalk was dark. Color was good.
- Could use some yellow lights as well. Possibly need more lighting.
- Definitely too dark. Not enough for all lanes. Sidewalk was very dark.
- The light is too dim.

Wet Pavement – 100% Light Level, Test Area 5

- Needs to be a tad brighter.
- Aren't very bright but minimally acceptable.
- Too dark; again, without commercial street fronts, I would use a flashlight to walk this street.
- I like this.
- More of day light feel - pleasant.
- White light.
- More commercial industry to aid in lighting.
- Glare in reflections.
- Spreads out more uniformly.
- Lighted signs for stores stand out more than the *streetlights*.
- I guess I now notice the glare on the street from the wet pavement, I actually like it. And although the light is darker on the sidewalk yes it looks more natural as opposed to an orange high glow.
- Dim.
- Spotty.
- Some glare on wet pavement but not distracting.
- Lot of lighting from businesses which helps.
- Neon signs affect perception of color contrast of non-luminescent sign.
- Lighting on sidewalk is lacking compared to street.
- I have had Lasik halo effect? Not aesthetically pleasing but wouldn't care if it meant saving energy.

- Perhaps distracting that you can make individual bulbs. Draws attention because different.
- Glaring.
- Not bright enough. Glarey and spotty on wet pavement.
- Need some more lighting source focused on sidewalk.
- Feels like inside light.
- Overhead light source is much cleaner.
- I felt there was more reflection from the stop light.
- The lighting does not feel as warm I can't decide if I like it or not.
- I dislike walking in this light because it makes me have a feeling something bad will happen. It is creepy and ominous.

Wet Pavement – 100% Light Level, Test Area 6

- Can't see…. too yellow/glaring.
- Good light but like LED more.
- I understand the LED's use less energy - however is there any way to get them brighter?
- This section seems dimmer than 3 (also sodium) maybe the lack of commercial lighting? I walk this block before dawn every day and seems visual, but only when all the lamps are functioning.
- This is different than 5 but I like both.
- A little glaring, but great light on roads & sidewalks - some of the trees blocked lighting in places on sidewalk.
- First 2/3 of this station was great. Then *streetlight* disappeared & last 1/3 more tenuous. My ratings ate on beginning walk.
- A little patchy on the sidewalk.
- Light seems dull & Yellow. A little old school *streetlight* feel.
- One spot was very dark due to big trees!
- If there was more "rain" I'm sure the road glare would be much worse w/this lighting.
- Dark spots in tree blocking reflection areas.
- Yellow, softer.
- This feels the most normative.
- Yucky yellow, but bright (good).
- Too many shadows created.
- Trees along sidewalk both shaded as well as impeded flow of light.
- The moon was very bright.
- This was my fave.
- These lights seem like typical old school Seattle lights. The control?
- A little spotty.
- I do like the yellow cast light, makes it easier to see headlights of cars.
- Could use more white lights.
- I like the warmth of the light color. Plenty of light for both sides of the street.
- This site is free of distracting lights.
- Warm familiar light we are all used to, but not very effective.

Wet Pavement – 50% Light Level, Test Area 1

- Don’t like that there are light and dark areas. Very uneven. Dark in the center of the street.
- Dim lighted.
- My favorite overall.
- Uneven brightness, where light is dimmer. It is harder to see the lines on the street. Driveway alleys are largely unlighted and a little unnerving.
- There was not enough light to read the questions in some areas.
- They wanted to know what I would say the professionals from NEEA walking south of the avenue lights were yellow some blue. Now they can evaluate as they may.
- I feel safe in my known environment which is this area. If I was in Beacon Hill, outside of my comfort zone, I would probably feel less safe. Maybe good to have people from outside of the area.
- Appears as a soft light, no washing out, but gives everything a soft gentle appearance.
- To be perfectly honest, I am not sure about #13. I chose about the same since it seemed the most neutral.
- Sidewalks not wet, were they supposed to be?
- Trees may have affected sidewalk light.
- Bright enough to drive and see any obstacles. Very even light. Too dim lighting to illuminate any dangers. around corners or out of sight. The bright signs create even more light. The color is aesthetically pleasing but not bright enough.
- I loved the lighting.
- Questions 2 and 8 are misguided. I wouldn't walk here after dark when the businesses are closed. In December it is dark before 5.
- Not bright enough to see colors except under *streetlights*.
- This not a safe street for a female to walk down alone at night. I could tell the colors of things due to other sources of lighting. The *streetlights* did not enable me to see colors.
- Too dark.
- Glare on roadway.
- Could be better.
- For a busy street, this is dark. These lights don't give off much light between actual light locations.
- Seemed like there was one light out, west side south most light.
- Without reliable light from stores, it would be too low. With it is the lowest amount I would find comfortable with in a community.
- Best area so far. Seems very soft but not as invasive feeling as the very bright bronze color. Good for commercial, bright for residential.
- Tone is a little cool, but brightness is just about right. Slightly patchy and dark spots, but adequate lights.
- Damn you budget rental truck! Do we get a party favor from the love zone?
- Unclear whether questions refer to street or sidewalk (1-3, 6, 9, 11, 12). I don't drive so can't respond to #10.
- Seems really patchy/dim in some areas (south end of test area and almost and north end of test area).

- 2nd favorite.
- Higher distribution of LED style lights this block.
- All through, areas 1-6, street trees will obscure.
- Too dark and patchy on road. Too dark on sidewalk.
- It is still too dim to make me fully comfortable walking around at night.
- Dark.
- Full moon!

<u>Wet Pavement – 50% Light Level, Test Area 2</u>

- This is better than test area 1.
- Seems a bit dim overall.
- Uniform lighting doesn't seem that much brighter but good shadows are reassuring. Lines on street uniformly visible.
- This area appeared to be patchier, although this may have been a result of hyper examination and over examination on my part.
- Maybe I am crazy but this feels like there is less lighting than Area 1 but that also might be because there are less stores with lights.
- Areas of shade beneath trees making it harder to see in the street. Too dark to see around corner if reflects off wet areas better than dry.
- IT was hard to answer #9 because the *streetlights* were the only thing on.
- same as area 1.
- Safe to walk on sidewalk, light to see obstacles.
- There was less lighting from businesses in this section.
- Green light.
- Looks good.
- This section is brighter and more even than the last.
- Not bright enough to feel safe in an urban area. Moonlight light. Most fill light from other sources.
- Not a lot of business lights so it was a truer test of the light spread on the sidewalk.
- Colors appeared muted. Shadows cast by the soft light are fuzzy and indistinct – creepy.
- More like there is hardly any light on the street! Also sidewalk lighting is only good under streetlight or in an area where the storefront has good lighting.
- #1 strip club! Not safe. Nothing to do with lighting.
- Way too dark, seems like hospital lighting only worse. Does nothing for my complexion.
- Appears to be less ambient light from businesses/residences this block. Sidewalk seems darker.
- Under awning, lights are distracting. It seems patchy on west side of street.
- Too patchy on streets, too dark on sidewalks.
- I didn't realize what patchy really meant until this test area. There seem to be pools of light and the contrast creates more of a sense of mystery. It makes me feel less safe. I am not sure wheat or who might be lurking in the dark corners.
- Too dark on the sidewalk.
- Lights seems bright enough, but poles seemed further apart.

Wet Pavement – 50% Light Level, Test Area 3

- The center of the street is very well lit compared to all the others. Also lights up the sidewalk as well.
- I know that orange color of the spectrum is best in terms of lights rendering the farthest from the source, but this makes the street look fairly ghetto. Some may not prefer this.
- Way, way too bright especially over wet pavement.
- Brighter lights, more yellow? Glare patches on wet pavement. Lines on pavement a little hard to see in areas. Nice bright sidewalks.
- The lighting in this area is very bright.
- Lights overall very well. Less dark areas on the sidewalk.
- Although not a fan of the more yellowish orange light, the clarity and evenness of the light in this area is much higher than the whiter lights in area 1 and 2. This light is much more even and covers more area.
- This feels really bright and I like it. For walking by yourself at night this would be really nice, I would feel much safer. However, it might be kind of glaring for drivers (I am not sure on that though).
- Note: I said worse, because I do not like extra bright lighting.
- More glare and distracting color but better lighting. Much brighter and makes me feel safer. A bit patchy and glare. Very safe driving
- The lights in this section are much brighter.
- Yellow lights are warmer color.
- This section is way brighter than 1 and 2. Although as a female, I wouldn't feel safe walking here, alone, at night. I feel much more comfortable with this lighting.
- This color of light.
- Best lighting for walking.
- The best of the 1st three.
- This is the kind of lighting I am used to - compared to the others, this is the brightest.
- Like the brightness level.
- Floods very evenly and bright. So bright it sort of drowns out surrounding lights. Car headlights - too over powering and invasive.
- Too/very bright, very glarey especially with wet street. Not a fan of the yellow tint. Good illumination on sidewalks, though.
- Way too freaking bright from the lights and the reflection of the street. Hurts the eyes! Glad I was wearing a ball cap.
- I may like a color of light, but that doesn't necessarily mean it is safer or easier to walk in it. The converse of this is also valid.
- Best light of the night.
- Too bright for a residential streets. Great for major thoroughfares.
- Main and first impression = lots of glare here.
- Very warm, comfortable light.
- Sodium type lights. Slight yellow orange shift. This block seems to have a higher concentration of lights that a typical street. Individuals sensitive to glare may be distracted in this area.

- The bleeding of light onto the aperture along here has got to annoy people. It is a bit bright - now would this look coming from a residential street. Arterials fine, residential no.
- Too bright for residential street, but great for main roads. Neighboring homes may find it annoying (too bright).
- The lighting is very bright and makes me feel safe.
- Very bright.

Wet Pavement – 50% Light Level, Test Area 4

- Way too dark, especially sidewalk..
- Spotty coverage. Blocked by vegetation especially once trees in leaf.
- Most dim out of all, so far.
- Too dim overall. Seems the dimmest.
- Lighting sees dimmer, particularly E streets overgrowing the sidewalk. Makes it feel less safe even though the street is wide open.
- Very dim. Do not like the bluish color it gives off. Least favorite so far. Sidewalk is hard to see in this light.
- This has been the worst of the 4 so far. Kind of patchy does not illuminate much. Area covered by each streetlight very low.
- I think this has less lighting but I could be feeling that way because the last section was so bright and I am comparing it to that.
- Much brighter than area 1 and 2. More glare. More patches on street, uneven lights. Too dark on sidewalk if not under light.
- This section was darkest because most of the businesses/houses had no exterior lights on.
- It feels dark and creepy compared to test area 3. Luckily there is someone singing karaoke in the tavern across the street to ease my fears. Since the lighting is not as bright, it probably saves energy, which is good.
- Too dark (worse so far).
- Dark!
- Might as well have no lights. Rely on lights from store signs. Have to stand directly under the lights.
- Lights on opposite side of street glare more than on my side. Business lights contribute to safety. In front of a business with no light son it was too dark.
- Almost too dim, patchy before with pools of light with lots of dark patches.
- First half was better than second half.
- Looking down or up the street the sides of the lights are visible and possibly distracting.
- Way too dim for driving or walking safely.
- Dark!
- Majority of actual *streetlights* on opposite side of street/sidewalk, seem very dark.
- Johnson agent awning light too bright = distracting. Look up e side no glare, look a w-side glare.
- Too dim. On sidewalks, can't see cracks plus lots of dark areas for strangers to be lurking.
- Area much darker than others.
- Too dark on the sidewalks.

- Darker.

Wet Pavement – 50% Light Level, Test Area 5

- Slightly patchy but not too bad.
- Something about these lights seems like they are the best out of all the LED lights I have seen so far.
- Some glare off the wet pavement. Sidewalks seem well enough lighted.
- Light seems blue. Dislike but the sidewalk isn't too bad.
- Best of all the white light areas so far. Not as patchy and illuminates a lot of area.
- This doesn't seem well lit but better than the last one. I think I am still comparing this to the area 3 where I felt the safest.
- Strong moonlight again, like last night, must affect results.
- Less patchy than some. But not bright enough.
- Better lighting on sidewalk, more even, wider light on street, sign light distracting, still bright with less glare.
- The lighting is really nice in this area. Much better than test area 3. Lighting is more even, making it more comfortable.
- Pretty dark, but not as bad as 4.
- Could be brighter - sidewalks are pretty dark.
- Like the light from a full moon. Pretty, but doesn't make things bright enough to feel safe at night.
- Needs to be brighter for ideal safety. Business lights did help with the safety.
- Adequate, but lower level of lighting. Not glare. Good! Even when looking up at directly of from reflections.
- Dr. Hoats wellness for life sign is freaking blinding, as the shop.
- This style of lighting seems to be more absorbed by the moisture on the roadway.
- Looking up or down the street, or long distances the sides of the lights are visible.
- Seems dimmer in a bad way that test area 6. Raises a few questions/concerns about walking or driving at night in this area.
- This light feels very "cold.”
- White/blue color shift (slight). Appears less luminous than are sodium (area 6).
- Seems dim on both street and sidewalk.
- I think for this kind of commercial street, the lighting works because it’s augmented by lights from the stores.
- Darker.

Wet Pavement – 50% Light Level, Test Area 6

- Lighting partially block by trees.
- Most mediocre/plain/typical lighting compared with other Seattle streets out there.
- Favorite test area, bright E good shadows on sidewalk, but not a hard white light.
- Even though the lighting is brighter, I did not think it was better.
- I like the warmth of this light. It is a bit on the bright side though.
- I am finding it difficult to rate glare and patchy in isolated instances might have been easier in relationship to each other.

- Not the best of the two orange lights, but still better than the white lights.
- With regards to the color - I think I prefer this yellow light not because it is yellow so much but because it makes it seem brighter.
- Test areas 3 and 6 were the brightest - test area 6, the best overall.
- Very bright and easy to see obstacles. Feel safe walking.
- Lighting suitable for downtown Seattle.
- This is a safer part of 15th than the other sections.
- Could see well.
- Looks good (for an old guy).
- Good.
- Made the area very visible and comfortable to walk through at night.
- Very different from when it was dry, much darker, but still good.
- #3 and #11 comfortable and I like the color mainly out of familiarity, not necessarily a true likeness of the color. Even though it is a widely used color, it reminds me of an industrial area.
- Bright, but glarey. I don't like the strong yellow tint of the light.
- The glare from the reflected light off of the street is very uncomfortable.
- The rain water makes the lighting different and more reflective.
- Sidewalk would feel safe if fewer cracks and more level - nothing to do with lighting.
- Patchy lighting (not really much of it) seems more attributed to road surface and paving and wetness that variations in lighting.
- I like the soft yellow effect of the light.
- Seems representative of usual arc-sodium type city lighting. Slight color shift yellow-orange.
- Light casts a lot on the utility poles. W-side seems brighter than e-side.
- Orange color is not too pleasing.
- I love this lighting!
- It is all a little dim, although well spread out.

<u>Wet Pavement – 25% Light Level, Test Area 1</u>

- Too dark.
- Too dim to write legibly.
- Seems better with wet roads. Remember not liking it a lot last night when dry. Sidewalks still a little dark.
- I live and walk up and down 15th Avenue NW almost every day.
- The biomat spotlight was distracting.
- Light is a bit too low.
- Very dark on sidewalks, seems a bit dark on streets.
- One dark alley no shadows. On all: the color depends on the distance.
- Street is dark and so is sidewalk.
- There was an area where there was one regular (not led) light shining over a budget rental place which lit up the street much more than the LED streetlights, but also created more glare.
- Dim but I like the wet reflections. The sodium light at the budget light is distracting.

- Seems a touch dim. I think a higher intensity light would be preferable.
- I like that there is very little glare off the water.
- Walked into the back of a person who had stopped on the sidewalk.
- The light doesn't seem much brighter than the ambient light from what you would get just from the businesses.
- Orange hued light is more glaring.
- Too dark, feels unsafe.
- Let there be light.
- I am standing directly under a streetlight and can barely see what I am writing. My yellow pencil looks red.
- This is part of the area I consider sketchier than the other points on the test zone.
- Full moon make made it seem lighter out.
- Lighting fills in the spaces between commercial light very nicely.
- Test sequence Area 6 to 1. Not impressed with intensity settings on LEDs. Seemed uniformly off. Made the old sodium look too bright (with horrendous amber color).
- I can at lease read what I am writing here. This was not the case in Test Area 2.
- Don’t be a tattle talk (directed at lady). As far as LED lights go, this section is the best.
- Sidewalks are a little better lit, but still kind of dark.
- You should say in the introduction and on the slides for the driving on the street that the signs are on the road, yesterday I missed the 1st 2 as I didn't understand.
- Lights are dimmer, yet comfortable. Of all test areas, I prefer this one.
- This is the best one. Smoothest lighting.
- Bright enough to see by, while still preserving ambiance. A very pleasing choice.
- Good color, even distribution, not quite enough lumens.
- Light directly down from *streetlight* patchy.
- My favorite of the LED styles.
- Very dark section, almost unsafely so. Rain not a factor. Sidewalks too dark, unsafe.
- I live in Ballard and I feel that all streets are safe day or night.

<u>Wet Pavement – 25% Light Level, Test Area 2</u>

- So dim I couldn't see the paper.
- Sidewalk a bit bright on this one, but creepy street.
- Seems brighter than test area 1.
- Not enough illumination.
- Fine on the streets, still a bit dark sidewalk.
- On bright bus light is distracting.
- Lighting is good.
- This section brighter. There were bright "patches" but that were private light () reflecting in the wet street
- The moon is pretty bright.
- Many patchy and again seems dim; underwhelming.
- Again, lack of glare is nice. Smell of doughnuts is, however, distracting.
- Light seems very patchy and gets overpowered by porch lights.
- Without light from businesses, it is hard to see lane lines on street.

- Not enough light.
- Better than test area 1.
- Tesses boutique and other storefronts gave off light so I could see. Crossing street, I stepped in a huge puddle that was invisible.
- I feel like the LED lights are better for really bright, but focused lighting.
- I would feel uncomfortable walking down this street alone.
- Still set too dim, needs to be brighter/whiter.
- The donut shop smelled so delicious that I almost walked straight in to the wall. Perhaps moving to a more lit location would have allowed met to find it easier and avoid walking into things.
- The color is not so harsh but it still not a lot of light on the sidewalk.
- Sidewalks are badly illuminated.
- Better for driving, worse for walking.
- Seems the same as Area 4.
- Lovely mood lighting, but could stand to be a touch brighter. Pleasant color, seems to preserve my night vision better. A little brighter and this would be my first choice.
- Patchy areas make this not comparable to other comm. Areas.
- I like this lighting.
- Fine for driving, not for walking - unless I had a headlamp.
- This is hilariously insufficient lighting!!! Totally unsafe. But perfect for a bad hair day.

Wet Pavement – 25% Light Level, Test Area 3

- Too bright, too orange, too glarey.
- I find the yellow to be pleasing and not at all harsh.
- Lighting on sidewalks is better and it needs to be. Another creepy street.
- This is the best lighting yet.
- Love! Bright, safe, and not intrusive.
- Light is a little glaring, but he amount of illumination is favorable.
- Seems like the existing lighting, plenty of light on sidewalks.
- A few deserted buildings, feels so isolated.
- Old light better but not cost efficient.
- I like this way better than Area 1 and 2.
- The brighter illumination is much more comfortable, better visibility, colors.
- During rainy conditions at night the glare could be too much. It is also a lot more yellow.
- These lights seems much brighter isn't more glaring.
- Very bright/maybe too bright.
- WOW! This is it!
- Feels like I am in a well lit room. Nice, warm, safe. Can see to the end of the driveways and lots, safe.
- These areas might be too well lit.
- Better for old eyes.
- Standard sodium lighting - similar to test area 6.
- Lots of shadows, but I can see pretty far ahead of me.
- Barely crosses over into too bright. Preferable to too dim.

- Glare hurts, giving me a headache. At least I can see the forms, can see the uneven sidewalk.
- Yellowish light bright like daylight.
- Very well illuminated section, warm color to the lights.
- This is optimal lighting - effective, warm, easy on the eye. Much better than the dim cool blue light. Feels safer. No reflective problems.
- I was in the group last night where our guide let slip that areas #3 and #6 were controls.

Wet Pavement – 25% Light Level, Test Area 4

- Feels very dark, maybe okay using brights but probably won't on busy arterial.
- Too dim.
- Darker street area in general, brighter lights might be more beneficial on areas like this with less business lights.
- Light is pleasant but too dark.
- Too dark on sidewalks.
- My apartment is on this section. It needs more light.
- It seemed more "patchy" here but not enough contrast to be a problem.
- This section seems pretty dark. This opinion is unaffected by doughnut aroma.
- Bushes on sidewalk are overgrown.
- The light is very uneven with patches of darkness between lights.
- This section seems a lot darker after the last section.
- Too little light to be safe.
- Back to test 1.
- Midas sign and apt lights seemed to be the only light source. Streets are in almost total blackness.
- Not sure if it was because of the lighting, or this sidewalk () more uneven ground, but I nearly tripped on a couple of cracks in the sidewalk.
- The man singing karaoke at the bar where we stopped would probably not win on American Idol. If he were to pass out in the street here it would be hard to see his body.
- Worst of the lot. Without the few commercial lights it would be a cave.
- Way too dim, to even see this page to fill out. Sidewalks too dim. More light comes from businesses along street.
- I don't feel safe here.
- Best version of Radiohead karaoke I have heard, ever. At waterwheel lounge.
- The screaming drunks were kind of distracting.
- Not nearly bright enough. Treacherous.
- Have to use store lighting to read form sidewalk is dark.
- Lights really dim but better light than # 5.
- Too dim for pedestrians.

Wet Pavement – 25% Light Level, Test Area 5

- Sidewalk better than sum. Glaring in spots but not all. Maybe depend on what is near.
- More residential areas could use brighter lights.
- Patchy light, too dim.

- Light is very blue, too dark on sidewalks.
- One glaring business light distracting. I like seeing shadows.
- Dark!
- The light seemed brighter, more comfortable. I liked it.
- Businesses have distracting lights in this section.
- Now I understand glaring.
- A bit dark.
- The brightness is similar to other streets but the lights aren't as glaring. Would be better if the light was more even.
- Darker but less glaring.
- Not bright enough.
- In life, there is always the unexpected.
- "The Shop" signs provided light. Streetlights did not and Scandinavian specialties.
- There are a lot of businesses with bright lights in this area so that makes it a little harder to judge the lighting.
- I would have a tight grip on some bear mace and a rape whistle if I had to walk through here along at night.
- Had to find a lighted storefront to be able to read the questions.
- Too dim.
- Can't see while writing this.
- Very dim, sidewalks are barely lit.
- I like that it feels like moonlight, but it would be better if it was brighter.
- Hard to see where I am walking - see sidewalk grade can’t see cracks (except by buildings with lights).
- More light on street from businesses than *streetlights*.
- I was in the car for this section. Note: objects stood out due to silhouetting by streetlights skews findings.
- Feels like I am in a cave.

<u>Wet Pavement – 25% Light Level, Test Area 6</u>

- Too bright, too orange, too glarey.
- Again with yellow, very nice! Again might be because of () though.
- A bit of glare when wet in spots, but overall good visibility.
- I like the brighter lights, but as a pedestrian in Ballard, I don’t generally feel safe ever.
- Light color and glare are disagreeable, but illumination is good.
- Color is a bit whiter, plenty of light on sidewalks; it seemed odd to me that there was not a section with LEDs that attempted to match the normal lights.
- Best lighted area in this section…6.
- Overall, I like the color of the LEDs. If you turn the lights down for efficiency, you will need to add pedestrian lighting to the commercial arterials. Too dim in some cases.
- I like this lighting the best.
- It is a very comfortable brightness but the yellow of the light is a bit harsh.
- Good overall lighting, feels safe.
- And there was light!

- Ah! Light!
- It seems like the lighting here is the same as it has always been.
- This lighting seems like normal, boring street lighting.
- Some areas near apartment parking lots are dark. These areas are probably scary for attractive women.
- Writing in the back of this booklet sucks.
- Lots of shadows on sidewalk, feels like it would be scary at night.
- Not unfriendly, but not the most personable.
- Some colors are easier to see than others yell/or = good, green not obvious.
- Trees make lighting on street patchy lighting yellowish.
- In the future, you should change the order of the test area pages in the booklet for ease of use. Oh and I like these lights a lot.
- The wet streets don't have much impact on my impressions.
- The bright porch lights on W side of Ballard HS were distracting and north side of pool.

Appendix D: Product Specifications

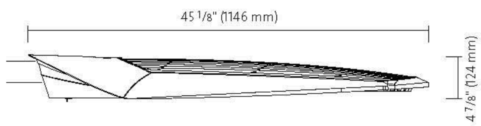
Project name		Type	
Date		Prepared by	

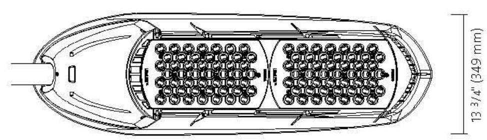
Luminaire	Lamp	Optical system	Voltage	Options	Finish

Roadstar series

GPLM
EPA: 1.10 sq. ft.
Weight: 31 lbs (14.1 kg)

GPLM





LUMINAIRE PERFORMANCE DATA (Nominal 4000K CCT)			
Lamp	Average lumens*	System watts	Max AC current (amps)**
❐ 105W79LED4K	8174	119	1.17
❐ 130W98LED4K	10469	147	1.4
❐ 150W79LED4K	9979	170	1.7
❐ 180W98LED4K	12543	204	2

* Lumens for Type II distribution. Consult photometric files for lumens of specific distributions.
** For 120 volt AC input.

