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Municipal Solid-State STREET LIGHTING CONSORTIUM

GATEWAY Demonstrations

Demonstration of LED Street Lighting

Host Site: City of Kansas City, Missouri

June 2013

Prepared for:

Solid-State Lighting Program
Building Technologies Office
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Prepared by:

Pacific Northwest National Laboratory

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Demonstration of LED Street Lighting in Kansas City, MO

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June 2013

Prepared for
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Preface

This document provides an evaluation of a lighting demonstration project conducted under the U.S. Department of Energy (DOE) GATEWAY Solid-State Lighting (SSL) Technology Demonstration Program (GATEWAY), in support of the Municipal Solid-State Street Lighting Consortium (MSSLC). GATEWAY conducts demonstrations of high-performance SSL products in order to develop empirical data and experience with applications of this advanced lighting technology. The MSSLC develops and shares information on solid-state lighting technology among owners and users of public street and area lighting. Both endeavors focus on providing independent, third-party data for use in decision making by lighting users and professionals; however, the data contained herein should always be considered in combination with other information relevant to the application(s) and site(s) under examination. Though products have been independently tested to establish their relative performance for purposes of the subject evaluation, DOE does not endorse any commercial product or in any way guarantee that users will achieve the same results through use of these products.

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Executive Summary

This report documents a study of nine different light-emitting diode (LED) street lighting products installed in February 2011 as replacements for incumbent high-pressure sodium (HPS) luminaires in the city of Kansas City, Missouri (KCMO). The subject lighting investigation was undertaken by the city as part of a continued focus on improving street safety that had begun with an earlier extensive upgrade to the streetlighting system in the late 1990s, which substantially improved both the quantity and uniformity of its lighting. The current study was conducted in support of the U.S. Department of Energy's Municipal Solid-State Street Lighting Consortium, via support of the GATEWAY Solid-State Lighting Technology Demonstration Program, and involved multiple staff from different organizations employing a variety of meters and procedures.

The street lighting applications investigated span four different incumbent wattage categories, including 100 W, 150 W, 250 W, and 400 W. Initial measurements and comparisons included power, illuminance, and luminance (with luminance restricted to only four of the nine locations); sample illuminance readings have continued at each of the nine locations at roughly 1,000-hour operating intervals since then. Because the luminaires were donated—and because prices for lighting products are affected by a host of factors that make fixed assumptions about pricing problematic—an economic analysis was not completed.[1]

Readers should use caution in comparing the documented performance of one product in one location against the performance of a different product installed somewhere else. Relatively speaking, the Kansas City site locations offered fairly uniform conditions and installations that closely matched the city's lighting specifications, but *identical* sites are rarely found anywhere. In this report, results on different streets that are within a few percentage points of one another should be considered equivalent.

Table ES.1 summarizes the results between the LED products and the original HPS luminaires they replaced. All of the LED products consumed less power than their HPS counterparts—with a mean difference of 39% and a range of 31% to 51%—but they also emitted 31% fewer lumens, on average. The net result is just a 15% increase in mean efficacy. Two of the LED products actually had lower efficacies than the products they replaced. These results partly stem from the opposing tendencies of LEDs to become less efficacious as their power use increases while HPS luminaires become more efficacious, skewing the averages when all values are lumped together. Note that even with lower efficacies, higher power products may still save considerably more energy in terms of absolute magnitude.

All of the chosen LED products emitted fewer lumens than the HPS luminaires they replaced, but only six of the LED products resulted in lower mean roadway illuminance according to field measurements. Six of the LED products also delivered a higher percentage of emitted lumens to the roadway[2] than their HPS counterparts, and had higher application efficacies as well, most likely because of the better targeted optical system allowed by LED technology. The delivery efficiency for one LED

[1] An economic analysis will be included in a future report as part of the city's planned LED conversion program.
[2] Calculated by multiplying the measured average illuminance (in footcandles) across the target area by that area (in square feet), divided by the luminaire total output (in lumens) as documented by laboratory measurement. Note that sidewalk illumination has not been considered in the table, which includes only the vehicular lanes; doing so would likely boost the apparent performance of some products and reduce that of others.

product (type G; Table ES.1) appeared to exceed 100% due to the unusually large contribution of spill light from an adjacent parking lot. Delivery efficiency and application efficacy at other sites have likely also been increased, though in less obvious fashion (note that spill light makes the same illuminance contribution to both LED and HPS measurements at any given site, but probably differs from site to site).

