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Seattle LED Adaptive Lighting Study

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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.
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)](image)

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.
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

\[ \text{Contrast} = \frac{L_{\text{target}} - L_{\text{background}}}{L_{\text{background}}} \]

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)
# Table of Contents

1 Executive Summary ........................................................................................................................................... i

1.1 Project Background ........................................................................................................................................ ii

1.2 Study Description ........................................................................................................................................... i

1.3 Research Results ........................................................................................................................................... ii

1.4 Industry Implications .................................................................................................................................... iv

2 Introduction .......................................................................................................................................................... 1

2.1 Background .................................................................................................................................................... 1

2.2 Technology and Market Overview ................................................................................................................ 2

2.3 Project Objectives ......................................................................................................................................... 3

2.4 Project Hypotheses ....................................................................................................................................... 3

3 Methodology ....................................................................................................................................................... 6

3.1 Overall Project Setup ................................................................................................................................... 6

3.2 Site Selection .................................................................................................................................................. 7

3.3 Public Outreach ............................................................................................................................................. 8

3.4 Lighting Criteria ........................................................................................................................................... 9

3.5 Luminaire Selection ..................................................................................................................................... 10

3.6 Controls Selection ....................................................................................................................................... 10

3.7 Asymmetric Luminaire Design .................................................................................................................... 11

3.8 Road Conditions ......................................................................................................................................... 13

3.9 Light Output Level ....................................................................................................................................... 14

3.10 Participant Recruitment ............................................................................................................................. 14

3.11 Written Evaluation .................................................................................................................................. 15

3.12 User Field Test .......................................................................................................................................... 16

4 Procedure ......................................................................................................................................................... 19

4.1 Equipment Pretesting ................................................................................................................................ 19

4.2 Equipment Installation ................................................................................................................................. 22

4.3 Setup of Visibility Targets ............................................................................................................................ 23

4.4 Written Evaluations and User Field Tests ................................................................................................. 24

4.5 Experimental Protocol ............................................................................................................................... 25

4.6 Dry Pavement ............................................................................................................................................. 25

4.7 Wet Pavement ........................................................................................................................................... 26

4.8 Luminance Measurements .......................................................................................................................... 27

5 Findings .............................................................................................................................................................. 28

5.1 Written Evaluation ..................................................................................................................................... 28

5.2 User Field Test .......................................................................................................................................... 32

5.3 Contrast ....................................................................................................................................................... 37

5.4 Illuminance and Detection Distance .......................................................................................................... 41

5.5 Lighting Metrics ......................................................................................................................................... 43

5.6 Sidewalk Lighting Characteristics ............................................................................................................... 49

5.7 Light Trespass .......................................................................................................................................... 51

5.8 Glare .......................................................................................................................................................... 52

5.9 Spectral Power Distribution ....................................................................................................................... 55

6 Discussion ............................................................................................................................................................ 58

6.1 Comparison to Previous Studies ................................................................................................................ 58

6.2 Adaptive Lighting Opportunities ............................................................................................................... 59

6.3 Future Design Standards ............................................................................................................................ 60
6.4 Economic Analysis .................................................................................................................................60

7 Conclusions .................................................................................................................................................68
  7.1 Written Evaluation .................................................................................................................................68
  7.2 User Field Test .......................................................................................................................................69
  7.3 Color Temperature .................................................................................................................................71
  7.4 Pavement Conditions .............................................................................................................................72
  7.5 Asymmetric Design ...............................................................................................................................73
  7.6 Control Systems .....................................................................................................................................73
  7.7 Lessons Learned .....................................................................................................................................74

8 References ......................................................................................................................................................75

Appendix A: Prior Work .................................................................................................................................76
Appendix B: Written Evaluation Form ...........................................................................................................78
Appendix C: Written Evaluation Comments ................................................................................................80
Appendix D: Product Specifications ...............................................................................................................110
Appendix E: Preliminary Luminaire Testing ................................................................................................115
Appendix F: Luminance Calculations .............................................................................................................133
Appendix G: Procedure ...................................................................................................................................166
Appendix H: Written Evaluation Findings ......................................................................................................170
Appendix I: Written Evaluation Results – Duplicate Participant Analysis ....................................................172
Appendix J: User Field Test Results ...............................................................................................................177
Appendix K: Public Outreach ........................................................................................................................183