Optical systems / LED

- ❐ **LE2** TYPE II / Asymmetrical distribution
- ❐ **LE3** TYPE III / Asymmetrical distribution
- ❐ **LE4** TYPE IV / Asymmetrical distribution
- ❐ **LEH2** Type II / Hyperextensive
- ❐ **LEH3** Type III / Hyperextensive
- ❐ **LEH4** Type IV / Hyperextensive

BUG RATINGS				
	WATTAGE			
Distribution	105W79	130W98	150W79	180W98
LE2	B2U1G2	B2U1G2	B2U1G2	B3U2G2
LE3	B2U1G2	B2U2G2	B2U1G2	B2U2G2
LE4	B2U2G2	B2U2G2	B2U2G2	B2U2G2
LEH2	B2U3G2	B2U3G2	B2U3G2	B2U3G3
LEH3	B2U3G2	B2U3G2	B2U3G2	B2U3G3
LEH4	B2U3G2	B2U3G2	B2U3G2	B2U3G3

Voltage

❐ 120 ❐ 208 ❐ 240 ❐ 277 ❐ 347 ❐ 480

Includes surge protector 10kV

347 and 480 volt for 180W98LED4K only

Luminaire options

- ❐ **BL** Bubble level
- ❐ **CDMG** Dynadimmer control
- ❐ **DMG** 0-10 volt dimming-ready power supply
- ❐ **PH8** Photoelectric cell, twistlock type includes receptacle
- ❐ **RC** Receptacle for a twist-lock photoelectric cell or a shorting cap
- ❐ **WPG** Without protective grid

Finishes

- ❐ **WH** White
- ❐ **BK** Black
- ❐ **NF** No finish
- ❐ **GY3** Medium Gray
- ❐ **NP** Aluminum

Specifications subject to change without notice.

PHILIPS

Lamp

Composed of high performance white LEDs. Color temperature of 4000 Kelvin nominal, 70 CRI. Ambient operating temperature range -40C (40F) - 50C (122F). L70 lifetime of 70000 hours at 25C ambient. Use of a metal core board insures greater heat transfer and longer lifespan of the light engine.

Optical system

Composed of high performance collimators, optimized with varying acrylic beam angles to achieve desired distribution. System is rated IP66. Performance shall be tested per LM63 and LM79 (IESNA) certifying its photometric performance. Dark sky compliant.

Surge protector

LED Driver 3 poles surge protectors and protect line-ground, line-neutral, and neutral-ground in accordance with IEEE / ANSI C62.41.2 guidelines. Surge rating 10kV.

Driver

High power factor of 99%. electronic driver, operating rang 50-60 Hz. Auto-adjusting to a voltage between 120v and 277 volt AC, Class II, THD of 20%. Lamp starting capacity -40F (40C) degrees. Certified in compliance to UL requirement. Weather tightness rating IP66. Assembled on a unitized removable tray with Tyco quick disconnect plug located in a separate enclosure in order to protect from heat generated by the LEDs.

The current supplying the LEDs will be reduced by the driver when a temperature is exceeded as a protection to the LEDs and the electrical components. Output is protected from short circuits, voltage overload and current overload. Automatic recovery after correction.

Housing

The upper and lower part of the housing are made of die cast A360 Aluminum alloy 0.100 (2.5mm) minimum thickness. The mounting means includes two brackets made of stamped galvanized steel (12ga.). Fits on a 1.9" (48mm) to 2 3/8" (60mm) OD by 7" (178mm) long tenon, fixed by 1/2 13 UNC steel zinc plated bolts. An integral part of the housing permits and adjustment of +/ 5°. The housing is complete with a secured access door avoiding accidental dropping, a ground lug and a terminal block that accepts (#8 max.) wires from the primary circuit.

Heat sink

Built in the upper housing, optimizing the LEDs efficiency and life.

Product does not use any cooling device with moving parts (passive cooling device).

Bird guard

Prevents birds from entering the luminaire. Made of high density polyethylene 0.030 (0.8mm) thick and captive to the housing.

Light engine

LifeLED composed of 4 main components: LED lamp / optical system / heat sink / driver electrical components are RoHS compliant.

Wiring

Luminaire wiring is done using a terminal block located inside the housing.

Hardware

All exposed screws shall be stainless steel with Ceramic primer-seal base coat to reduce seizing of the parts. All seals and sealing devices are made and/or lined with EPDM and/or silicone.

Finish

Application of a polyester powder coat paint. (4 mils/100 microns). The chemical composition provides a highly durable UV and salt spray resistant finish in accordance to the ASTM-B117-73 standard and humidity proof in accordance to the ASTM-D2247-68 standard. The specially formulated Lumital powder coat finish is available in white, black, gray and bare. Additional colors are available. Consult factory for complete specifications.

Vibration resistance

Meets the ANSI C136.31-2001 table 2, American National Standard for Roadway Luminaire Vibration specifications for Bridge/overpass applications.

Certification

CSA, UL or CUL. ISO 9001-2008.

PHILIPS

Document order number: GPLMTS100R01

Philips Roadway Lighting
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Rosemont IL 60018
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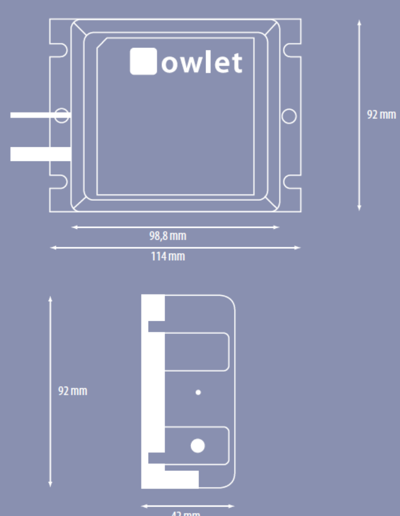
Customer Support/Technical Service: 847-390-5111
www.philips.com/roadwaylighting
A Division of Genlyte Thomas Group LLC

Datasheet
Luminaire Controller



black ○ ⇢ **L** — **230V 50/60Hz** +10% -15%
blue ○ ⇢ **N**
brown ○ ⇠ **LL** — **Load** 230V/1100 VA (max.)
violet ○ ⇠ **+** — **Dimming Interface** 1–10 V
grey ○ ⇠ **–**

Order Information		
Luminair Controller -M -D 1xEM;1xDO; 1xAO	230 V	LC-5204-2230-2100-1100 (LC-MD EU1 02A)
Luminair Controller -M -B 1xEM;1xDO; 1xPC	230 V	LC-5204-2230-2100-0110 (LC-MB EU1 02A)
Luminair Controller -C -DALI 1xCD;1xDO; 1xDALI	230 V	LC-5204-2230-2011-0100 (LC-DA EU1 02A)

Environmental Conditions	
Storage temperature	- 20 °C to +70°C
Storage humidity (relative)	10 % to 90 %
Operating Temperature (Ambient)	- 20 °C to +70°C
Operating humidity (relative)	10 % to 90 %
Dimensions	114 mm x 92 mm x 42 mm (outside edge) 98,8 x 92 x 42 mm
Weight	390 g
Ingress protection class	IP 44
Electrical protection class	II
Housing material controller	ABS

Mains Connection	
Related Voltage	230 VAC +10 %/ -15 %
Frequency	50/60 Hz
Supply and switched voltage (L)	10A fused
Impulse withstand voltage	4kV

Power Switch (Output)	
Switched Output Voltage	230 VAC
Max. power	1100 VA (any type of ballast)
Relays Type	Bistable; Zero crossing switch strategy

Control Switch (Step Down Signal- depends on product type)	
Switched Output Voltage	230 VAC
Max. current step down signal	10 mA
Relays Type	Bistable

Dim Interface (depends on product type)	
Dim interface	0/1–10 V DC polarity sensitive

Communication	
Frequency	2.4 GHz (ISM Band; international) (2400 … 2483.5 MHz)
Channel	16 (dynamic)
Transmitting Power	2 mW (Optional 10mW)
Pysical / Protocol	IEEE 802.15.4 (2400 … 2483.5 MHz) ZigBee
Topology	ZigBee Meshnet
Baud rate	250 kbps

Norms	
Electromagnetic Compatibility for R&TTE	EN 301 489-17 / EN 61000-4
Radio	EN 300 328
Safety	EN 60950-1
	EN 61347-2-11

Features	
Real Time Clock	automatically synchronisation
Astronomical clock	Redundancy functionality

DS_CoCo_LuCo_10-0003

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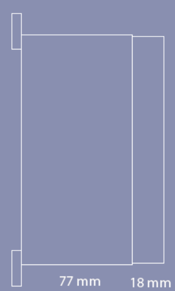
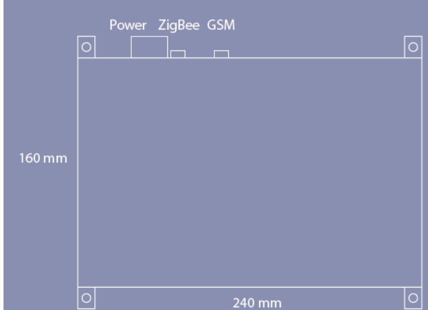
Datasheet
Segment Controller





Order Information		
SeCo CPX4 LAN	230 V	SC-0211-1230-0000-0000
SeCo CPX4 WLAN	230 V	SC-0211-1230-0000-0000
SeCo CPX4 GPRS	230 V	SC-0311-1230-0000-0000
SeCo CPX4 IP66 IO LAN	230 V	SC-1011-1230-0000-0000
SeCo CPX4 IP66 IO GPRS	230 V	SC-1111-1230-0000-0000
SeCo CPX4 IP66 IO 3G	230 V	SC-1211-1230-0000-0000

Features	
Enclosure	NEMA 4X/IP66 rated
Network Protocols	UDP/TCP, DHCP
LEDs	Ethernet status, power, cellular link/activity, signal strength (5 bars), ZigBee link/activity
Security	SSL tunnels, SSHv2, FIPS 197 (IPsec, HTTPS)
Real-Time Clock	Yes
Routing Features	NAT, Port forwarding, Access control lists (IP filtering)
VPN	IPsec with IKE/ISAKMP; Multiple tunnel support; DES, 3DES and up to 256-bit AES encryption; VPN pass-through, GRE forwarding
Management	HTTP/HTTPS web interface, Password access control, IP service port control, Optional secure enterprise management via iDigi or Digi Connectware® Manager
Industrial Protocol Support	Modbus bridge enables Modbus serial to Modbus/TCP conversion Integrated Python code allows gateway to act as Modbus client/master or Modbus server/slave Functions like an Ethernet to serial bridge, but uses ZigBee to transport serial data Handles unique timing issues per Modbus protocol rules Uses Modbus Unit ID to look up IP or mesh MAC address
Antenna Types	ZigBee/802.15.4 external antenna, Cellular: 2" dual band dipole, magnetic mount
Antenna Connector Type	XBee: 1 x 50 Ω SMA, male (on gateway), Cellular: 1 x 50 Ω SMA, female (on gateway)
Dimensions (L x W x H)	7.60 in x 5.63 in x 2.72 in (193 mm x 143 mm x 69 mm) 3.10 lb (1.41 kg)
Power Requirements	
Power Input Rating	90 - 254VAC
Power Consumption	Approx. 15W
Surge Protection	2 kV burst (EFT) (with included power supply)
Interfaces	
Serial	Software-selectable RS-232/485, screw terminal block connection; Throughput up to 230 Kbps; Full signal support for TXD, RXD, RTS, CTS, DTR, DSR and DCD; Hardware and software flow control
USB	1 powered USB Type A connector (Host)
Analog I/O	4 ports to connect sensors or other devices; Digital I/O option available upon request
Ethernet	1 RJ-45 port; Standard: IEEE 802.3; Physical Layer: 10/100Base-T; Data rate: 10/100 Mbps (auto-sensing); Mode: full or half duplex (auto-sensing)
ZigBee/802.15.4	XBee-PRO® module, 2.4 GHz
Cellular (via PCI Express Module)	GSM/GPRS 2G (HSPA and EV-DO 3G modules can be suppor-ted)
Environmental	
Operating Temperature	-30o C to +70o C (-22 F to +158 F) with selected PCIe module
Relative Humidity	N/A – enclosure is water-tight
Ethernet Isolation	1500VAC min per IEEE 802.3/ANSI X3.263
Serial Port Protection (ESD)	+15 kV Air Gap and +8 kV contact discharge per IEC 1000-4-2
General	
Safety	UL 60950, CSA 22.2 No. 60950, EN60950
Emissions/Immunity	CE, FCC Part 15 (Class A), AS/NZS CISPR 22, EN55024, EN55022, Class A
Mobile Certifications (GSM/UMTS)	PTCRB, NAPRD.03, GCF-CC, R&TTE, EN 301 511

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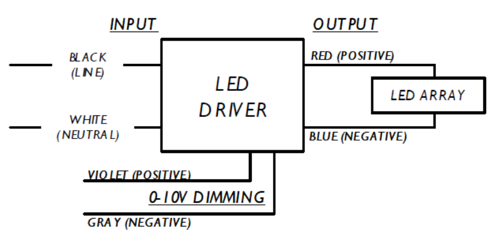
PHILIPS ADVANCE

LED-INTA-0024V-20-DL-O	
Brand Name	XITANIUM
Description	48W 24V 2.0A Dim
Input Voltage	120~277V
Input Frequency	50/60Hz
RoHS	Yes
Status	Active

Electrical Specifications

Max. Output Power (W)	Output Voltage (V)	Output Current (A)	Tcase Max	Input Current (A)	Max. Input Power (W)	Inrush Current ($A_{pk}/\mu s$)	Max. THD (%)	Min. Power Factor	Surge Protection (KV)	Weight (Lbs)	IP Rating
48	24.0	0.10~2.0	85°C	0.48 @ 120V 0.22 @ 277V	57	100/200	20	0.9	3.0	2.8/1270	IP66

Wiring Diagram



Input, Output and 0-10V Dimming use lead-wires.
Lead-wires are 18AWG 105C/600V solid copper

Standard Lead Length

	in.	cm.
Black	9	22
White	9	22
Blue	9	22
Red	9	22
Gray	9	22
Violet	9	22

Maximum Wiring Distance (at full load)

Wire Size (AWG)	Distance (feet)
26	7
24	11
22	18
20	29
18	45
16	71
14	115
12	176
10	300

Dimming Method	Dimming Range (%)	Min. Output Voltage (V)	Min. Output Power (W)
0-10V	15% ~100%	15.0~24.0	30.0

Enclosure

	in. (mm)
Case Length	8.38 (211.1)
Case Width	2.35 (59.1)
Case Height	1.47 (37.1)
Mounting Length	9.0 (226.2)
Mounting Width	1.7 (42.9)
Overall Length	9.54 (240.5)

UL Class 2
E220165

7310_S-000
3426-32

Revised 08/05/2010

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Appendix E: Preliminary Luminaire Testing

Equipment Pretesting

The luminaire pole stands on a level surface offset in the measurement grid. The pole is fitted with an attachment bracket for luminaires and the bracket can be adjusted based on the type of luminaire. The LED luminaire was mounted at a height of 30 feet. The measurement grid extends six meters (19.7 feet), behind 13 meters (42.7 feet) in front of, and 20 meters (65.6 feet) to each side of the luminaire. This is a modification from the standard measurement technique developed in IES-TM-73 which specifies wheel path measurement only. The technique here includes glare, light trespass and a more comprehensive pavement evaluation. This configuration allowed the team to evaluate the backlight not directed at the roadway, (the "house-side" of the luminaire) as well as the light output to the roadway-side (the "street-side," of the luminaire). Horizontal and vertical illuminance measurements were performed on two-meter spacing in the test grid using Minolta T-10 illuminance meters. The data was recorded manually at each point along the grid.

Horizontal measurements were taken with an illuminance meter on the pavement, facing up, at two-meter spacing locations on the 20x40 meter grid. Vertical measurements were taken using an illuminance meter affixed to a mobile cart, mounted 1.5 meters from ground level (Figure 45). For the vertical measurements the meter was aimed along the roadway direction with the meter facing the luminaire. This means that in the top half of the grid the meter was aimed parallel to the grid facing the bottom half of the grid and in the bottom of the grid, the meter was reversed and faced toward the top of grid, parallel to the grid.

Additional vertical measurements were recorded along each edge of the grid with the meter aimed into the grid to estimate light trespass.

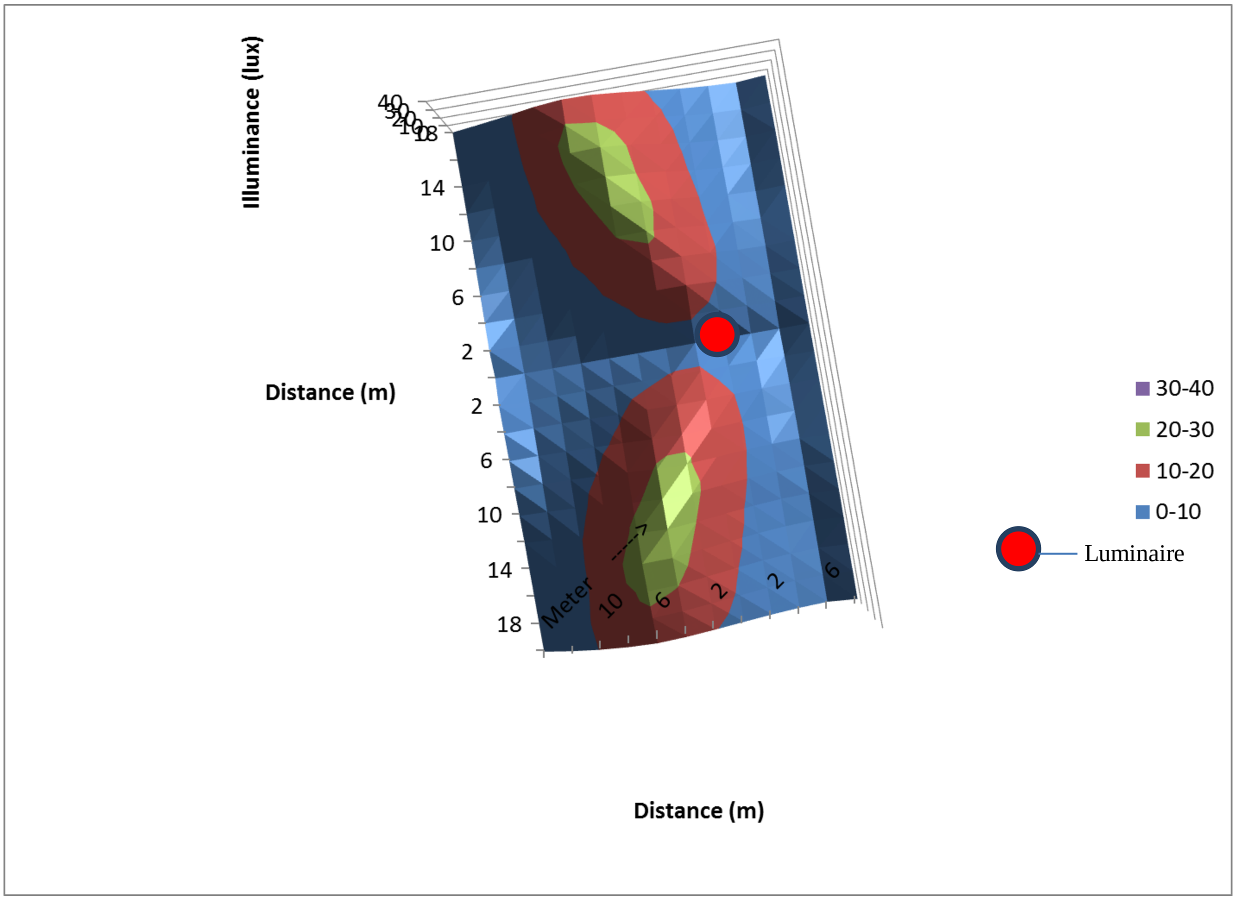
Figure 45: Vertical illuminance meter on cart

The electrical power usage and the spectral power distribution of the sample luminaires were also recorded. A Yokogowa WT 110 power meter was used to measure electrical power usage. The spectral power distribution was measured using an Ocean Optics S4000 spectraradiometer with a Teflon integrating sphere acceptance optic.

Vertical Illuminance

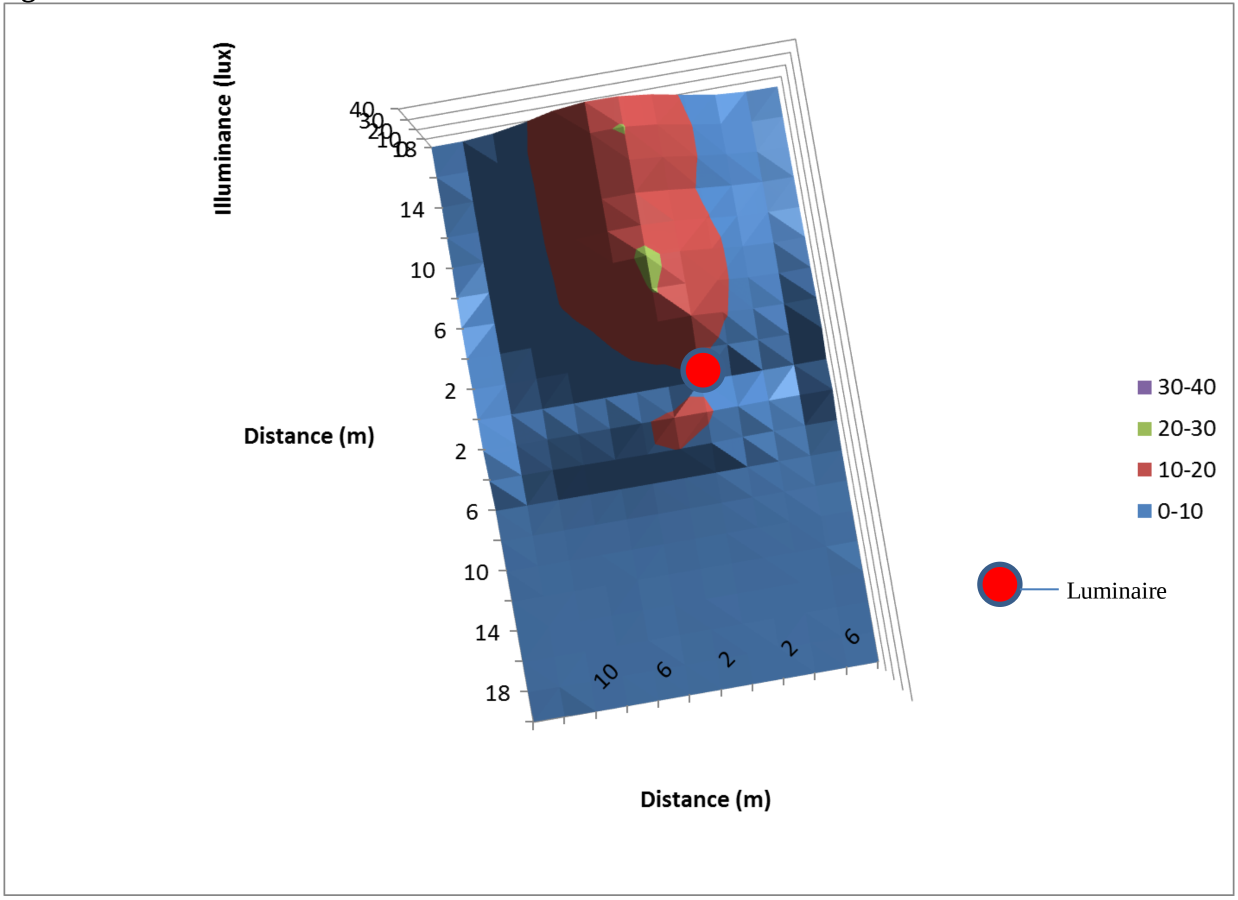
Each luminaire was evaluated at the VTTI laboratory in the grid environment. Figure 46, shows the vertical illuminance for the 4100K Type II LED luminaire as an example.

Figure *46*: 4100K Type II Grid - Vertical Illuminance



Vertical illuminance measurement gives an indication of the light that would affect an observer's eyes 1.5 meters from the ground. Each measurement is taken facing the direction of the luminaire per the orientation of Figure 46, the vertical plane below the luminaire are facing up the road and the vertical plane above the luminaire is facing down. The roadside is the area to the left of the luminaire and the house side is the smaller area to the right. This measurement provides information about both the ability of the luminaire to highlight objects and pedestrians in the roadway as well as the glare experienced by a driver. The Federal Highway Administration (FHWA) recommends 20 vertical lux in crosswalks for pedestrian detection; these values are shown in the top half of the grid. The levels in the lower portion of the chart indicate light aimed toward a driver and higher values in the lower part of the grid indicate higher levels of glare. Though the legend indicates a possibility of 30-40 lux, not all luminaires achieved this level. Each vertical illuminance figure, however, is derived using the scale necessary for the luminaire that did provide 30-40 lux levels. In the case of this 4100K luminaire, one can see the overall uniformity of the output of the luminaire; however, Figure 47 shows the vertical illuminance grid for the asymmetric luminaire.

Figure *47*. ASYM Grid - Vertical Illuminance



Horizontal Illuminance

Horizontal illuminance was also measured at the ground level at the VTTI Laboratory. This measurement gives an indication of the distribution of the light actually reaching the ground. It also shows the level of uniformity of the luminaire's output. This data provides the information required to assess the overall lighting of the roadway brightness of the road surface. Figure 48 and Figure 49 show horizontal illuminance grids for the 4100K and asymmetric luminaire.

Figure *48*. 4100K Type II Grid - Horizontal Illuminance

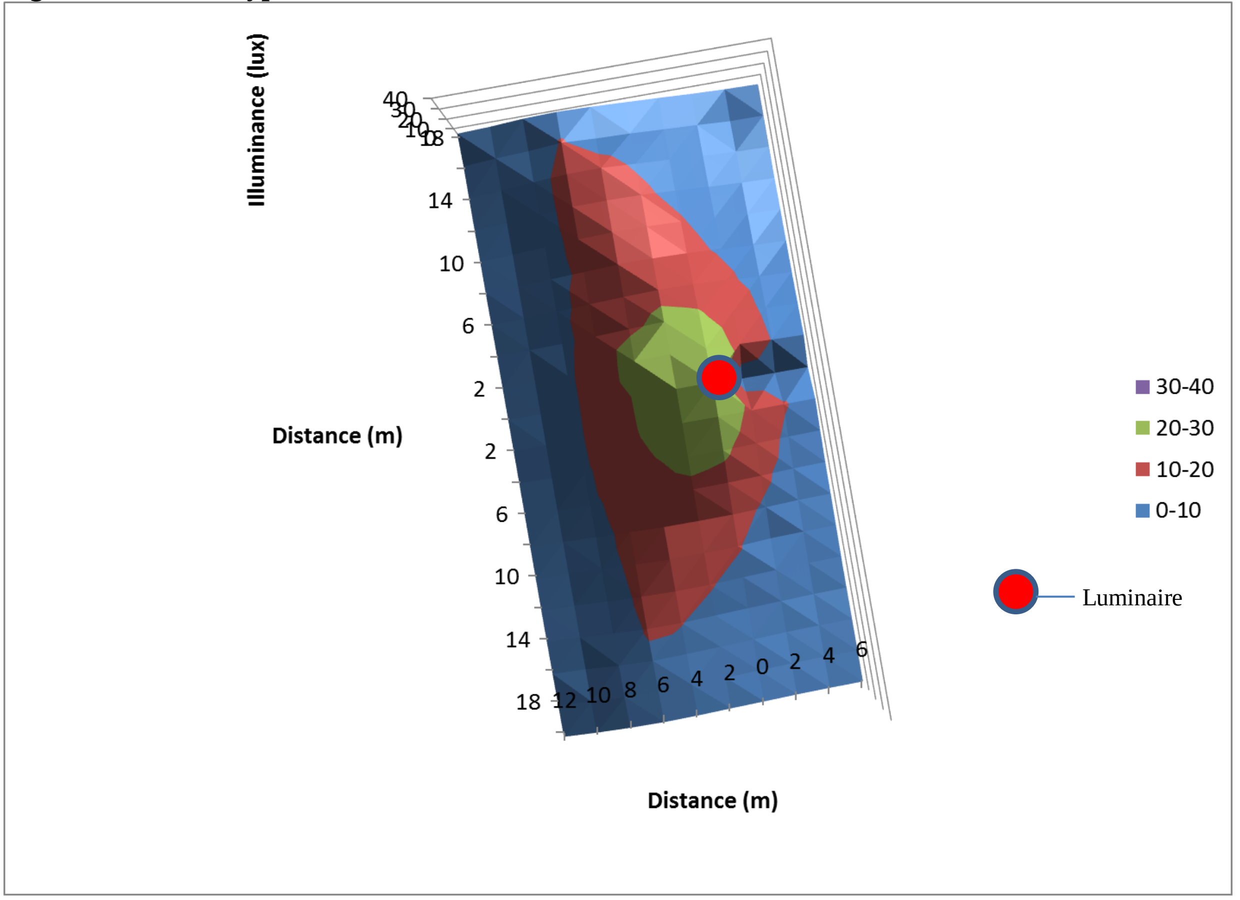


Figure *49*. Asymmetric Grid - Horizontal Illuminance

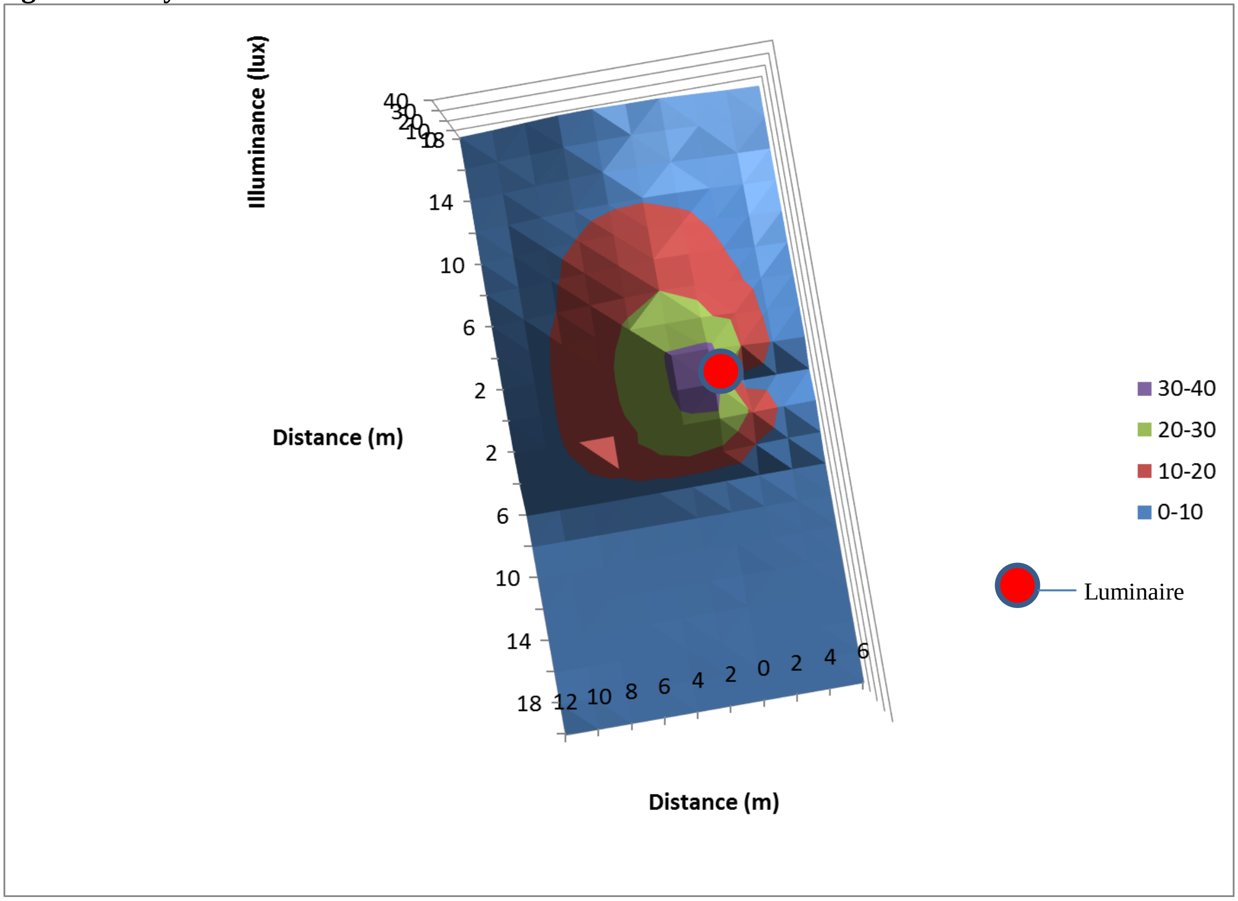


Table 24 provides a summary of the illuminance measures within each luminaire's grid. It is noteworthy that the luminaires had very similar performance across the grid with the exception of the asymmetric design where only one half of the test area was illuminated.

Table *24*: Summary of Lab Illuminance

Summary of Lab Illuminance	4100K		ASYM		3500K		5000K	
	HS	**SS**	**HS**	**SS**	**HS**	**SS**	**HS**	**SS**
Average Vertical Grid Illuminance (lux)	4.49	11.74	3.25	6.37	4.71	10.97	4.54	10.75
Average Horizontal Grid Illuminance (lux)	4.83	9.83	3.80	7.25	5.03	9.48	4.73	9.25
Max Grid Vertical Illuminance (lux)	24.76		20.93		27.40		21.62	
Min Grid Vertical Illuminance (lux)	0.57		0.29		0.67		0.59	
Max Grid Horizontal Illuminance (lux)	28.74		32.20		27.41		26.05	
Min Grid Horizontal Illuminance (lux)	0.62		0.19		0.64		0.76	

Note: HS = House-Side, SS = Street-Side

Light Trespass

The level of light trespassing beyond the roadway to the house-side of the luminaire was also evaluated. This measurement is considered due to the concern for light that is directed or "spilled" into areas where light is not intended to reach (such as into residential homes or commercial locations). The Illuminating Engineering Society recommends (IES TM-11-00) the following limitations on light trespass (Table 25).

Table *25*: IES Light Trespass Limitations

Environmental Zone	Pre-Curfew Limitations*	Post-Curfew Limitations*
E1	1.0 (0.10)	0.0 (0.00)
E2	3.0 (0.30)	1.0 (0.10)
E3	8.0 (0.80)	3.0 (0.30)
E4	15.0 (1.50)	6.0 (0.60)

Note: * Lux (foot-candles)

Environmental Zone 3 is described as generally "urban residential areas," so this corresponds to the locations for this cobra head style. Each of the luminaires was evaluated in the laboratory setting for this factor on both the house-side of the luminaire and what would be considered beyond the intended reach of the luminaire on the street-side of the luminaire. Figure 50 and Figure 51 show an example of the light trespass measured in the laboratory setting. The figures represent house side, light trespass with the luminaire facing 6m out (5 meter overhang and 1 meter sidewalk).

Figure *50*: 4100K - Light Trespass - House Side

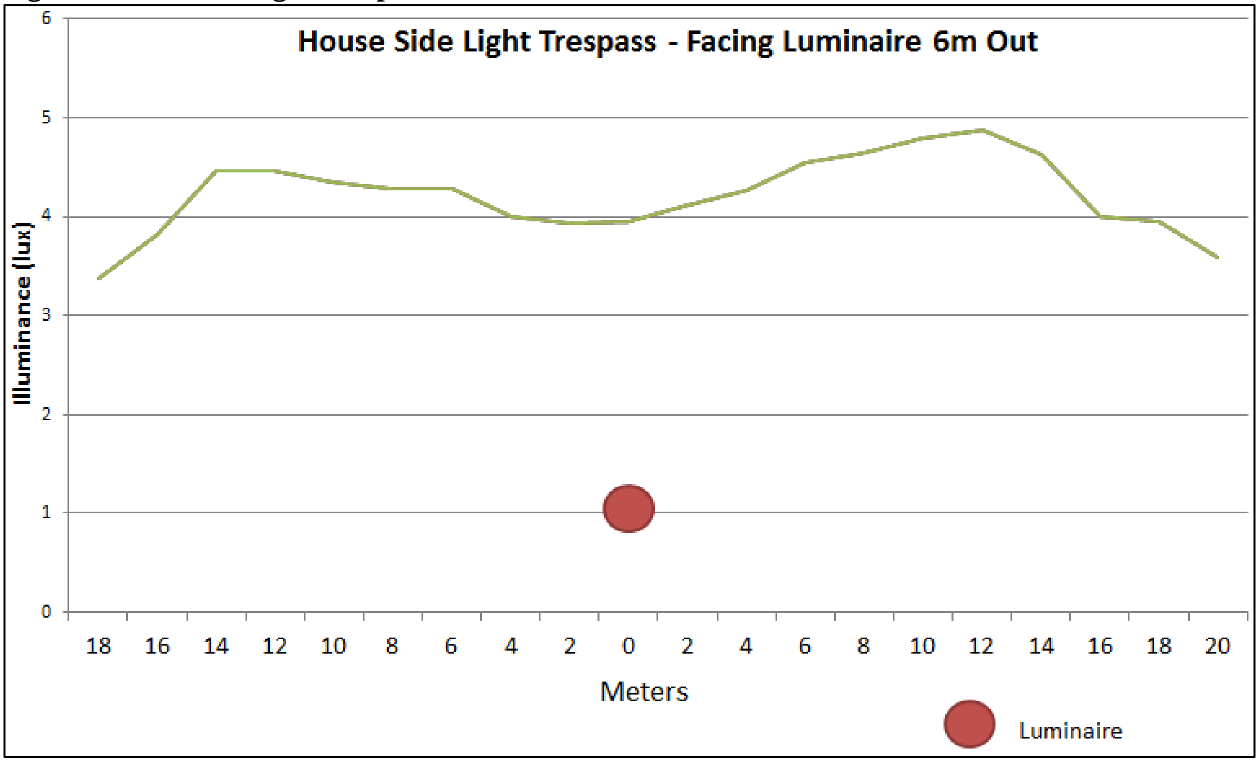


Figure *51*. 4100K - Light Trespass - Street Side

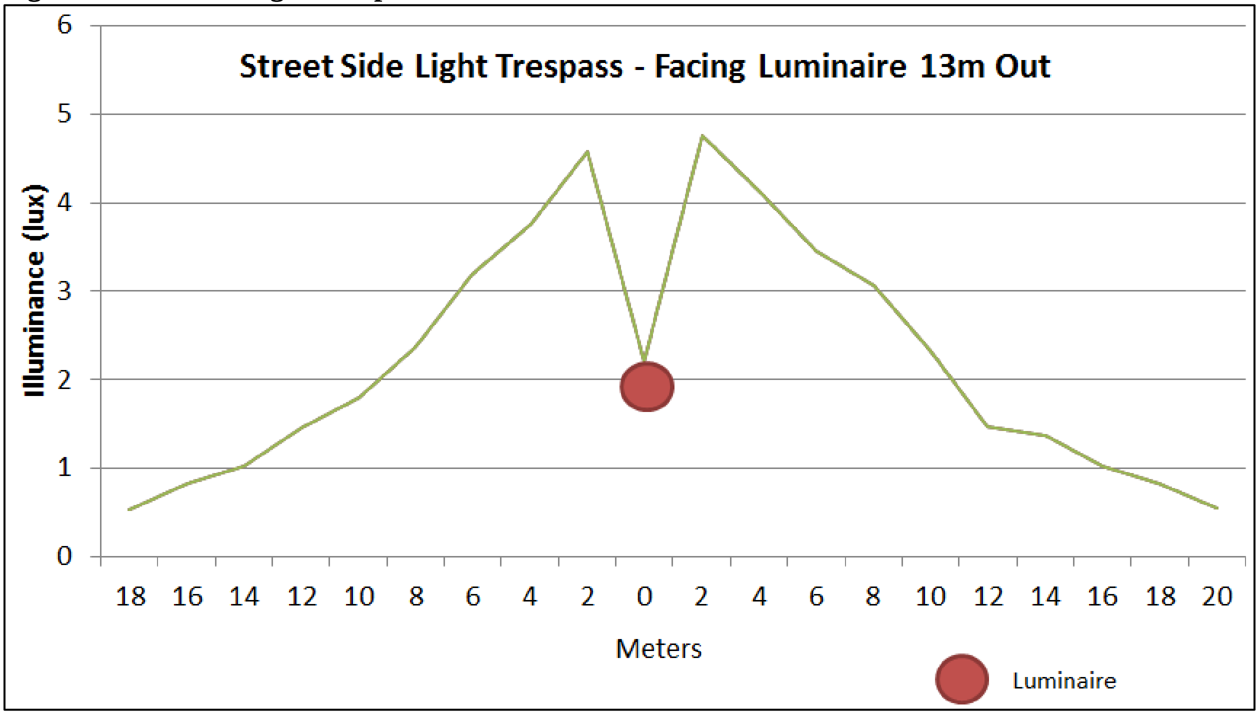


Table 26 provides a summary of light trespass as evaluated in the laboratory setting. VTTI used the average to give a single value for each luminaire. In cases of a maximum value that is meant to be a threshold, for example if light trespass is not allowed to exceed five lux behind the luminaire, the value is listed as a maximum value in the table.

Table *26*. Summary of Dimming Pretesting

	Dimming	Illuminance (lux)	% Light Output	V	A	W	VA	var	PF	deg.
	0	102.8	21.3	122.9	0.219	24.7	27	10.8	0.916	23.7
	1	108.1	22.4	122.8	0.227	25.7	27.9	10.9	0.921	22.9
	2	171.4	35.5	121.8	0.322	37.6	39.3	11.4	0.957	17
	3	237.1	49.1	122.1	0.431	51.2	52.6	12.1	0.973	13.2
	4	297	61.5	122.9	0.542	65.3	66.5	12.7	0.982	11
4100K	5	356	73.7	122.8	0.657	79.7	80.8	13	0.987	9.3
	6	416	86.1	122.7	0.788	95.7	96.7	13.3	0.99	7.9
	7	468	96.9	123.7	0.902	110.6	111.5	13.8	0.992	7.1
	8	483	100	123.7	0.934	114.8	115.6	14.1	0.993	7
	9	483	100	122.2	0.947	114.9	115.6	13.8	0.993	6.8
	10	483	100	122	0.948	114.9	115.7	13.9	0.993	6.9
	0	132.4	21.6	123.2	0.226	25.6	27.9	11.1	0.918	23.3
	1	137.4	22.5	123.5	0.232	26.4	28.7	11.1	0.921	22.9
	2	215.8	35.3	123.5	0.324	38.3	40.1	11.7	0.956	17.1
	3	298	48.7	123.6	0.431	51.8	53.2	12.1	0.974	13.1
	4	374	61.1	123.6	0.54	65.6	66.8	12.5	0.982	10.8
Asymmetric	5	448	73.2	122.7	0.659	79.8	80.9	12.5	0.988	8.9
	6	525	85.8	122.8	0.788	95.8	96.6	12.6	0.991	7.5
	7	591	96.6	122.5	0.909	110.6	111.4	12.9	0.993	6.7
	8	611	99.8	122.6	0.946	115.2	116	12.9	0.994	6.4
	9	611	99.8	122.8	0.946	115.3	116.1	13	0.994	6.5
	10	612	100	122.2	0.951	115.5	116.2	13.1	0.994	6.5
	0	96	18.6	119.9	0.224	24.8	26.9	10.6	0.92	23.1
	1	100.7	19.5	120.7	0.229	25.6	27.7	10.7	0.923	22.7
	2	163.9	31.8	120.8	0.322	37.2	38.8	11.3	0.957	16.9
	3	233.4	45.2	120.6	0.428	50.2	51.5	11.5	0.974	13.1
	4	300	58.1	119.2	0.544	63.7	64.8	12.1	0.983	10.7
3500K	5	367	71.1	119.2	0.66	77.7	78.6	12.1	0.988	8.9
	6	438	84.9	119.4	0.792	93.7	94.5	12.4	0.991	7.6
	7	498	96.5	119.3	0.911	107.9	108.7	12.7	0.993	6.7
	8	516	100	118.9	0.952	112.7	113.4	12.7	0.994	6.5
	9	517	100.2	120.1	0.952	112.7	113.4	12.8	0.994	6.5
	10	516	100	120.1	0.945	112.8	113.5	13	0.993	6.6
	0	71.3	18.7	120.1	0.234	26	28.1	10.8	0.923	22.7
	1	72.9	19.1	119.1	0.239	26.4	28.5	10.7	0.927	22.1
	2	118.4	31.1	119.2	0.332	37.9	39.5	11	0.96	16.2
	3	169.2	44.4	120.1	0.439	51.5	52.7	11.6	0.976	12.5
	4	217.7	57.1	119	0.556	65.1	66.2	11.9	0.984	10.4
5000K	5	266	69.8	118.8	0.675	79.3	80.2	11.8	0.989	8.4
	6	319	83.7	118.9	0.812	95.7	96.6	11.8	0.992	7.1
	7	362	95	118.8	0.931	110	110.6	12.1	0.994	6.3
	8	379	99.5	120	0.967	115.3	116	12.2	0.995	6
	9	380	99.7	119.9	0.967	115.5	116.1	12.2	0.994	6.1
	10	381	100	118.8	0.979	115.6	116.3	12.1	0.995	6

Vertical Illuminance

Figure 52. 3500K Grid - Vertical Illuminance

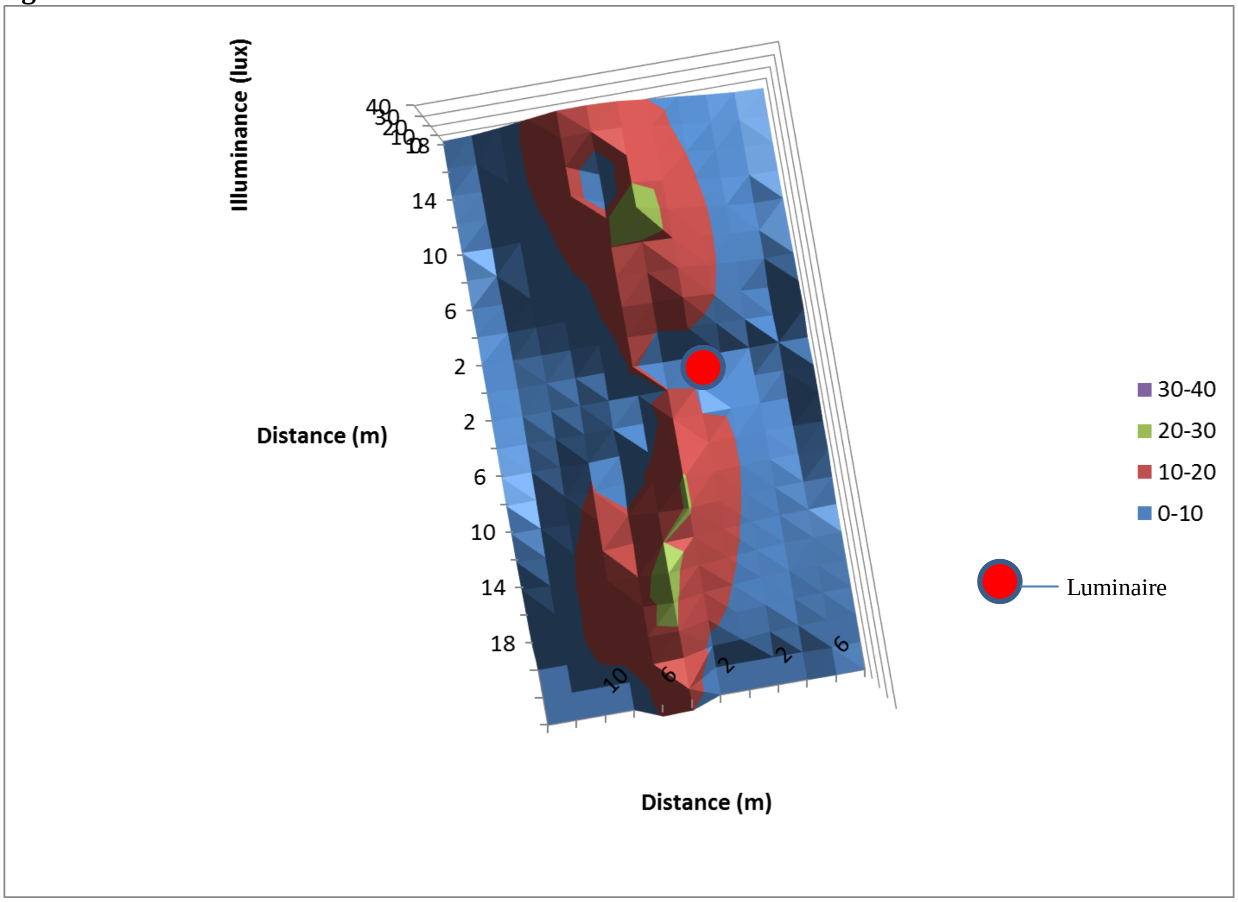
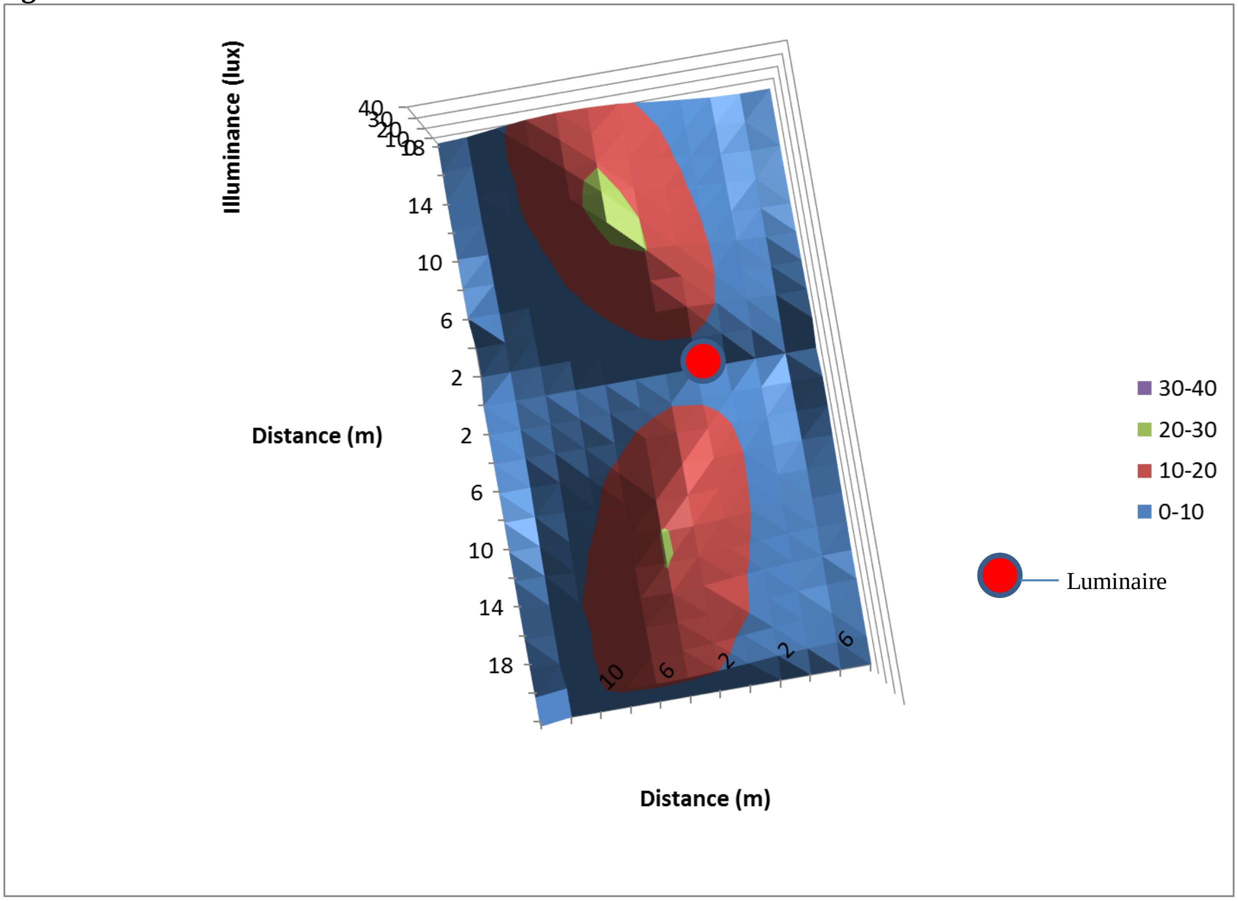


Figure 53. 5000K Grid - Vertical Illuminance



Horizontal Illuminance

Figure 54. 3500K Grid - Horizontal Illuminance

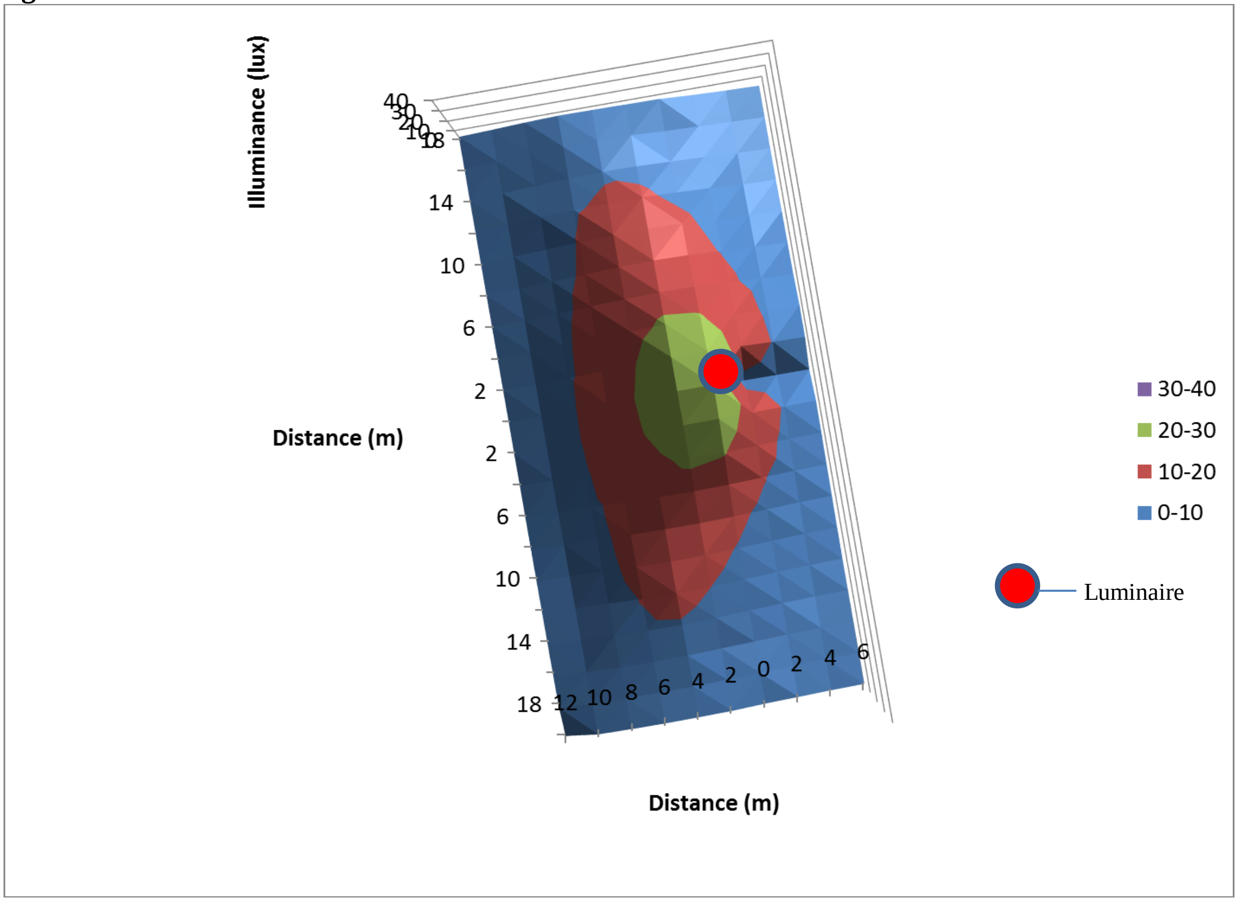
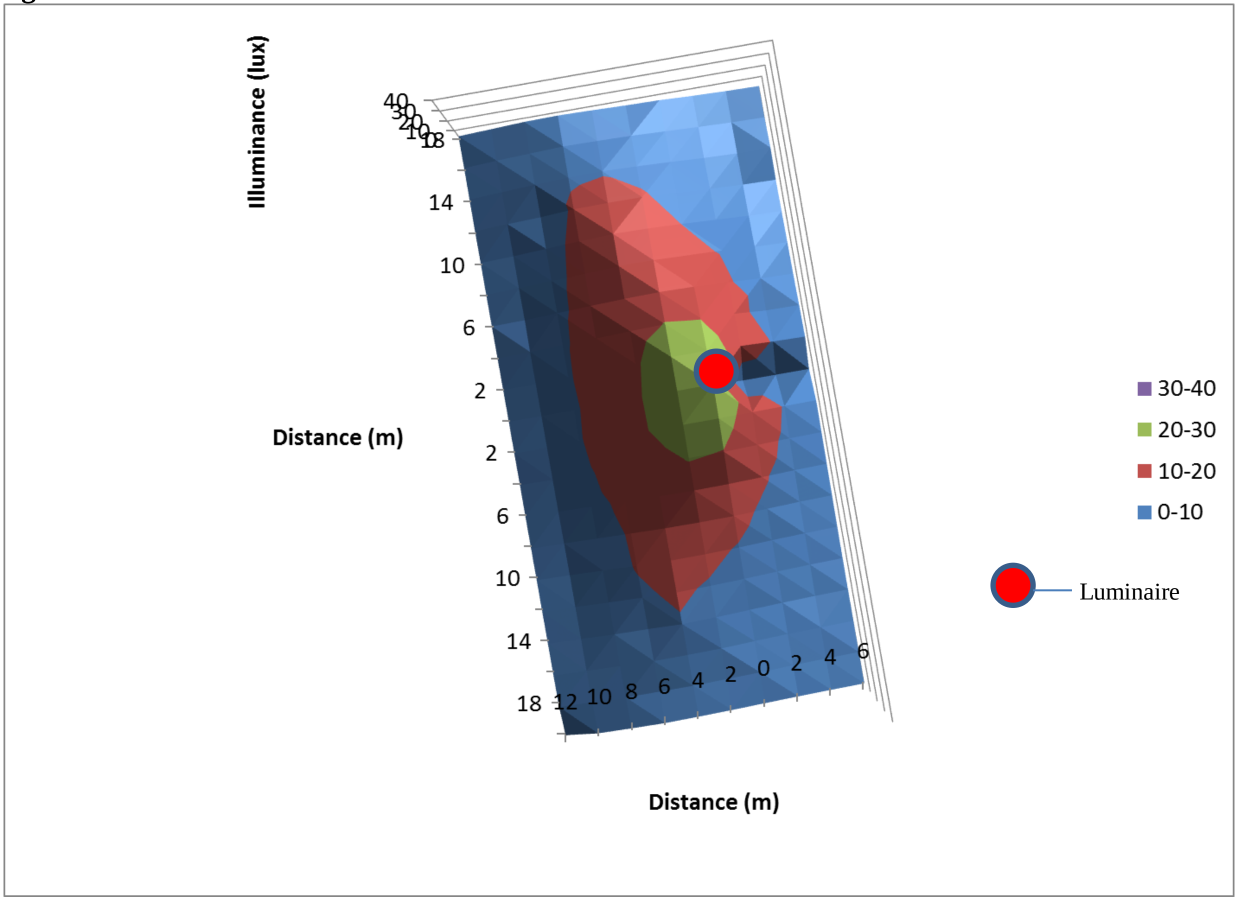


Figure 55. 5000K Grid - Horizontal Illuminance



Light Trespass

Figure 56. ASYM - Light Trespass - House Side

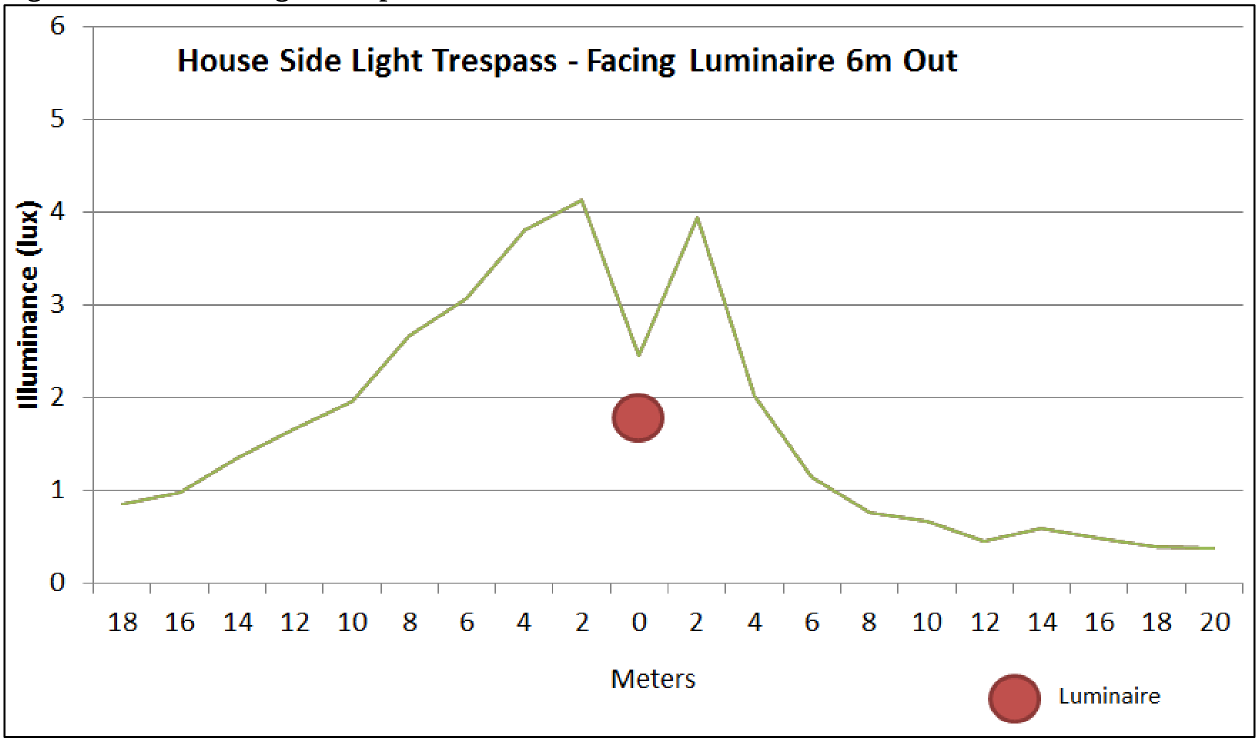


Figure 57. ASYM - Light Trespass - Street Side

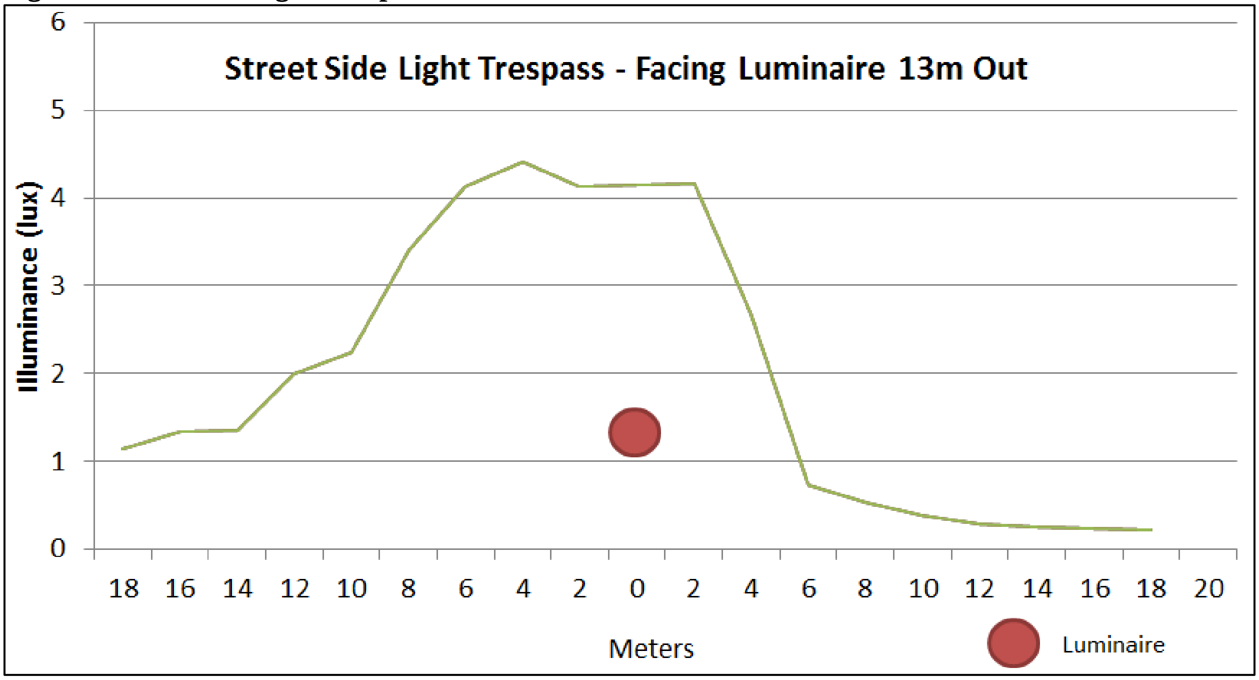


Figure 58. 3500K - Light Trespass - House Side

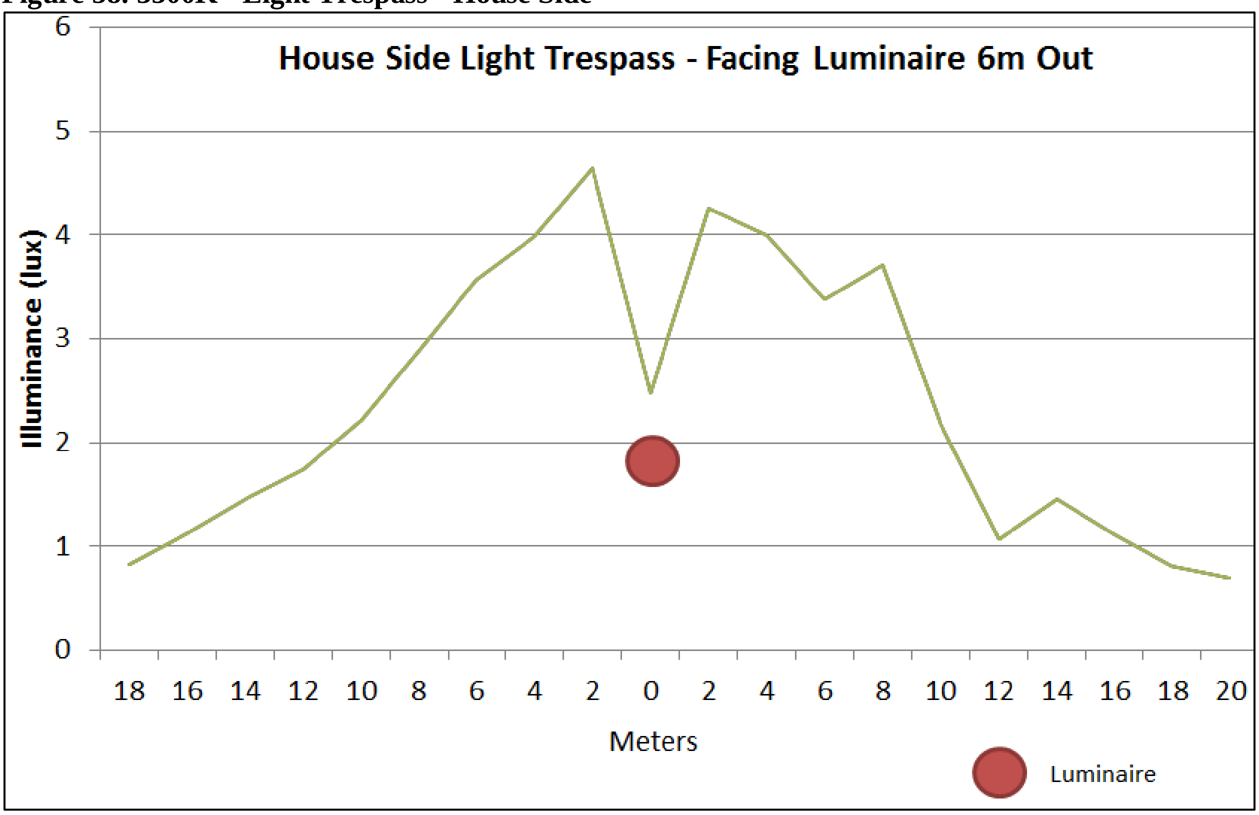


Figure 59. 3500K - Light Trespass - Street Side

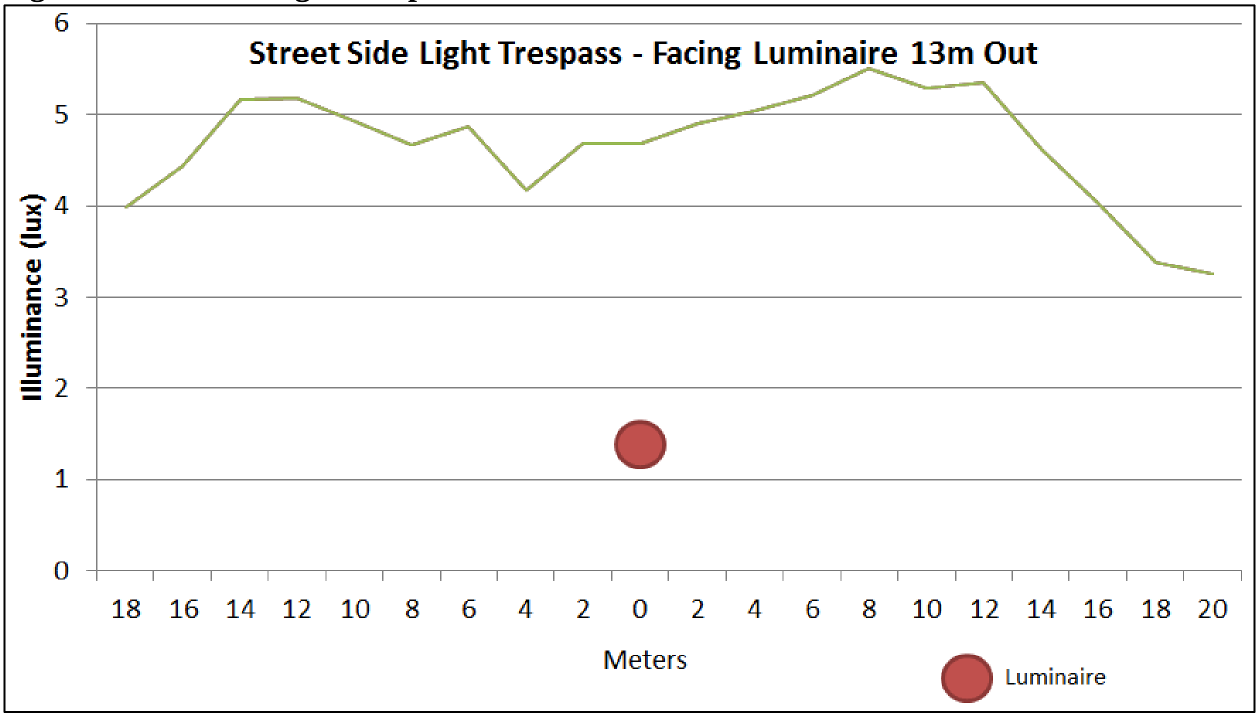


Figure 60. 5000K - Light Trespass - House Side

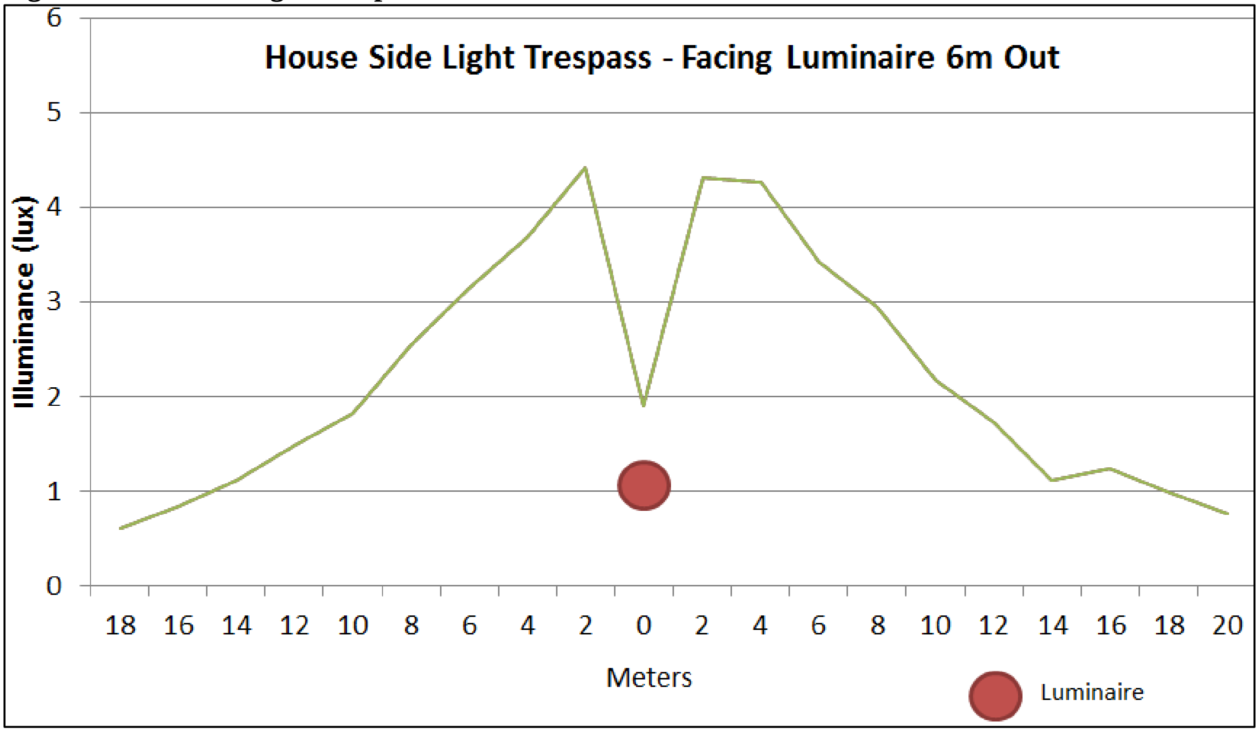
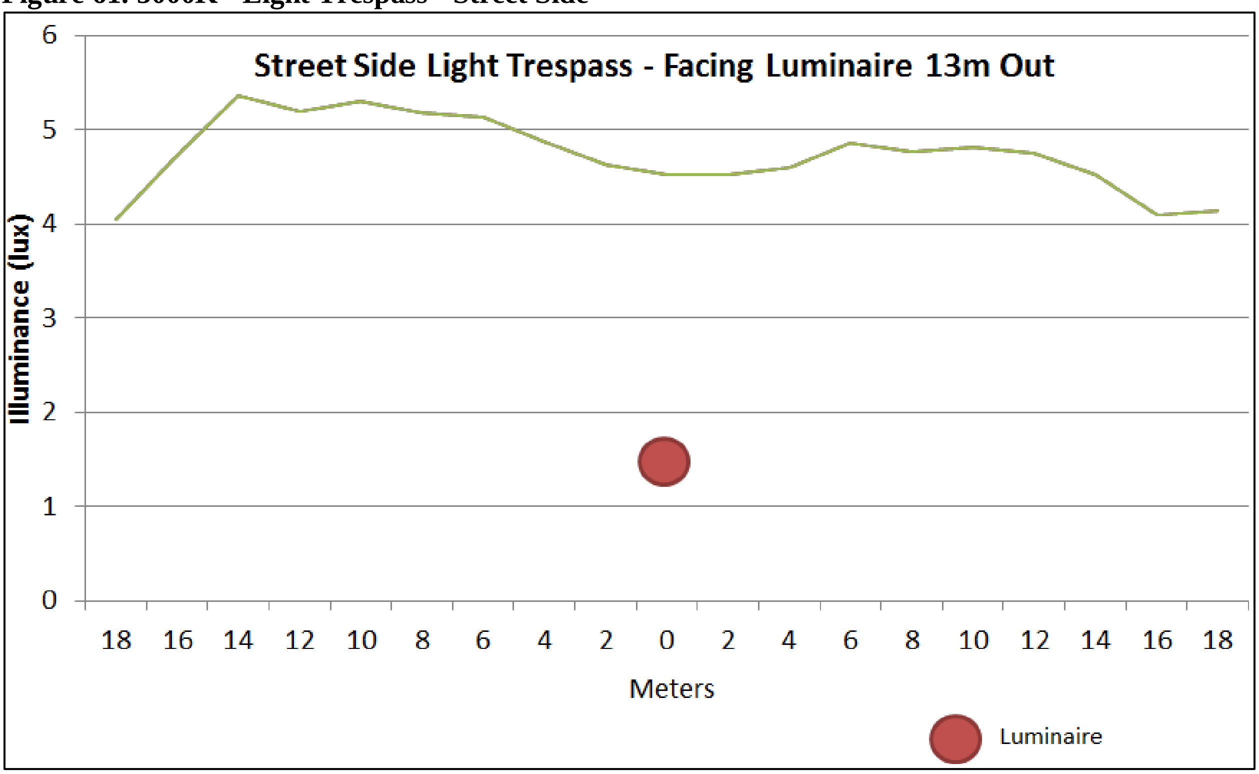


Figure 61. 5000K - Light Trespass - Street Side



Appendix F: Luminance Calculations

400 W HPS

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400 W HPS

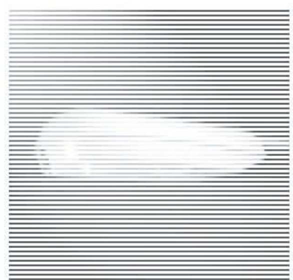
General:

Roadway Standard: IES RP-8-2000
R-Table: R3 (Slightly Specular), Q0=0.07   Actual Q0 Value: 0.07

Roadway Layout:

Layout Type: Two Rows, Opposite, With Median; 2R_OPP_w/M
Roadway Width: 30 ft
Median Width: 10 ft
Lanes In Direction Of Travel: 3
Driver's Side Of Roadway: Right

Label: OVF40SXX2D
Description: OVF40SXX2D
File Name: OVF40SXX2D.ies
Luminaire Arrangement: SINGLE
Arm Length: 6 ft
Lumens Per Lamp: 50000
Number Of Lamps: 1
Luminaire Lumens: 37171
Efficiency (%): 74
Luminaire Watts: 400
Total Light Loss Factor: 0.810



Luminaire Location Summary:
Coordinates in ft

Spacing - Row 1: 130
Spacing - Row 2: 130

Label	X-Coord	Y-Coord	Z-Coord	Orient	Tilt	Spin
OVF40SXX2D	520	-3	30	90	0	0
OVF40SXX2D	-260	-3	30	90	0	0
OVF40SXX2D	-130	-3	30	90	0	0
OVF40SXX2D	0	-3	30	90	0	0
OVF40SXX2D	130	-3	30	90	0	0
OVF40SXX2D	260	-3	30	90	0	0
OVF40SXX2D	-390	-3	30	90	0	0
OVF40SXX2D	390	-3	30	90	0	0
OVF40SXX2D	520	73	30	270	0	0
OVF40SXX2D	-260	73	30	270	0	0

1

400 W HPS

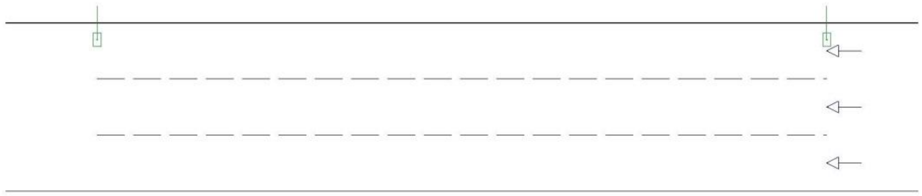
Luminaire Location Summary:
Coordinates in ft

OVF40SXX2D	-130	73	30	270	0	0
OVF40SXX2D	0	73	30	270	0	0
OVF40SXX2D	130	73	30	270	0	0
OVF40SXX2D	260	73	30	270	0	0
OVF40SXX2D	390	73	30	270	0	0
OVF40SXX2D	-390	73	30	270	0	0

Total Number of locations: 16

400 W HPS

RoadOpt_Luminance



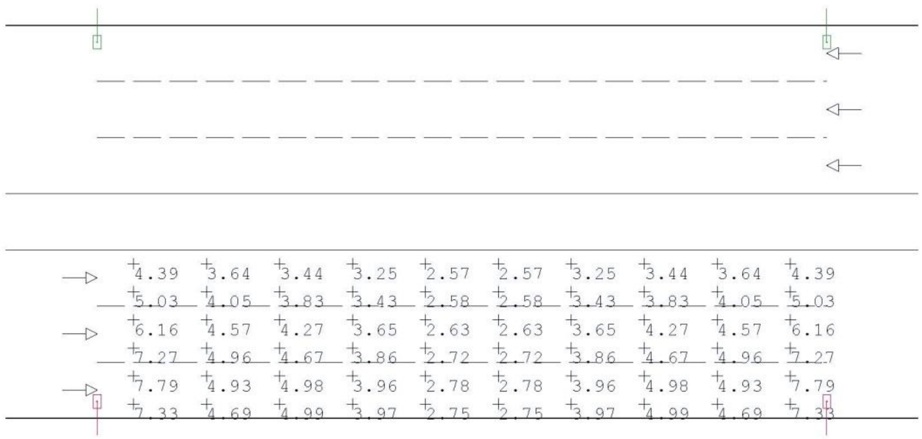
1.82	1.86	2.16	2.36	2.13	2.15	2.38	2.07	1.72	1.74
2.10	2.08	2.52	2.76	2.37	2.47	2.92	2.54	2.01	2.07
2.54	2.49	3.12	3.38	2.95	3.15	3.86	3.24	2.54	2.54
3.02	2.84	3.95	4.71	4.13	4.28	5.18	4.19	3.10	3.04
3.47	3.51	5.23	6.31	5.66	5.89	6.71	5.53	3.36	3.45
3.41	3.66	5.77	7.11	6.35	6.51	7.47	5.99	3.38	3.37

Luminance (Cd/SqM)
Average = 3.58
Maximum = 7.47
Minimum = 1.72
Avg/Min Ratio = 2.08
Max/Min Ratio = 4.34
Max/Avg Ratio = 2.09

3

400 W HPS

RoadOpt_Illum

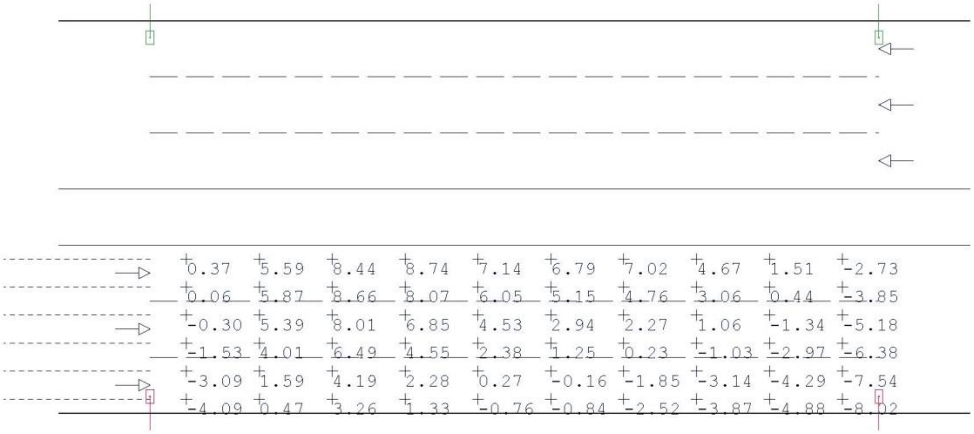


Illuminance (Fc)
Average = 4.31
Maximum = 7.79
Minimum = 2.57
Avg/Min Ratio = 1.68
Max/Min Ratio = 3.03
Max/Avg Ratio = 1.81

4

400 W HPS

RoadOpt_Vis_Level

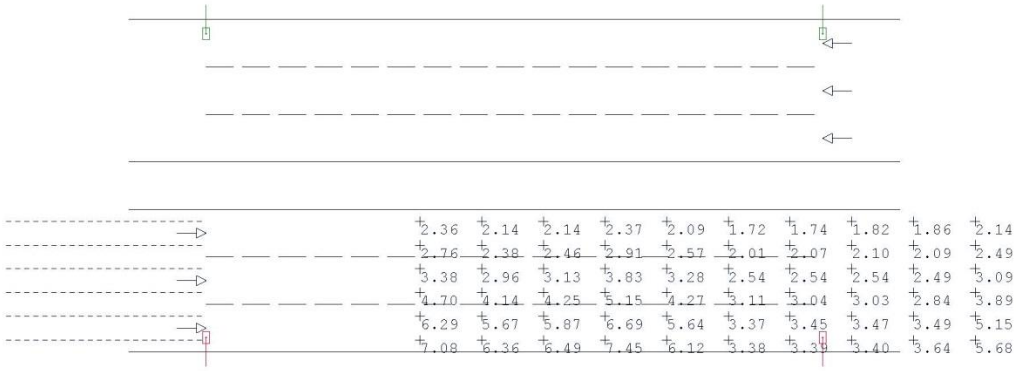


Visibility Level
STV = 3.070405

5

400 W HPS

RoadOpt_Vis_Level_Bkgd_Lum

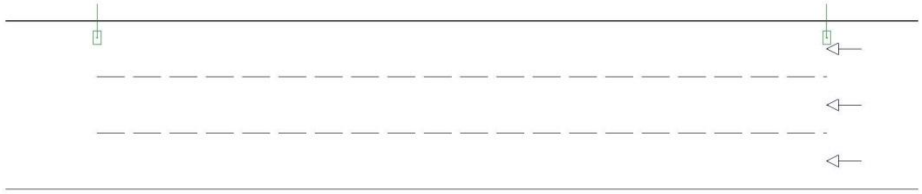


Background Luminance (Cd/SqM)
Average = 3.58
Maximum = 7.45
Minimum = 1.72
Avg/Min Ratio = 2.08
Max/Min Ratio = 4.33
Max/Avg Ratio = 2.08

6

400 W HPS

RoadOpt_Vis_Level_Target_Lum



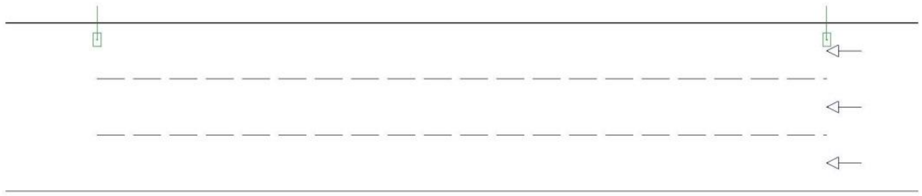
2.23	4.07	5.46	6.13	5.08	4.62	4.83	3.71	2.32	1.26
2.46	4.55	6.22	6.72	5.25	4.48	4.63	3.63	2.22	1.20
2.86	5.15	7.12	7.44	5.51	4.33	4.39	3.41	2.09	1.15
3.26	5.60	7.96	8.05	5.72	4.45	4.25	3.18	1.91	1.08
3.42	5.59	8.59	8.38	5.86	4.55	4.11	2.99	1.73	1.01
3.20	5.33	8.67	8.47	5.77	4.50	4.04	2.77	1.53	0.89

Target Luminance (Cd/SqM)
Average = 4.36
Maximum = 8.67
Minimum = 0.89
Avg/Min Ratio = 4.9
Max/Min Ratio = 9.74
Max/Avg Ratio = 1.99

7

400 W HPS

RoadOpt_Veil_Lum



0.10	0.14	0.20	0.33	0.46	0.44	0.31	0.27	0.20	0.13
0.11	0.15	0.22	0.36	0.50	0.51	0.38	0.36	0.28	0.15
0.13	0.16	0.24	0.39	0.56	0.61	0.47	0.46	0.39	0.18
0.15	0.17	0.25	0.41	0.63	0.74	0.59	0.57	0.48	0.22
0.16	0.17	0.26	0.43	0.70	0.86	0.68	0.66	0.56	0.25
0.15	0.16	0.24	0.41	0.70	0.89	0.71	0.69	0.59	0.24

Veiling Luminance (Cd/SqM)
Average = 0.38
Maximum = 0.89
Minimum = 0.10
Avg/Min Ratio = 3.8
Max/Min Ratio = 8.9
Max/Avg Ratio = 2.34
MaxLv Ratio = 0.25
Threshold Increment (TI) = 20.85

8

250 W HPS

250 W HPS

General:

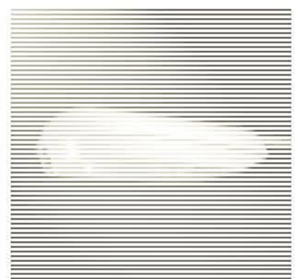
250W HPS

Roadway Standard: IES RP-8-2000
R-Table: R3 (Slightly Specular), Q0=0.07   Actual Q0 Value: 0.07

Roadway Layout:

Layout Type: Two Rows, Opposite, With Median; 2R_OPP_w/M
Roadway Width: 30 ft
Median Width: 10 ft
Lanes In Direction Of Travel: 3
Driver's Side Of Roadway: Right

Label: OVF25SXX2D
Description: OVF25SXX2D
File Name: OVF25SXX2D.ies
Luminaire Arrangement: SINGLE
Arm Length: 6 ft
Lumens Per Lamp: 27500
Number Of Lamps: 1
Luminaire Lumens: 21535
Efficiency (%): 78
Luminaire Watts: 250
Total Light Loss Factor: 0.810



Luminaire Location Summary:
Coordinates in ft

Spacing - Row 1: 130
Spacing - Row 2: 130

Label	X-Coord	Y-Coord	Z-Coord	Orient	Tilt	Spin
OVF25SXX2D	520	-3	30	90	0	0
OVF25SXX2D	-260	-3	30	90	0	0
OVF25SXX2D	-130	-3	30	90	0	0
OVF25SXX2D	0	-3	30	90	0	0
OVF25SXX2D	130	-3	30	90	0	0
OVF25SXX2D	260	-3	30	90	0	0
OVF25SXX2D	-390	-3	30	90	0	0
OVF25SXX2D	390	-3	30	90	0	0

250 W HPS

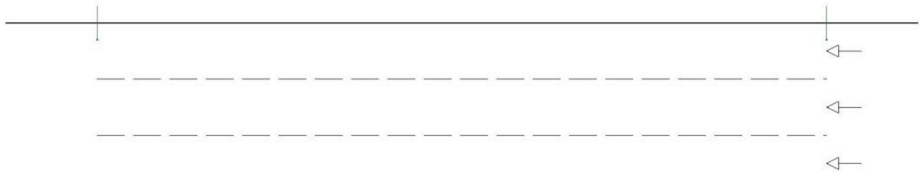
Luminaire Location Summary:
Coordinates in ft

OVF25SXX2D	520	73	30	270	0	0
OVF25SXX2D	-260	73	30	270	0	0
OVF25SXX2D	-130	73	30	270	0	0
OVF25SXX2D	0	73	30	270	0	0
OVF25SXX2D	130	73	30	270	0	0
OVF25SXX2D	260	73	30	270	0	0
OVF25SXX2D	390	73	30	270	0	0
OVF25SXX2D	-390	73	30	270	0	0

Total Number of locations: 16

250 W HPS

RoadOpt_Luminance



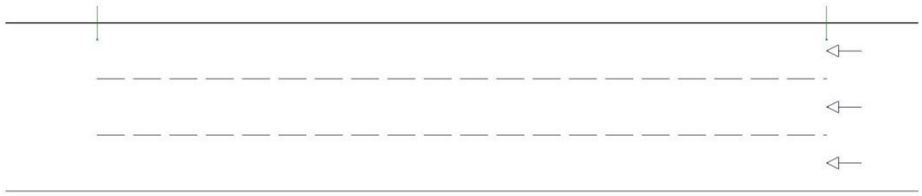
1.13	1.15	1.34	1.37	1.23	1.26	1.37	1.22	1.03	1.06
1.27	1.29	1.62	1.71	1.44	1.52	1.82	1.55	1.20	1.23
1.55	1.57	2.06	2.16	1.83	2.00	2.47	2.00	1.54	1.52
1.84	1.77	2.61	2.99	2.54	2.68	3.31	2.62	1.84	1.82
2.10	2.18	3.26	3.76	3.33	3.50	4.07	3.27	1.95	2.03
2.02	2.26	3.26	3.81	3.40	3.50	4.09	3.13	1.91	1.91

Luminance (Cd/SqM)
Average = 2.14
Maximum = 4.09
Minimum = 1.03
Avg/Min Ratio = 2.08
Max/Min Ratio = 3.97
Max/Avg Ratio = 1.91

3

250 W HPS

RoadOpt_Illum



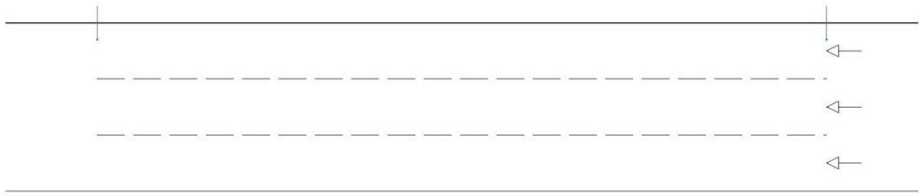
2.60	2.11	2.01	1.86	1.48	1.48	1.86	2.01	2.11	2.60
2.95	2.39	2.33	2.11	1.56	1.56	2.11	2.33	2.39	2.95
3.71	2.77	2.64	2.31	1.63	1.63	2.31	2.64	2.77	3.71
4.42	2.95	2.92	2.44	1.67	1.67	2.44	2.92	2.95	4.42
4.59	2.85	2.95	2.38	1.64	1.64	2.38	2.95	2.85	4.59
4.08	2.62	2.61	2.16	1.48	1.48	2.16	2.61	2.62	4.08

Illuminance (Fc)
Average = 2.54
Maximum = 4.59
Minimum = 1.48
Avg/Min Ratio = 1.72
Max/Min Ratio = 3.1
Max/Avg Ratio = 1.81

4

250 W HPS

RoadOpt_Vis_Level



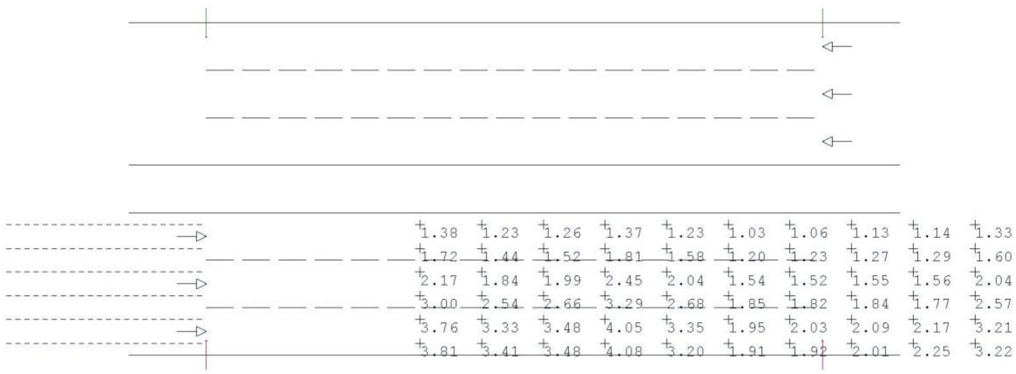
0.54	4.44	6.36	6.93	5.95	5.05	5.54	4.51	1.78	-1.71
-0.04	4.54	6.80	6.86	5.10	4.01	3.78	3.06	0.72	-3.04
-0.54	4.28	6.26	5.88	3.98	2.24	1.85	1.32	-0.99	-4.50
-1.60	3.07	5.25	3.97	2.08	0.95	0.11	-0.48	-2.43	-5.74
-2.86	1.03	3.32	2.05	0.29	-0.21	-1.86	-2.55	-3.56	-6.66
-3.50	0.27	2.21	1.21	-0.47	-0.83	-2.48	-3.13	-4.08	-6.77

Visibility Level
STV = 2.661259

5

250 W HPS

RoadOpt_Vis_Level_Bkgd_Lum

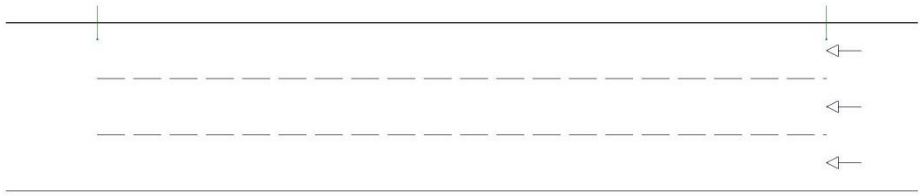


Background Luminance (Cd/SqM)
Average = 2.14
Maximum = 4.08
Minimum = 1.03
Avg/Min Ratio = 2.08
Max/Min Ratio = 3.96
Max/Avg Ratio = 1.91

6

250 W HPS

RoadOpt_Vis_Level_Target_Lum



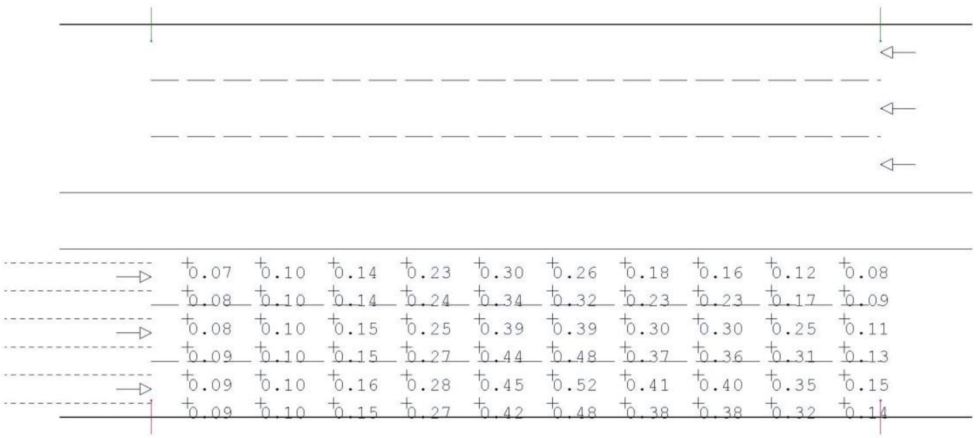
1.40	2.39	3.14	3.51	3.01	2.58	2.79	2.42	1.55	0.88
1.49	2.69	3.76	4.20	3.23	2.64	2.77	2.37	1.45	0.79
1.73	3.12	4.37	4.75	3.49	2.60	2.71	2.25	1.33	0.71
1.96	3.33	4.94	5.14	3.58	2.68	2.62	2.09	1.19	0.64
2.00	3.22	5.08	5.09	3.49	2.65	2.38	1.84	1.07	0.59
1.78	2.96	4.51	4.65	3.13	2.42	2.13	1.57	0.95	0.53

Target Luminance (Cd/SqM)
Average = 2.61
Maximum = 5.14
Minimum = 0.53
Avg/Min Ratio = 4.92
Max/Min Ratio = 9.7
Max/Avg Ratio = 1.97

7

250 W HPS

RoadOpt_Veil_Lum



0.07	0.10	0.14	0.23	0.30	0.26	0.18	0.16	0.12	0.08
0.08	0.10	0.14	0.24	0.34	0.32	0.23	0.23	0.17	0.09
0.08	0.10	0.15	0.25	0.39	0.39	0.30	0.30	0.25	0.11
0.09	0.10	0.15	0.27	0.44	0.48	0.37	0.36	0.31	0.13
0.09	0.10	0.16	0.28	0.45	0.52	0.41	0.40	0.35	0.15
0.09	0.10	0.15	0.27	0.42	0.48	0.38	0.38	0.32	0.14

Veiling Luminance (Cd/SqM)
Average = 0.24
Maximum = 0.52
Minimum = 0.07
Avg/Min Ratio = 3.43
Max/Min Ratio = 7.43
Max/Avg Ratio = 2.17
MaxLv Ratio = 0.24
Threshold Increment (TI) = 18.39

8

105 W Typical LED

105 W LED - 428mA

General:

Roadway Standard: IES RP-8-2000
R-Table: R3 (Slightly Specular), Q0=0.07   Actual QO Value: 0.07

Roadway Layout:

Layout Type: Two Rows, Opposite, With Median; 2R_OPP_w/M
Roadway Width: 30 ft
Median Width: 10 ft
Lanes In Direction Of Travel: 3
Driver's Side Of Roadway: Right

Label: GPLM-105W79LED4K-LE2-SCA
Description: GPLM-105W79LED4K-LE2-SCALED
File Name: GPLM-105W79LED4K-LE2-SCALED (S1008271m).ies
Luminaire Arrangement: SINGLE
Arm Length: 6 ft
Lumens Per Lamp: N.A.
Number Of Lamps: 1
Luminaire Lumens: 8174
Efficiency (%): N.A.
Luminaire Watts: 119
Total Light Loss Factor: 0.765

Luminaire Location Summary:
Coordinates in ft

Spacing - Row 1: 130
Spacing - Row 2: 130

Label	X-Coord	Y-Coord	Z-Coord	Orient	Tilt	Spin
GPLM-105W79LED4K-LE2-S	520	-3	30	90	0	0
GPLM-105W79LED4K-LE2-S	-260	-3	30	90	0	0
GPLM-105W79LED4K-LE2-S	-130	-3	30	90	0	0
GPLM-105W79LED4K-LE2-S	0	-3	30	90	0	0
GPLM-105W79LED4K-LE2-S	130	-3	30	90	0	0
GPLM-105W79LED4K-LE2-S	260	-3	30	90	0	0
GPLM-105W79LED4K-LE2-S	-390	-3	30	90	0	0
GPLM-105W79LED4K-LE2-S	390	-3	30	90	0	0
GPLM-105W79LED4K-LE2-S	520	73	30	270	0	0
GPLM-105W79LED4K-LE2-S	-260	73	30	270	0	0

1

105 W LED - 428mA

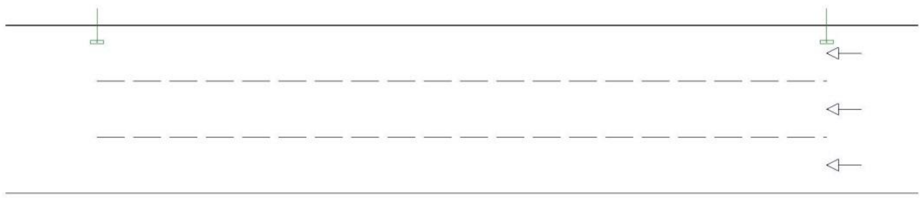
Luminaire Location Summary:
Coordinates in ft

GPLM-105W79LED4K-LE2-S	-130	73	30	270	0	0
GPLM-105W79LED4K-LE2-S	0	73	30	270	0	0
GPLM-105W79LED4K-LE2-S	130	73	30	270	0	0
GPLM-105W79LED4K-LE2-S	260	73	30	270	0	0
GPLM-105W79LED4K-LE2-S	390	73	30	270	0	0
GPLM-105W79LED4K-LE2-S	-390	73	30	270	0	0

Total Number of locations: 16

105 W LED - 428 mA

RoadOpt_Luminance



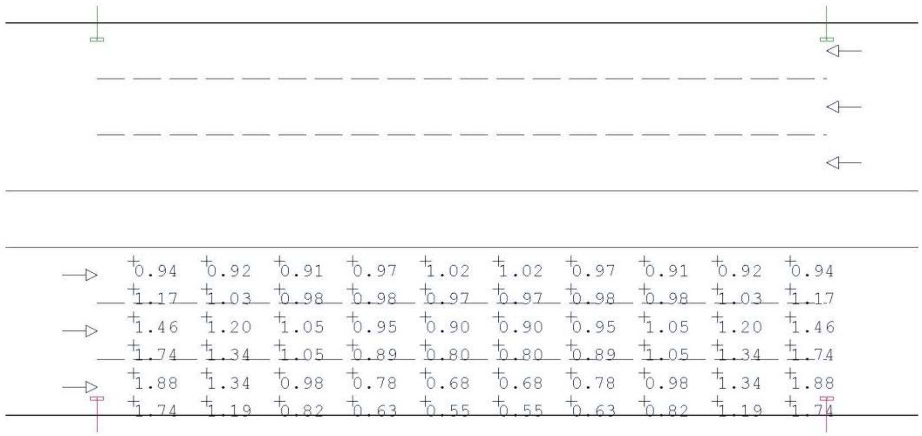
0.37	0.41	0.51	0.67	0.84	0.85	0.72	0.54	0.42	0.36
0.46	0.46	0.56	0.74	0.89	0.93	0.84	0.66	0.50	0.46
0.56	0.55	0.66	0.82	1.01	1.07	1.02	0.81	0.65	0.58
0.66	0.62	0.76	1.01	1.23	1.26	1.22	0.96	0.82	0.69
0.75	0.72	0.89	1.15	1.39	1.46	1.36	1.11	0.89	0.79
0.71	0.69	0.86	1.09	1.29	1.33	1.22	1.02	0.84	0.76

Luminance (Cd/SqM)
Average = 0.82
Maximum = 1.46
Minimum = 0.36
Avg/Min Ratio = 2.28
Max/Min Ratio = 4.06
Max/Avg Ratio = 1.78

3

105 W LED - 428 mA

RoadOpt_Illum

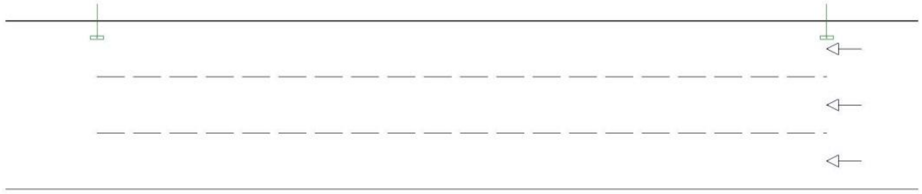


Illuminance (Fc)
Average = 1.06
Maximum = 1.88
Minimum = 0.55
Avg/Min Ratio = 1.93
Max/Min Ratio = 3.42
Max/Avg Ratio = 1.77

4

105 W LED - 428 mA

RoadOpt_Vis_Level

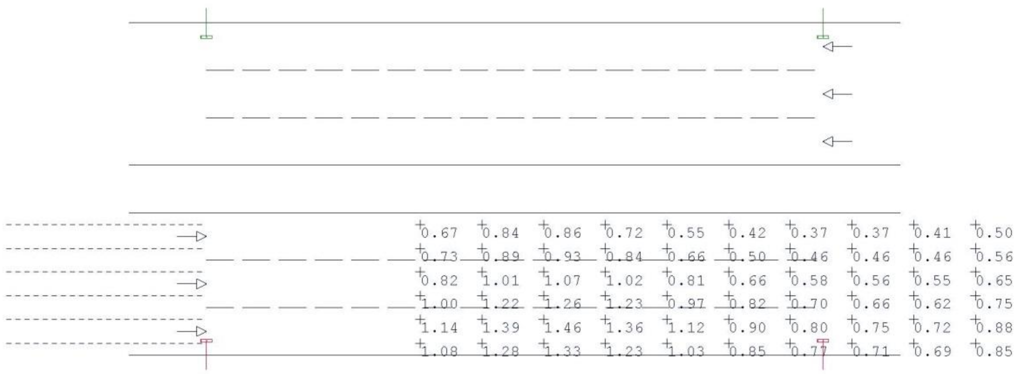


-0.47	2.29	4.36	6.18	6.55	5.84	3.91	1.60	-0.21	-2.05
-0.37	2.63	4.62	5.67	5.52	4.50	2.42	0.61	-0.88	-2.59
-0.23	2.87	4.37	4.69	3.98	2.74	0.93	-0.47	-1.89	-3.24
-0.50	2.65	3.51	3.11	2.20	1.10	-0.35	-1.67	-2.75	-3.84
-0.88	1.95	2.12	1.58	0.65	-0.29	-1.67	-2.62	-3.39	-4.38
-0.98	1.63	1.43	0.79	0.04	-1.00	-2.06	-2.78	-3.55	-4.42

Visibility Level
STV = 2.171917

105 W LED - 428 mA

RoadOpt_Vis_Level_Bkgd_Lum

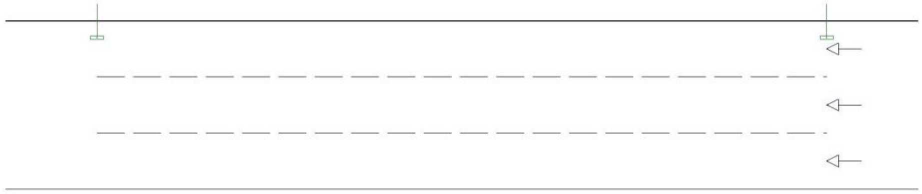


Background Luminance (Cd/SqM)
Average = 0.83
Maximum = 1.46
Minimum = 0.37
Avg/Min Ratio = 2.24
Max/Min Ratio = 3.95
Max/Avg Ratio = 1.76

6

105 W LED - 428 mA

RoadOpt_Vis_Level_Target_Lum



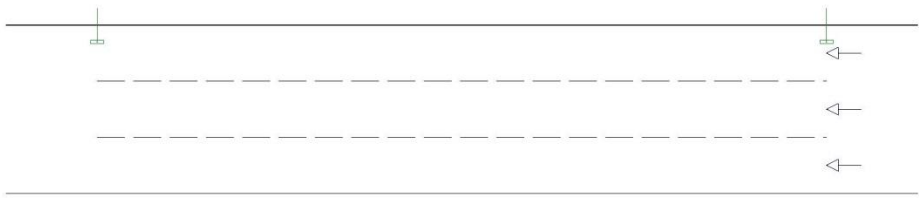
0.47	1.05	1.53	1.93	2.03	1.81	1.27	0.73	0.39	0.22
0.55	1.18	1.69	2.01	1.97	1.67	1.16	0.67	0.38	0.21
0.66	1.38	1.83	2.01	1.85	1.51	1.02	0.61	0.36	0.20
0.76	1.53	1.86	1.92	1.67	1.33	0.90	0.55	0.32	0.19
0.80	1.53	1.73	1.69	1.44	1.12	0.77	0.49	0.29	0.17
0.74	1.37	1.46	1.36	1.17	0.91	0.64	0.42	0.24	0.15

Target Luminance (Cd/SqM)
Average = 1.06
Maximum = 2.03
Minimum = 0.15
Avg/Min Ratio = 7.07
Max/Min Ratio = 13.53
Max/Avg Ratio = 1.92

7

105 W LED - 428 mA

RoadOpt_Veil_Lum



0.03	0.04	0.04	0.06	0.09	0.13	0.13	0.10	0.06	0.04
0.04	0.04	0.05	0.07	0.10	0.14	0.16	0.13	0.08	0.05
0.04	0.04	0.05	0.07	0.11	0.16	0.18	0.15	0.10	0.06
0.04	0.04	0.05	0.08	0.12	0.17	0.19	0.17	0.12	0.07
0.04	0.04	0.05	0.08	0.12	0.17	0.19	0.16	0.12	0.07
0.04	0.04	0.05	0.07	0.11	0.14	0.16	0.14	0.10	0.07

Veiling Luminance (Cd/SqM)
Average = 0.09
Maximum = 0.19
Minimum = 0.03
Avg/Min Ratio = 3
Max/Min Ratio = 6.33
Max/Avg Ratio = 2.11
MaxLv Ratio = 0.23
Threshold Increment (TI) = 14.47

8

105 W Asymmetric LED

105 W LED ASYMMETRIC - 428mA

General:

Roadway Standard: IES RP-8-2000
R-Table: R3 (Slightly Specular), Q0=0.07   Actual QO Value: 0.07

Roadway Layout:

Layout Type: Two Rows, Opposite, With Median; 2R_OPP_w/M
Roadway Width: 30 ft
Median Width: 10 ft
Lanes In Direction Of Travel: 3
Driver's Side Of Roadway: Right

Label: GPLS-105W78LED4K-LE2-PB-
Description: RoadStar
File Name: GPLS-105W78LED4K-LE2-PB-R1.1.ies
Luminaire Arrangement: SINGLE
Arm Length: 6 ft
Lumens Per Lamp: 9490
Number Of Lamps: 1
Luminaire Lumens: 5957
Efficiency (%): 63
Luminaire Watts: 105
Total Light Loss Factor: 0.765

Luminaire Location Summary:
Coordinates in ft

Spacing - Row 1: 130
Spacing - Row 2: 130

Label	X-Coord	Y-Coord	Z-Coord	Orient	Tilt	Spin
GPLS-105W78LED4K-LE2-P	390	-3	30	90	0	0
GPLS-105W78LED4K-LE2-P	-260	-3	30	90	0	0
GPLS-105W78LED4K-LE2-P	-130	-3	30	90	0	0
GPLS-105W78LED4K-LE2-P	0	-3	30	90	0	0
GPLS-105W78LED4K-LE2-P	130	-3	30	90	0	0
GPLS-105W78LED4K-LE2-P	260	-3	30	90	0	0
GPLS-105W78LED4K-LE2-P	520	-3	30	90	0	0
GPLS-105W78LED4K-LE2-P	-390	-3	30	90	0	0
GPLS-105W78LED4K-LE2-P	-390	73	30	270	0	0
GPLS-105W78LED4K-LE2-P	-260	73	30	270	0	0

:105 W LED ASYMMETRIC - 428mA

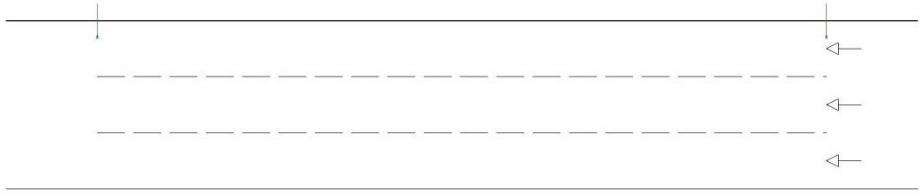
Luminaire Location Summary:
Coordinates in ft

GPLS-105W78LED4K-LE2-P	-130	73	30	270	0	0
GPLS-105W78LED4K-LE2-P	0	73	30	270	0	0
GPLS-105W78LED4K-LE2-P	130	73	30	270	0	0
GPLS-105W78LED4K-LE2-P	260	73	30	270	0	0
GPLS-105W78LED4K-LE2-P	390	73	30	270	0	0
GPLS-105W78LED4K-LE2-P	520	73	30	270	0	0

Total Number of locations: 16

105 W LED ASYMMETRIC - 428mA

RoadOpt_Luminance



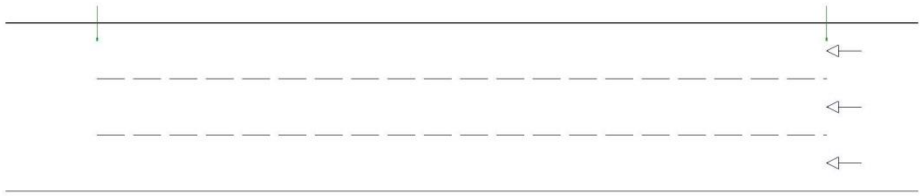
0.56	0.39	0.34	0.35	0.44	0.44	0.37	0.31	0.31	0.59
0.58	0.41	0.32	0.32	0.43	0.42	0.35	0.28	0.26	0.63
0.58	0.42	0.31	0.29	0.42	0.39	0.31	0.24	0.20	0.64
0.59	0.42	0.29	0.27	0.38	0.35	0.26	0.20	0.15	0.69
0.60	0.40	0.27	0.24	0.32	0.30	0.22	0.17	0.13	0.70
0.57	0.37	0.24	0.21	0.24	0.24	0.18	0.14	0.11	0.68

Luminance (Cd/SqM)
Average = 0.36
Maximum = 0.70
Minimum = 0.11
Avg/Min Ratio = 3.27
Max/Min Ratio = 6.36
Max/Avg Ratio = 1.94

3

105 W LED ASYMMETRIC - 428mA

RoadOpt_Illum



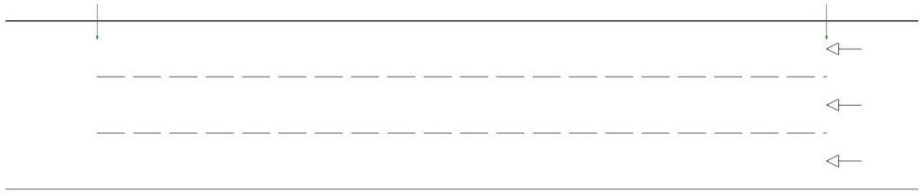
1.46	0.90	0.69	0.63	0.73	0.69	0.57	0.51	0.55	1.52
1.57	1.07	0.77	0.66	0.81	0.71	0.55	0.45	0.45	1.60
1.69	1.20	0.81	0.66	0.83	0.69	0.50	0.37	0.33	1.67
1.80	1.30	0.79	0.60	0.77	0.61	0.41	0.28	0.21	1.84
1.92	1.22	0.74	0.53	0.64	0.50	0.33	0.22	0.17	1.82
1.87	1.13	0.65	0.44	0.48	0.38	0.25	0.17	0.15	1.75

Illuminance (Fc)
Average = 0.83
Maximum = 1.92
Minimum = 0.15
Avg/Min Ratio = 5.53
Max/Min Ratio = 12.8
Max/Avg Ratio = 2.31

4

105 W LED ASYMMETRIC - 428mA

RoadOpt_Vis_Level

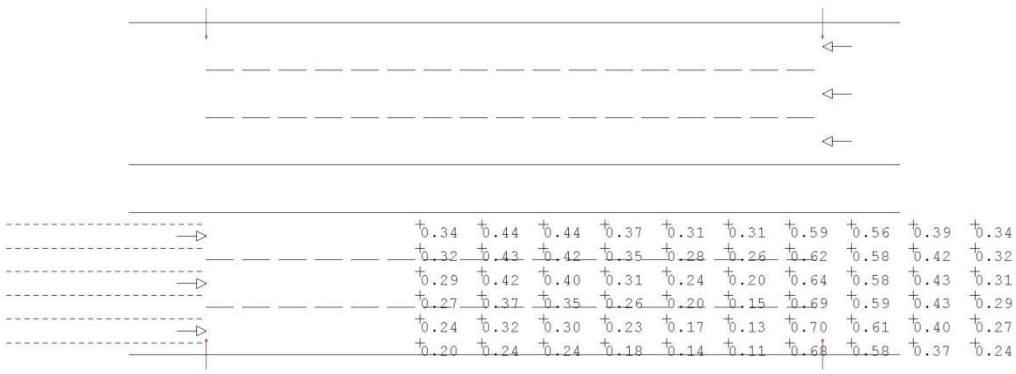


2.43	4.76	5.82	7.36	10.84	11.53	6.84	4.35	3.11	0.17
2.80	6.18	7.63	9.68	14.96	15.00	8.20	5.11	3.49	0.13
3.19	7.34	8.95	11.20	17.86	17.66	8.55	5.30	3.55	0.00
3.49	8.51	9.65	11.47	18.55	18.60	7.73	4.90	3.44	-0.42
3.73	8.70	9.86	10.90	17.17	17.11	6.48	3.93	3.10	-0.79
3.74	8.89	9.58	9.96	14.49	14.47	4.58	2.76	2.41	-1.19

Visibility Level
STV = 5.295707

105 W LED ASYMMETRIC - 428mA

RoadOpt_Vis_Level_Bkgd_Lum

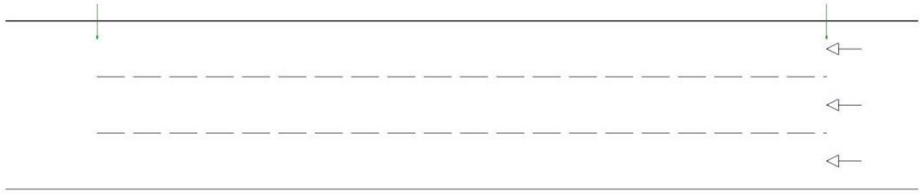


Background Luminance (Cd/SqM)
Average = 0.36
Maximum = 0.70
Minimum = 0.11
Avg/Min Ratio = 3.27
Max/Min Ratio = 6.36
Max/Avg Ratio = 1.94

6

105 W LED ASYMMETRIC - 428mA

RoadOpt_Vis_Level_Target_Lum

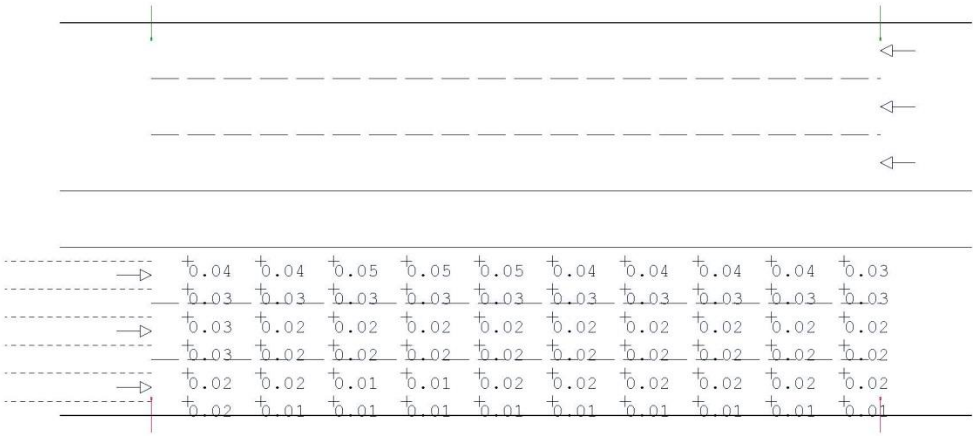


0.83	1.12	1.24	1.39	1.93	2.01	1.58	1.11	0.77	0.49
0.88	1.33	1.44	1.62	2.39	2.32	1.80	1.20	0.80	0.49
0.92	1.50	1.56	1.70	2.64	2.47	1.82	1.18	0.76	0.48
0.95	1.61	1.55	1.59	2.52	2.33	1.68	1.08	0.70	0.45
0.97	1.52	1.46	1.41	2.15	1.99	1.46	0.94	0.63	0.40
0.92	1.40	1.28	1.18	1.63	1.54	1.10	0.73	0.51	0.34

Target Luminance (Cd/SqM)
Average = 1.33
Maximum = 2.64
Minimum = 0.34
Avg/Min Ratio = 3.91
Max/Min Ratio = 7.76
Max/Avg Ratio = 1.98

105 W LED ASYMMETRIC - 428mA

RoadOpt_Veil_Lum



Veiling Luminance (Cd/SqM)
Average = 0.02
Maximum = 0.05
Minimum = 0.01
Avg/Min Ratio = 2
Max/Min Ratio = 5
Max/Avg Ratio = 2.5
MaxLv Ratio = 0.14
Threshold Increment (TI) = 7.36

8

Appendix G: Procedure

Controls Commissioning

Once the SeCo was installed and the ZigBee labels were placed on the commissioning spreadsheet, representatives from Owlet scanned the ZigBee labels and associated each with that particular SeCo. Researchers requested GPS coordinates from the City, but global positioning coordinates are not used within the City; instead local northings and eastings are used. Rather than use a converter between the two coordinate systems, researchers placed each of the LED luminaires via Google Maps satellite view. They then recorded GPS coordinates into the system.

After all of the components of the control system registered with the control system and each of the luminaires was energized, the system began propagating each of the LuCos. Soon after the system was up and running, only a small number of LuCos were appearing out of the forty-two that should have been propagating in the system. Seattle City Light (SCL) determined that the installation crew had installed some of the LuCos at a higher voltage, 240V, rather than at the specified voltage of 120V. Because the LuCos can only accept one voltage, either 120V or 240V, they had to replace the majority of the LuCos.

After SCL had replaced the original 120V LuCos energized at 240V with 240V LuCo versions, nearly all of them began to appear in the control system monitors. At the time of the demonstration, a few LuCos still appeared only sporadically. After the demonstration, researchers determined why these LuCos were not fully registering into the system; a malfunctioning AT&T cell tower adjacent to the non-registering LuCos created interference. These malfunctioning LuCos meant the last two luminaires of one series were unable to dim; they operated at one hundred percent light output throughout the demonstration.

Weather Conditions

Approximately two weeks before the demonstration, researchers asked a local meteorologist from the KING5 television station to help the team forecast the weather. Rain was in the forecast during the days leading up to the demonstration, although the meteorologist forecast March 6 to be dry by evening. The meteorologist forecast rain for both March 7 and March 8.

The day before the demonstration, March 5, the meteorologist predicted dry weather for all three days. After receiving this forecast, the researchers decided to artificially wet the roads one night (March 8).

As forecasted, all three evenings of the demonstration had dry roads. The sky was mostly clear, the moon was full, and the temperature was in the mid-forties. The moon delivers approximately one hundredth of a foot-candle to the roadway surface. While the brightness was noticeable, the 0.01 footcandle contribution of moonlight did not affect the results of the user field test.

Written Evaluation

On the test days, Continuum Industries directed participants to meet at the Salmon Bay Middle School, located a few blocks from the test site. On each night of testing, the first group of participants arrived at 7:00 p.m. After the participants were all registered and given their survey booklets, they received an orientation explaining their task. Three team members answered their questions and concerns at this time. They also addressed safety precautions, instructing participants to remain on the sidewalk. At the conclusion of the orientation, the participants were escorted to the front of the school to board a bus to the demonstration test site.

Experimental Protocol

When the general participants arrived at the testing site, three of them volunteered for the driving portion of the study. The participants chose among themselves who sat in the front versus the back of the vehicle. Researchers then asked participants to enter the vehicle and review the tasks prior to starting this portion of the research study.

While participants were sitting in the stationary experimental vehicle, the in-vehicle experimenter reviewed the detection task with them. The experimenter pointed out the response buttons positioned both in the front and rear seats of the vehicle and told participants to press the response buttons upon detecting a target on the roadway. The experimenter showed participants an example target after the buttons were introduced. The experimenter instructed participants to press a response button only when they were confident that they had seen a target and requested they notify the experimenter if they accidentally pressed a button during the experimental run.

Prior to beginning the experimental drive, the in-vehicle experimenter asked the participants in the back seat to move to where they could comfortably see the forward view of the roadway and thus detect targets out of the front windshield (rather than through the side windows). The experimenter asked participants not to converse or hint to the other participants when they had seen a target in order to minimize influencing detection distances. The experimenter addressed additional questions and concerns prior to starting the experimental run.

The experimenter then started recording a data collection file. For targets present at or near the starting location, the experimenter marked the data so these targets would be ignored. The starting location of the experimental vehicle varied during the testing sessions and was dependent on the location at that time of the participants. The experimenter took the research vehicle to one of the written evaluation groups, at which point the participants were dropped off and a new set of participants picked up at the end of each in-vehicle test session.

Dry Pavement

Sixty-two people completed the written evaluations for the one hundred percent light output level. Twenty-four people completed the user field test.

While the first group of participants was on site evaluating the lighting, the second group of participants took part in the orientation and safety presentation at the middle school. The second group of participants left the middle school via bus and was dropped off in the same fashion as the first group. This group evaluated all of the LED test areas both at fifty percent light output. The two HPS test areas were not dimmed and remained at one hundred percent light output. Researchers did not alert participants to the lower light output; rather they were told that it was important to get as many people as possible through the survey safely and that the best way to do that was to split up into three groups over the course of the evening.

Fifty-four people completed the written evaluations for the fifty percent light output level. Twenty-four people completed the user field test.

As the second group of participants arrived at the test site, the third and final group of participants attended the orientation and safety presentation at the middle school. This group then evaluated all of the LED test areas at twenty-five percent light output. The two HPS test areas were not dimmed and remained at one hundred percent light output. Again, researchers did not tell the participants that the lights were tuned to a lower output.

Forty-nine people completed the written evaluations for the twenty-five percent light output level. Twenty-four people completed the user field test.

With each group, a representative from SDOT tuned all of the LED lights in the field via an iPad with a 3G Internet connection. The response time for the command was approximately one minute. The light output level was changed when participants were on the bus either departing or arriving at the demonstration site.

Wet Pavement

The bus schedule was slightly revised after the first night of general testing. Researchers allotted approximately one hour for each group to evaluate all six test areas. Participants completed the evaluations in approximately forty-five minutes.

The first group of participants on the second night of testing still arrived at 7:00 p.m. for the overview and safety presentation, although to allow enough time for road closure, dry pavement luminance data measurements, road wetting, and setup of the visibility targets, they were not bussed to the demonstration site until 8:30 p.m. The team used the same dropoff and pickup bus route as for the evening of the dry pavement. This first group evaluated all six test areas at one hundred percent light output.

Fifty-nine people completed the written evaluations for the one hundred percent light output level. Twenty-four people completed the user field test.

The second group of participants attended the safety and overview presentation during the time that the first group was evaluating the test areas. During the time between the first group leaving the second group arriving, flusher trucks again wet the road surface. This second group evaluated all of the LED test areas at fifty percent light output. The two HPS test areas remained at one hundred percent light output.

Fifty-nine people completed the written evaluations for the fifty percent light output level. Twenty-one people completed the user field test.

The third group of participants completed the overview and safety demonstration while the second group evaluated the test areas. During the time between the first group leaving the second group arriving, the flusher trucks wet the road a final time. This third group evaluated all of the LED test areas at twenty-five percent light output. The two HPS test areas remained at one hundred percent light output.

Forty-nine people completed the written evaluations for the twenty-five percent light output level. Due to a system failure in the data collection activity, only six people in this group completed the user field test.

Appendix H: Written Evaluation Findings

Responses to Written Evaluation Statements

S1: *It would be safe to walk here alone during daylight hours.* This statement sets a baseline for the statements regarding safety and evaluates the other environmental factors that determine the safety of an area.. Average ratings for this statement ranged from 4.4 to 4.8 (or on the high side between "Agree" and "Strongly Agree"), indicating that participants considered the street fairly safe to walk during daylight hours.

S2: *It would be safe to walk here alone during darkness hours.* Dimming to fifty percent and twenty-five percent of full light output did not necessarily correlate to less perceived safety within any given test area. In fact, no statistically significant differences existed in the responses to this question among dimming to one hundred percent, fifty percent, and twenty-five percent of full light output under wet or dry conditions. The only exception was for the asymmetric luminaire under wet conditions, for which participants agreed with this statement slightly more (safer) on average at twenty-five percent of full light output as compared to fifty percent of full light output.

S3: *The lighting is comfortable.* The results showed no statistical differences among responses within in a given test area with a seventy-five percent light output reduction. Interestingly, men generally preferred cooler color temperatures while women preferred warmer (including HPS) – a phenomenon observed for this statement and several others,

S4: *There is too much light on the street.* Even when the LED areas were dimmed to twenty-five percent of full light output, participants did not assign higher agreement ratings for this statement to the HPS luminaires (always at full output) compared to their agreement ratings for this statement for the much lower-output LED luminaires.

S5: *There is not enough light on the street.* These results yielded the expected trend, with participants most strongly agreeing with this statement at the twenty-five percent of full light output level. However, the standard LED products still resulted in neutral ratings. Participants agreed with this statement for the asymmetric luminaire at all levels and road conditions, and conversely disagreed with this statement for the HPS sources.

S6: *The light is uneven (patchy).* The pre-study calculations showed the worst uniformity for the asymmetric test area; not surprisingly, participants agreed most strongly with this statement for the asymmetric test area over the other test areas. However, because the asymmetric luminaire was designed to reduce veiling reflections under wet conditions and low light levels, it earned comparable agreement ratings to the others at twenty-five percent of full light output and wet roads.

S7: *The light sources are glaring.* As expected, participants agreed <u>least</u> with this statement for the asymmetric luminaire, meaning they perceived it had the least amount of glare of any of the luminaires. Participants agreed next-least for this statement (meaning lower perceived glare) for the 3500K and 4100K LEDs.

S8: *It would be safe to walk on sidewalk here at night.* Participants agreed most strongly with this statement for the 400 W HPS, followed by the 250 W HPS. No significant differences existed among the three standard LED luminaires. The second data collection trip indicated that the amount of backlight present for the HPS luminaires was approximately four times greater than that for the LED luminaires, which may have contributed to ratings for this statement.

S9: *I cannot tell the colors of things due to the lighting.* Surprisingly, the agreement ratings for this statement showed virtually no statistically significant differences across color temperatures, including HPS, across all three dim levels. Most of the ratings fell between “Disagree” and “Neutral” for this statement.

S10: *The lighting enables safe vehicular navigation.* The two HPS sources (250 watt and 400 watt) earned the highest agreement scores for this statement, exceeding an average response of 4 (“Agree”). The three standard LED sources averaged ratings between “Neutral” and “Agree” (3 and 4). Participants agreed least with this statement for the asymmetric luminaire, with a neutral score of three.

S11: *I like the color of the light.* Interestingly, the standard 4100K LED and the asymmetric source showed statistically significant differences (at fifty percent light output) despite being the exact same LED color. This suggests that the participants may not have liked the asymmetric luminaire for reasons other than color. Again, this statement showed men preferring cooler colors and women warmer colors. Both HPS sources showed nearly the same levels of agreement for this statement as the LED sources.

S12: *I would like this style of lighting on my city streets.* With the exception of the asymmetric test area, participants agreed with this statement for the LED luminaires as much as for the current 400 W and 250 W HPS standards. They agreed with this statement for the asymmetric group to a significantly lower degree than they did for the existing HPS systems.

Appendix I: Written Evaluation Results – Duplicate Participant Analysis

Figure *62*. Question 3 – Wet Pavement

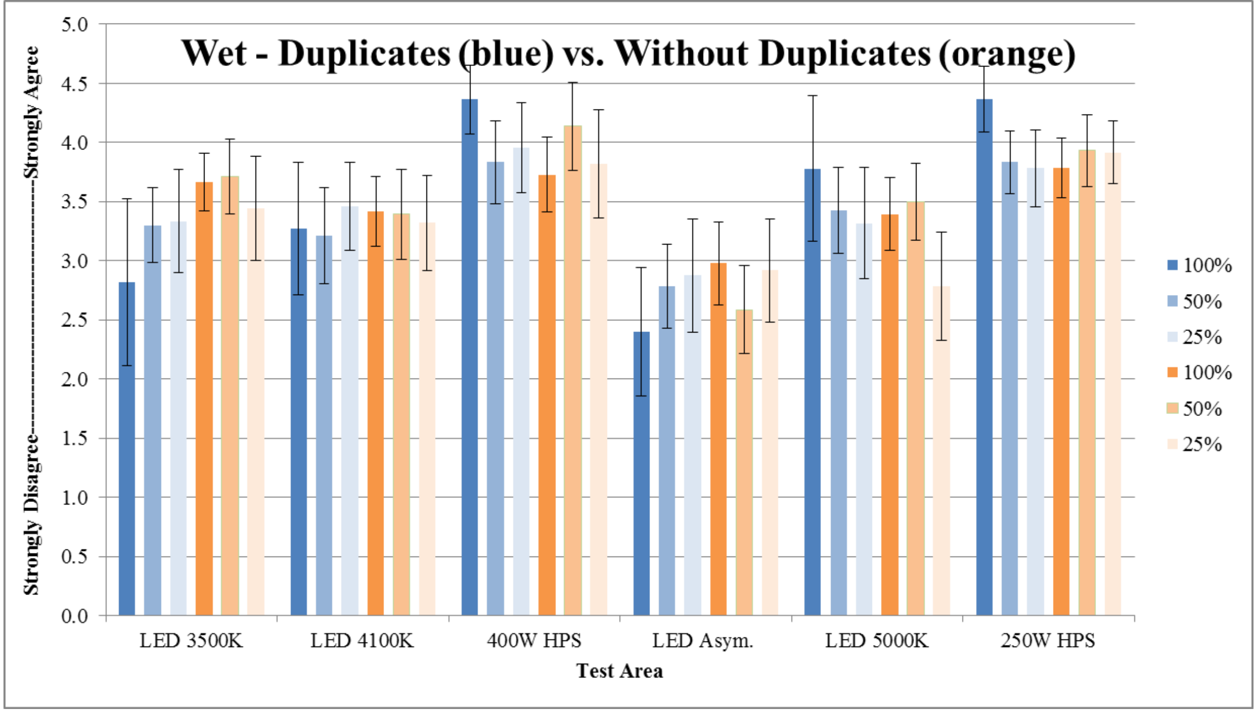


Figure 63. Question 5 – Wet Pavement

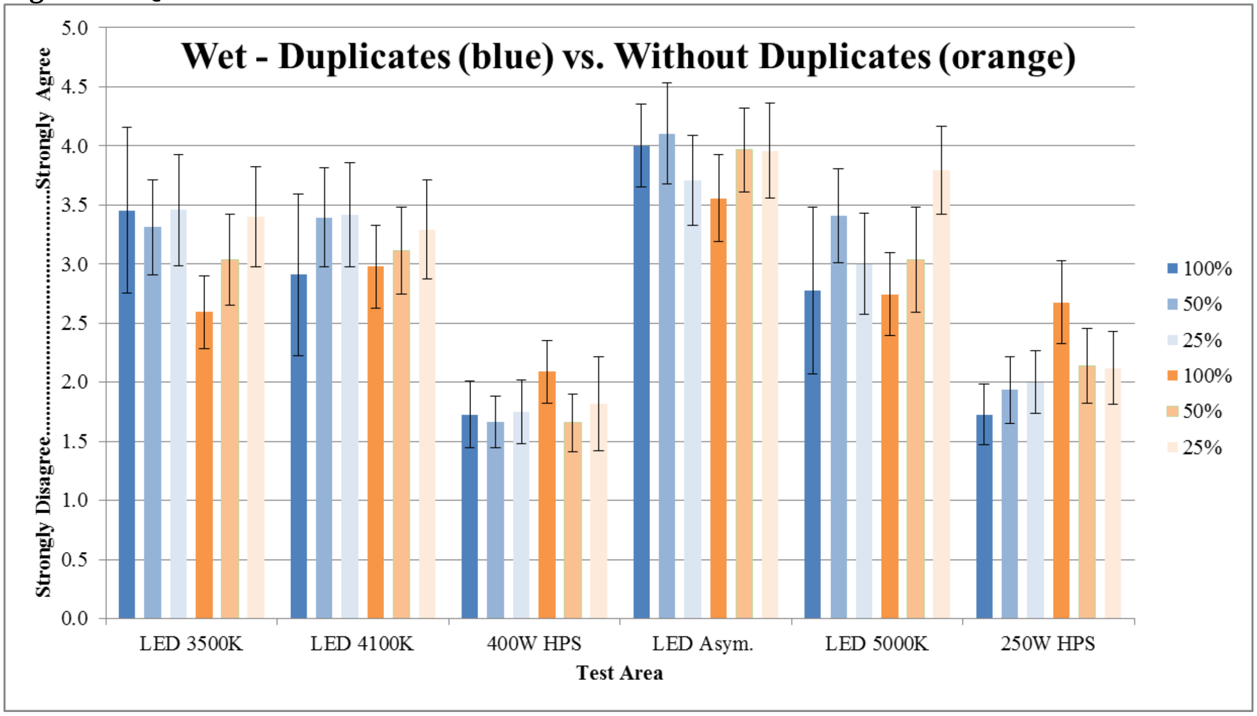


Figure 64. Question 6 – Dry Pavement

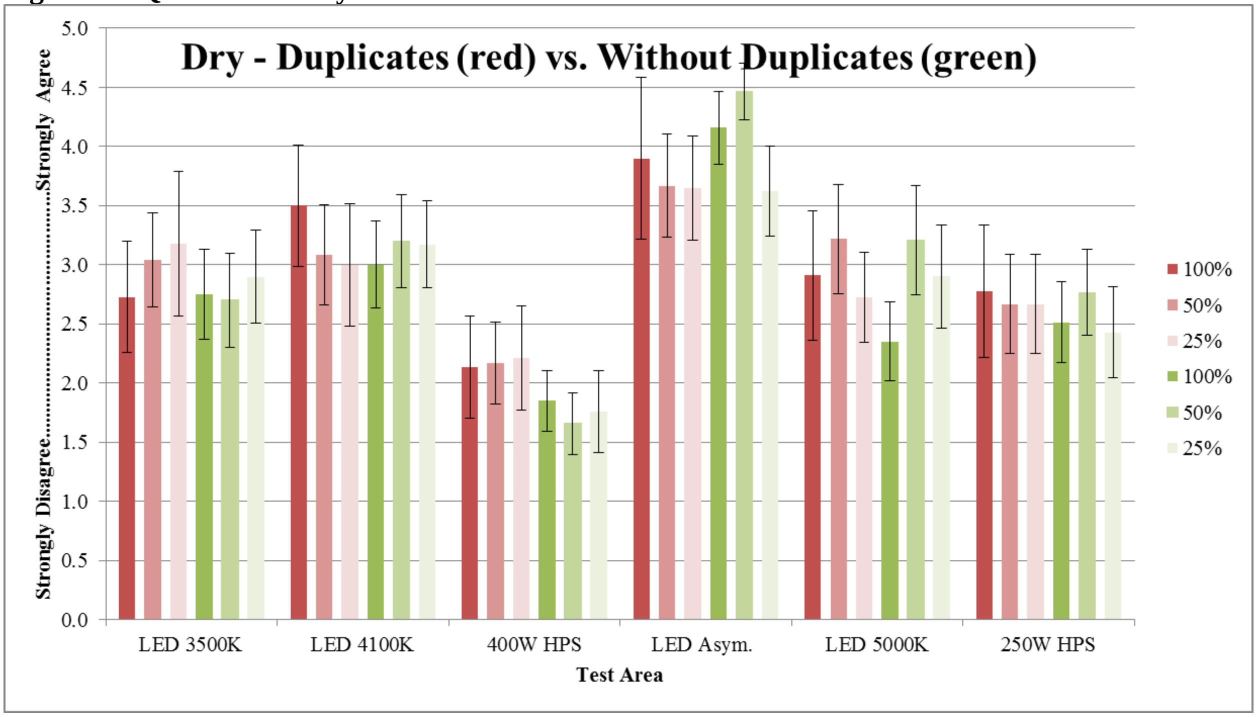


Figure *65*. Question 7 – Dry Pavement

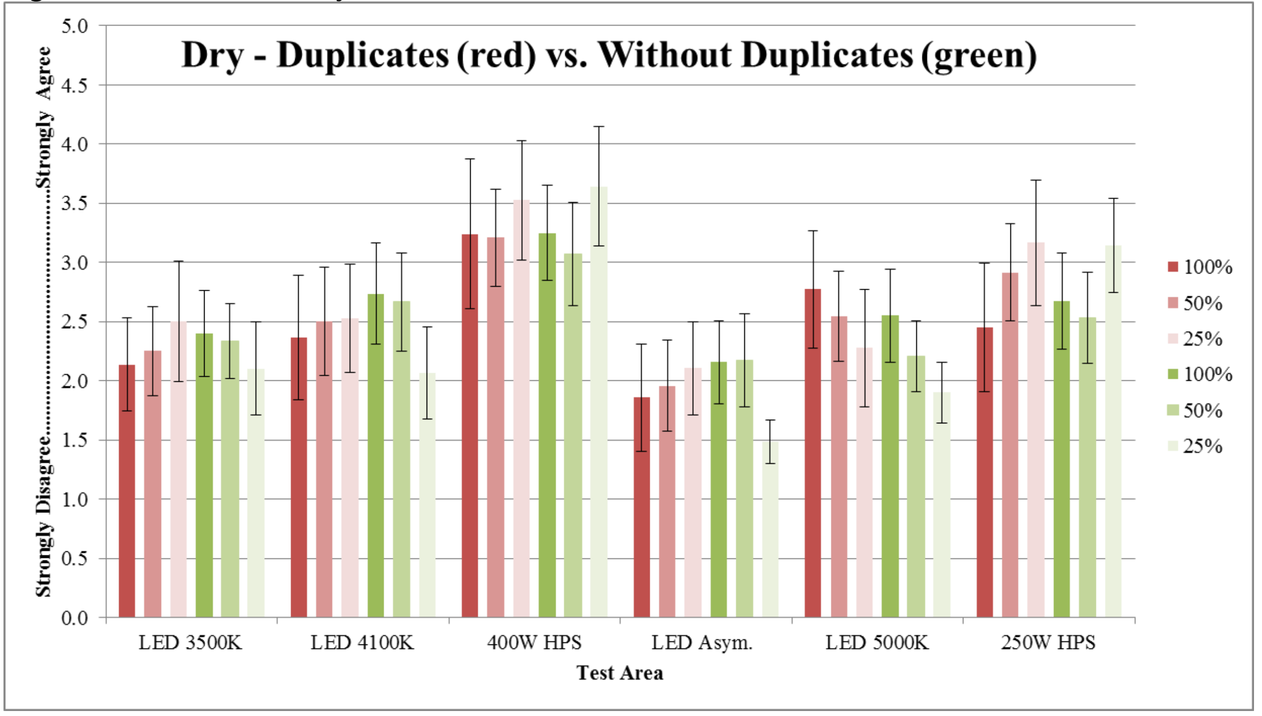


Figure *66*. Question 10 – Wet Pavement

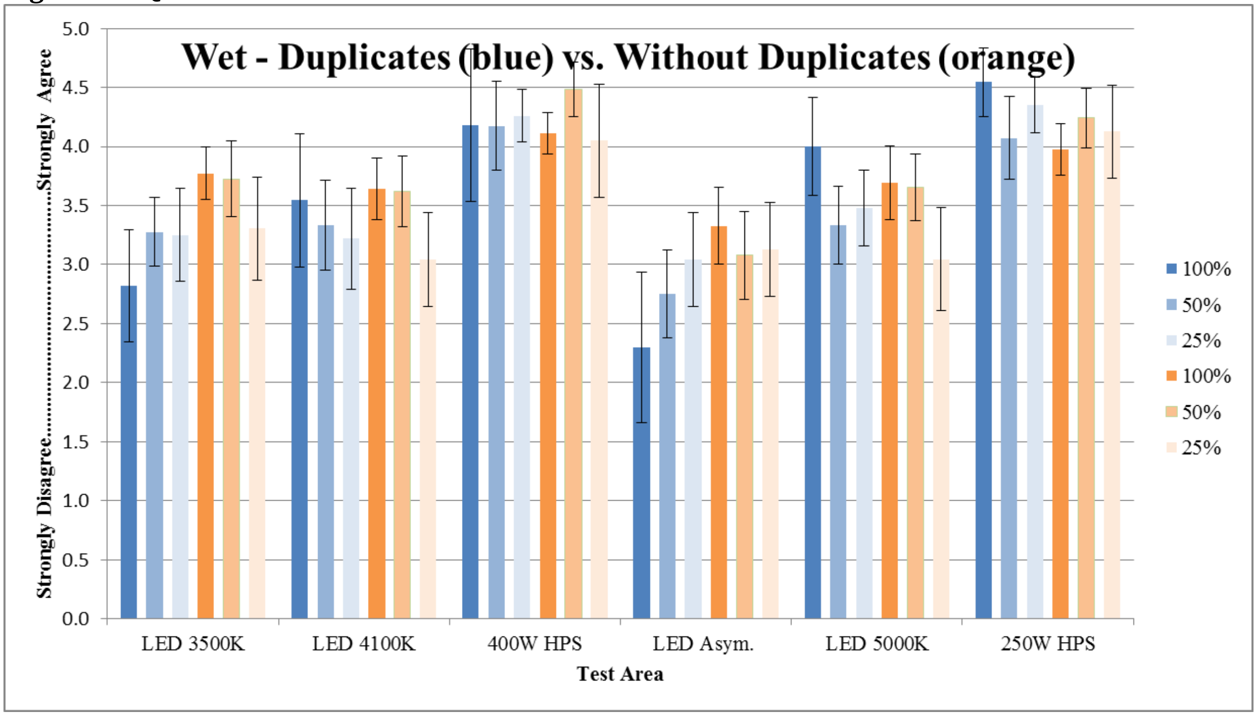


Figure 67. Question 12 – Wet Pavement

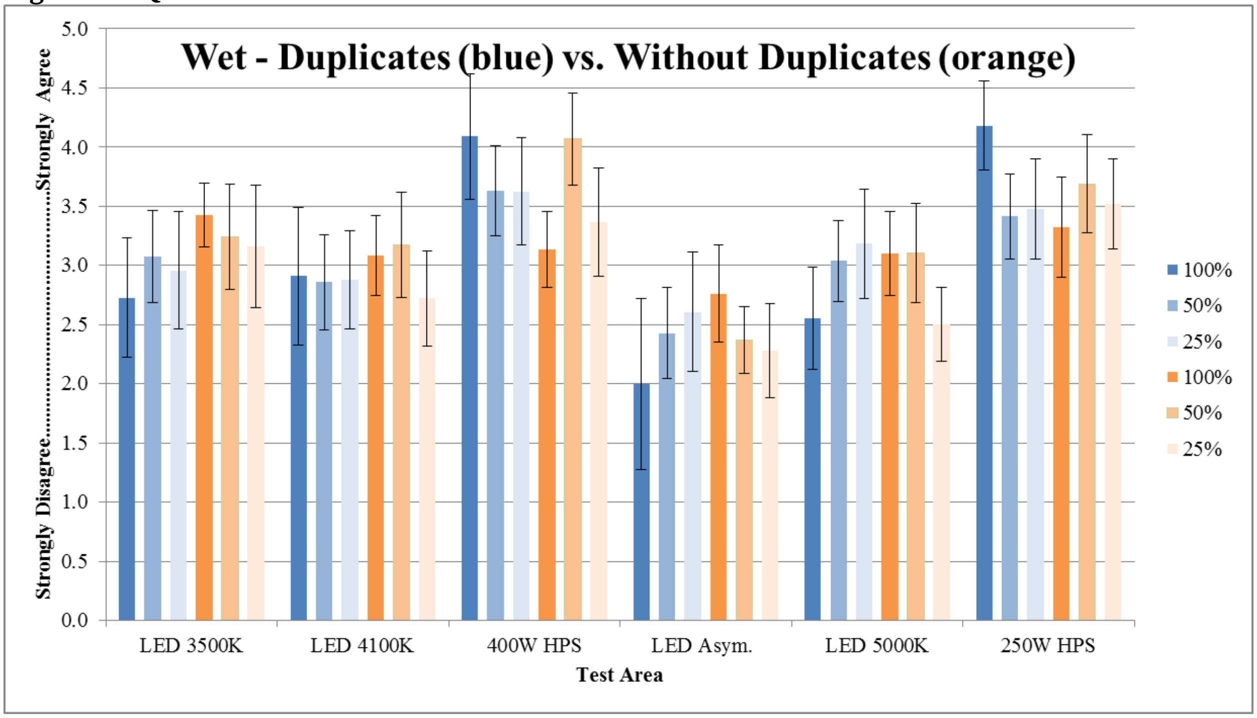
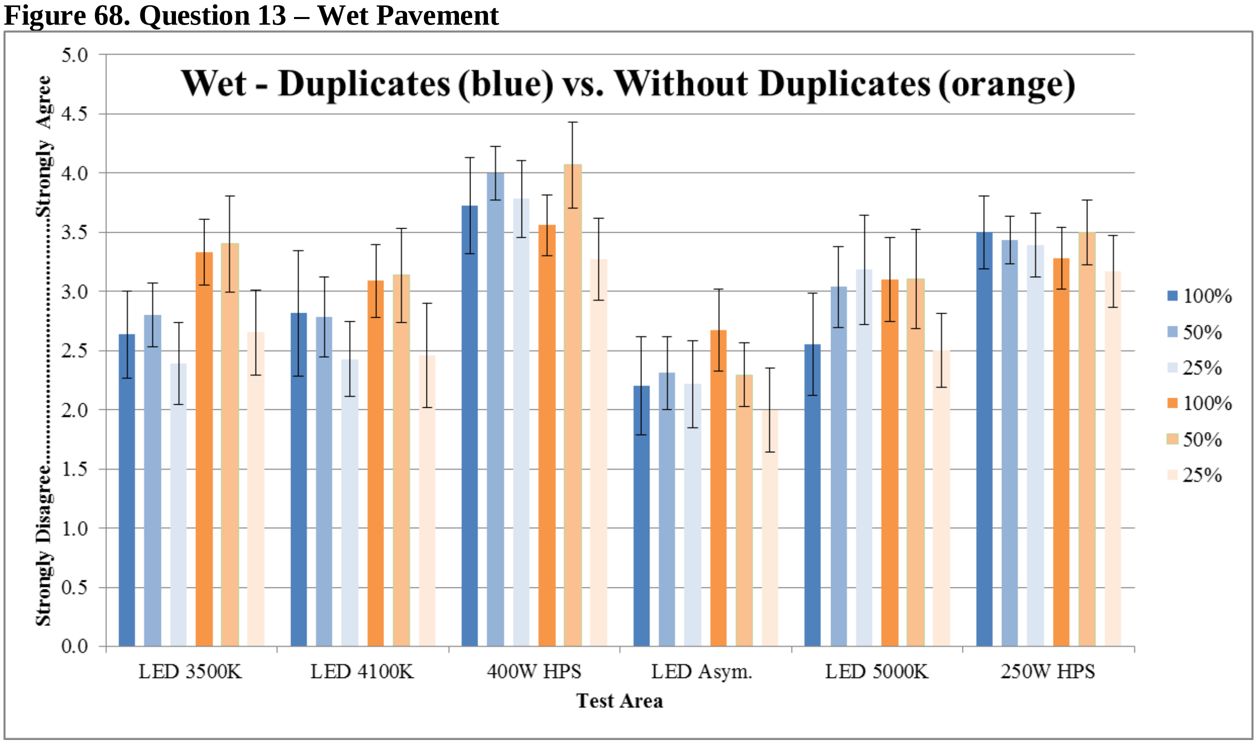


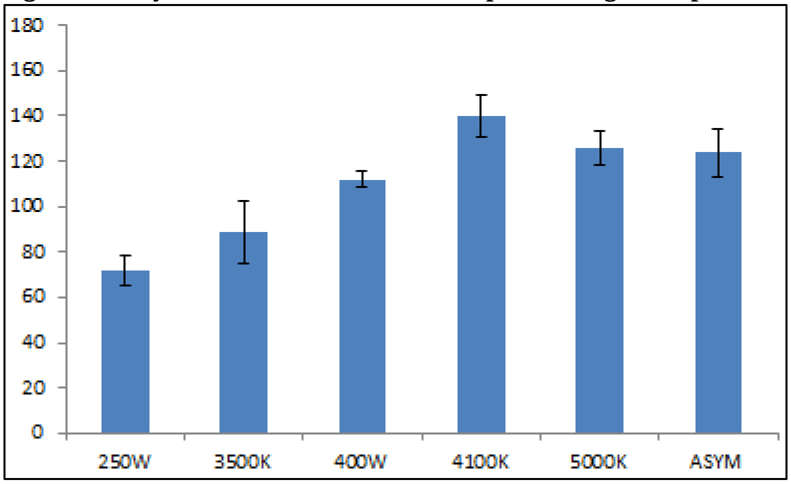
Figure 68. Question 13 – Wet Pavement



Appendix J: User Field Test Results

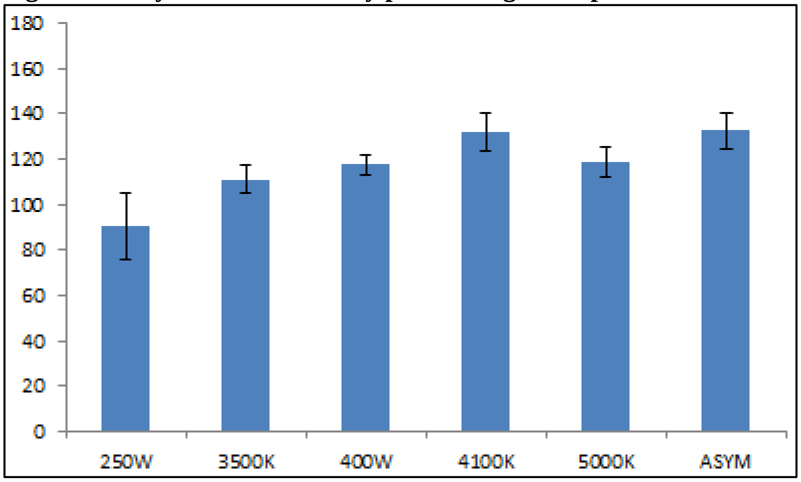
The following figures (Figure 69 through Figure 79) show the measured detection distance (in meters) for each test area. The corresponding light level is noted in the caption.

Figure 69. Dry Pavement at One Hundred percent Light Output



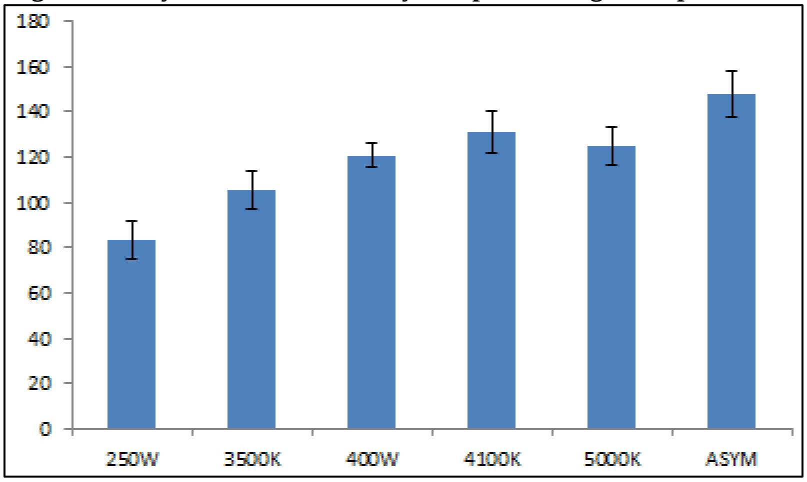
Note: Y-axis shows measured detection distance in meters.

Figure 70. Dry Pavement at Fifty percent Light Output



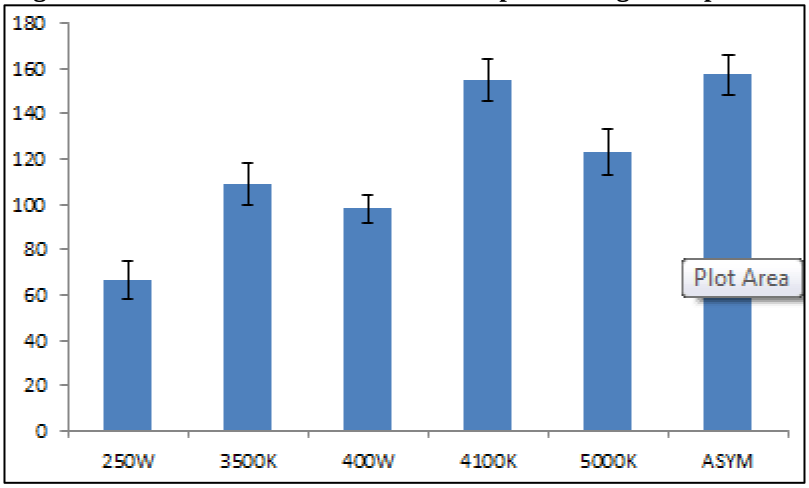
Note: Y-axis shows measured detection distance in meters.

Figure 71. Dry Pavement at Twenty-five percent Light Output



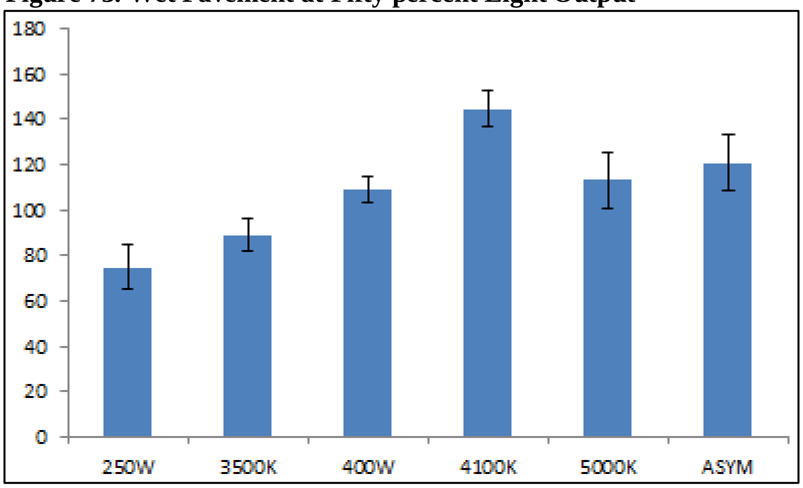
Note: Y-axis shows measured detection distance in meters.

Figure 72. Wet Pavement at One Hundred percent Light Output



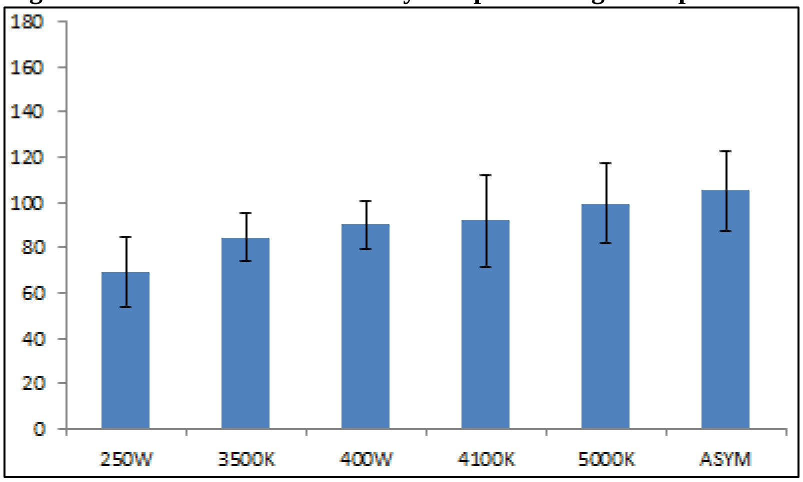
Note: Y-axis shows measured detection distance in meters.

Figure 73. Wet Pavement at Fifty percent Light Output



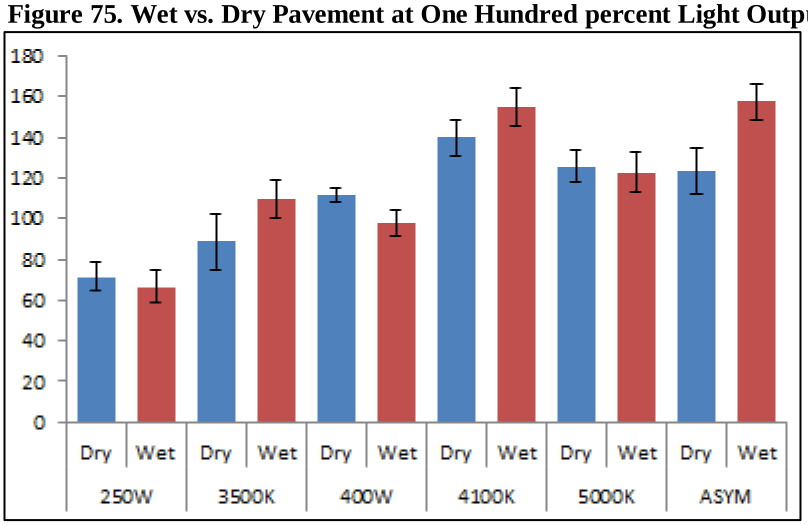
Note: Y-axis shows measured detection distance in meters.

Figure 74. Wet Pavement at Twenty-five percent Light Output



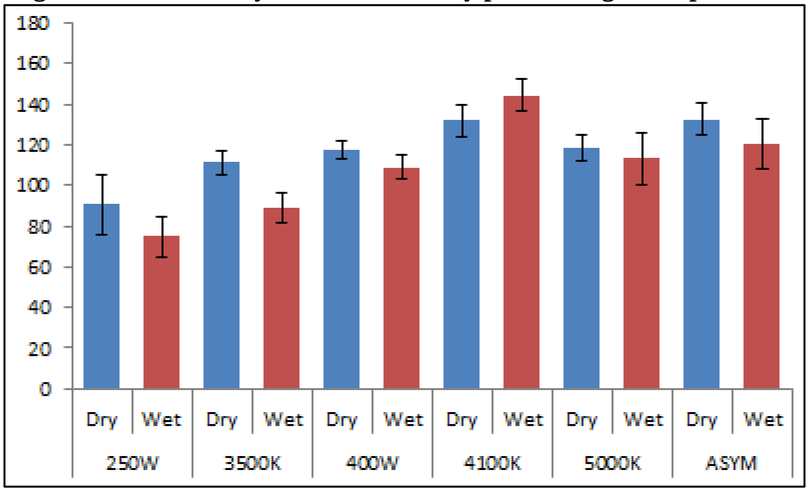
Note: Y-axis shows measured detection distance in meters.

Figure 75. Wet vs. Dry Pavement at One Hundred percent Light Output



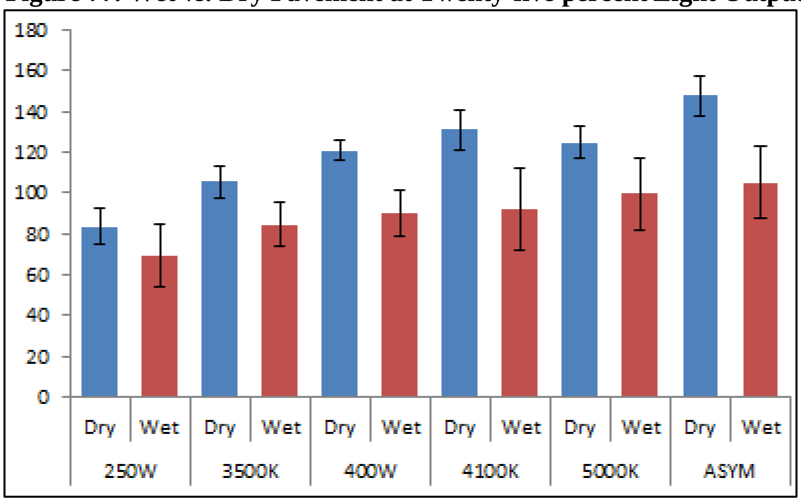
Note: Y-axis shows measured detection distance in meters.

Figure 76. Wet vs. Dry Pavement at Fifty percent Light Output



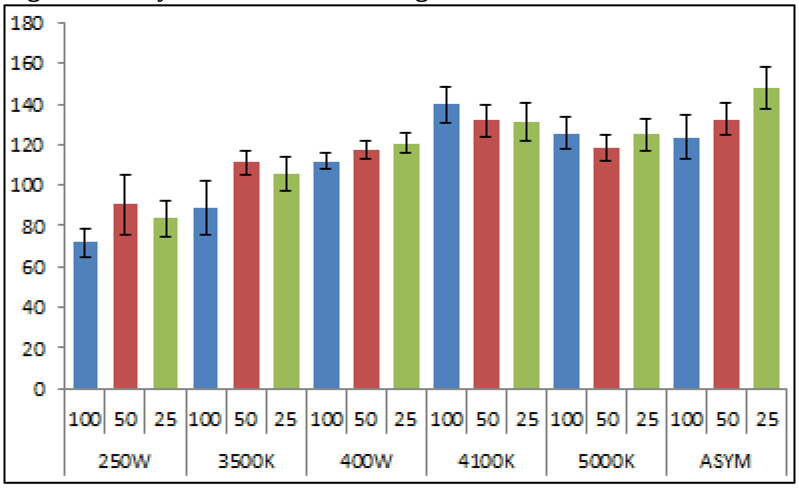
Note: Y-axis shows measured detection distance in meters.

Figure 77. Wet vs. Dry Pavement at Twenty-five percent Light Output



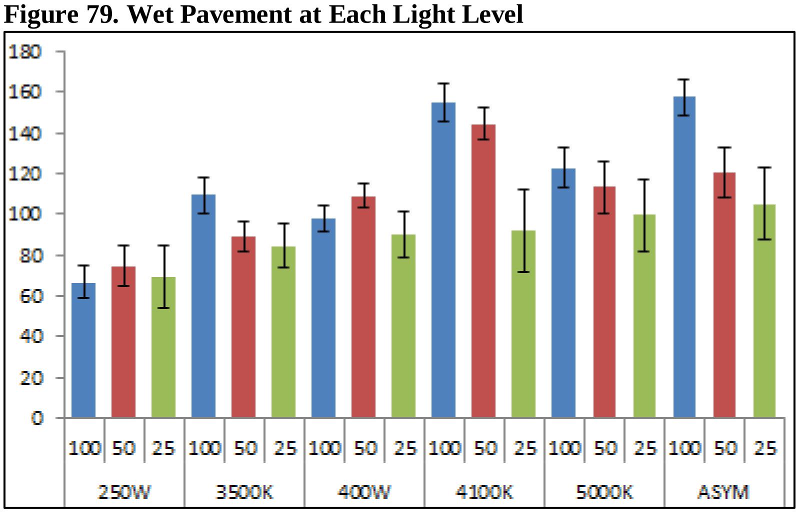
Note: Y-axis shows measured detection distance in meters.

Figure 78. Dry Pavement at Each Light Level



Note: Y-axis shows measured detection distance in meters.

Figure 79. Wet Pavement at Each Light Level



Note: Y-axis shows measured detection distance in meters.

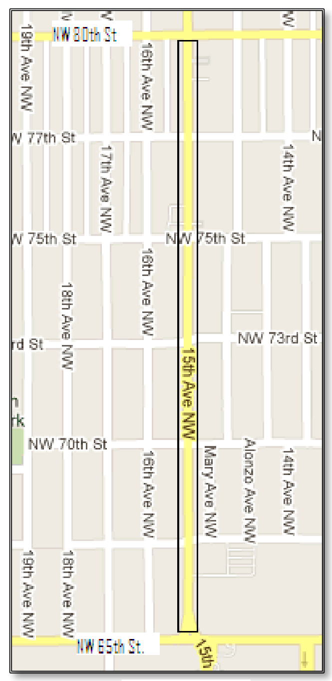
Appendix K: Public Outreach

Five Hour Nighttime Closure of 15th Avenue NW in early March for Roadway Visibility Study

The Seattle Department of Transportation (SDOT) and Seattle City Light (SCL) in collaboration with the Northwest Energy Efficiency Alliance (NEEA) are conducting a demonstration project to evaluate the use of energy-saving LED streetlights. Similar studies have been conducted in Anchorage, San Jose, and San Diego, all intended to help local governments determine how LED streetlights can meet safety goals while reducing energy costs.

To conduct the study, it will be necessary to close **15th Avenue NW from NW 65th Street to NW 80th Street**, for three consecutive nights in early March – Tuesday thru Thursday, **March 6, 7, & 8**. The study will require a **complete closure of the roadway between 8 p.m. and 1 a.m.** on each of these nights.

- No parking will be allowed in the study area during the study hours
- The only non-test vehicles permitted in the study area will be emergency vehicles.
- Residents who live in the study area will not be able to enter or leave 15th Avenue NW during the test period with their vehicles.
- The closure will not impact east/west traffic on either NW 65th or NW 80th Streets.
- 15th Avenue NW traffic will be detoured to 24th Avenue NW during the closure.
- For information on changes to bus service, look for Rider Alert notices at bus stops, see Metro Online, www.kingcounty.gov/metro or call (206)553-3000.
- Participants are now being recruited to take part in the test and will be paid $40 for 2 to 2 ½ hours of their time. To register online, please visit www.neea.org/seattletest.
- Residents of the community are welcome to watch from the sidelines on any of the nights.



Study Area

We realize that these tests are an inconvenience for local residents and businesses and thank you for your patience and understanding. If you'd like specific information on how your business or residence will be affected by the streetlight test, please contact:

Paul Elliott, Community Relations, SDOT / paul.elliott@seattle.gov / (206)684-5321

For more information on this study, its sustainability goals, and its resulting energy-efficiency assessments, please visit www.neea.org/streetlighttest. You may also contact:

Mark Rehley, Emerging Technology Operations Manager, NEEA / MRehley@neea.org /Robert Sawyer, Project Manager, Seattle City Light / robert.sawyer@seattle.gov / (206)684-3925

City of Seattle
Seattle Department of Transportation

News Release

Peter Hahn, Director

Contact: Marybeth Turner (206) 684-8548 or Peg Nielsen (206) 684-8114

For Immediate Release
February 3, 2012

LED Streetlight Demonstration to Close Stretch of 15th Avenue Northwest in Early March

SEATTLE – The Seattle Department of Transportation (SDOT) and Seattle City Light (SCL), working in collaboration with the Northwest Energy Efficiency Alliance (NEEA), will be closing 15th Avenue Northwest from NW 65th to NW 80th Streets for three nights in early March. The closures, March 6, 7, and 8 (Tuesday through Thursday) from 8 p.m. each evening until 1 a.m. the following morning, are needed in order to conduct a demonstration project evaluating the use of energy-saving LED streetlights.

During the closure, no on-street parking will be permitted along the study area of 15th Avenue NW, and only emergency or test vehicles will be able to drive it. Residents who live in the study area will not be able to enter or leave 15th Avenue NW during the test period with their vehicles, although individuals are welcome to watch from the sidelines on any of the nights.

The goal of the demonstration project is to evaluate the use of energy-saving LED streetlights in wet and dry pavement conditions. The study is similar to demonstrations conducted in Anchorage, San Jose, and San Diego. The guidance provided by these studies will help municipalities in selecting proper lighting levels for LED streetlights, which use up to 50% less energy than traditional streetlighting technologies.

The test results in other cities have shown that LEDs provide a broader spectrum of frequencies and better visibility versus typical high-pressured sodium lights, yet use far less energy. The Northwest utilities currently have more than two million streetlights with many coming to the end of life. LEDs could replace them over the next decade.

The test sponsors are recruiting individuals to take part in the test, which involves a commitment of 2 to 2 ½ hours on any of the test evenings. Participants will be paid upon completion of the test with a $40 Visa gift card for their efforts. Those interested in participating can register online at www.neea.org/seattletest.

Additional information on the study, its sustainability goals, and its resulting energy-efficiency assessments can visit the project website, located at www.neea.org/streetlighttest.

For information on changes to bus service during the closures, look for Rider Alert notices at bus stops, see Metro Online at www.kingcounty.gov/metro or call (206)553-3000.

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Seattle Municipal Tower, 700 5th Avenue, Suite 3800, PO Box 34996, Seattle, WA 98124-4996
Tel: (206) 684-ROAD Tel: (206) 684-5000 Fax: (206) 684-5180
Web: www.seattle.gov/transportation

Nighttime Street Closure Coming to 15th Avenue NW

15th Avenue NW From NW 65th to NW 80th Street to be closed March 6 - 8, 8 p.m. to 1 a.m.

Energy Saving LED Street Lighting Study

PARKING PROHIBITED 8 P.M. to 1 A.M. Nightly Monday, March 5 – Thursday, March 8

The Seattle Department of Transportation (SDOT) and Seattle City Light in collaboration with the Northwest Energy Efficiency Alliance (NEEA) will be conducting a demonstration project to evaluate the use of energy-saving LED streetlights.

- No one except emergency or test vehicles will be able to enter or leave 15th Avenue NW during the test period.
- Traffic will be detoured to 24th Avenue NW during the closure.
- The closure will not impact east/west traffic on either NW 65th or NW 80th. Access to 15th Avenue NW from other east-west streets will not be permitted.
- No on-street parking will be allowed in the study area during the closure, as well as on **Monday, March 5, from 8 P.M to 1 A.M.** when preparation for the study is underway.
- For information on changes to bus service, look for Rider Alert notices at bus stops, see Metro Online, **www.kingcounty.gov/metro or call 206/553-3000.**
- Community members are welcome to watch the test from the sidelines.

City of Seattle SDOT Seattle Department of Transportation