Table ES.1. Comparison of LED and HPS initial performance at the nine demonstration sites

Site Label	**LED A**	**LED B**	**LED C**	**LED D**	**LED E**	**LED F**	**LED G**	**LED H**	**LED I**
Category	**150**	**100**	**250**	**250**	**400**	**400**	**150**	**250**	**100**
Lab Measured Input Power (W)	122	68	146	206	291	284	130	195	63
Lab Measured Output (lm)	7,698	5,391	10,277	11,952	21,739	21,413	8,455	14,021	5,304
Lab Measured Efficacy (lm/W)	63.3	79.5	70.4	58.1	74.6	75.4	65.2	72.1	84.6
Measured Road Illuminance (fc)	0.99	0.92	1.24	1.69	2.76	1.45	1.70[(a)]	1.66	0.81
Pole Spacing (ft)	147	115	173	180	179	171	144	175	154
Area of Roadway (ft^2)	4,704	3,680	5,536	5,760	5,728	5,472	6,336	5,600	3,696
Delivered Lumens	4,674	3,379	6,864	9,759	15,785	7,952	10,782[(a)]	9,307	3,006
Delivery Efficiency[(b)]	61%	63%	67%	82%	73%	37%	128%[(a)]	66%	57%
Application Efficacy (lm/W)[(c)]	38.4	49.8	47.0	47.4	54.2	28.0	83.1[(a)]	47.9	48.0

Site Label	**HPS A**	**HPS B**	**HPS C**	**HPS D**	**HPS E**	**HPS F**	**HPS G**	**HPS H**	**HPS I**
Category	**150**	**100**	**250**	**250**	**400**	**400**	**150**	**250**	**100**
Lab Measured Input Power (W)	189	128	296	296	446	446	189	296	128
Lab Measured Output (lm)	12,227	6,432	19,573	19,573	32,020	32,020	12,227	19,573	6,432
Lab Measured Efficacy (lm/W)	64.9	50.1	66.0	66.0	71.8	71.8	64.9	66.0	50.1
Measured Road Illuminance (fc)	1.72	1.00	1.80	1.93	3.21	2.87	1.34	1.59	0.73
Pole Spacing (ft)	147	115	173	180	179	171	144	175	154
Area of Roadway (ft^2)	4,704	3,680	5,536	5,760	5,728	5,472	6,336	5,600	3,696
Delivered Lumens	8,098	3,678	9,958	11,135	18,396	15,704	8,495[(a)]	8912	2,694
Delivery Efficiency[(b)]	66%	57%	51%	57%	57%	49%	69%[(a)]	46%	42%
Application Efficacy (lm/W)[(c)]	43.0	28.6	33.6	37.6	41.3	35.2	45.1[(a)]	30.1	21.0

(a) Measured value includes significant contributions from adjacent site lighting (spill light).

(b) *Delivery efficiency* is calculated as the quotient of lumens delivered to the target area (in this case, vehicular travel lanes) and the laboratory measured lumen output. **This metric should not be used to compare luminaires installed in different locations due to individual differences in site geometries and other relevant factors; i.e., comparisons in the table can be made vertically between the incumbent HPS and its replacement LED located in the same column, but such comparisons are not valid across columns.**

(c) *Application efficacy* is calculated as the quotient of total lumens delivered to the target area (in this case, vehicular travel lanes) and the laboratory measured input power of the luminaire. **This metric is subject to the same column restriction as stated in note (b).**

GATEWAY and other studies of LED installations often stress the importance of matching products to the application. The variability of applications in the real world makes this a formidable challenge for all lighting, LED and non-LED alike. The latter is illustrated even for the carefully designed HPS system in Table ES.1 by the disparity between the delivery efficiencies of sites HPS B and HPS I. Both of these sites employed the *same* HPS luminaire, but have different pole spacing and street widths that cause that luminaire's suitability to vary accordingly, at least as suggested by this particular metric.

As a group, the LED products tended to be slightly more efficacious than their HPS counterparts, but provided more substantial energy savings by reducing overall light levels and limiting spill light. In some

cases, the reduced levels met the desired performance levels, but in others they did not (or were so predicted in calculations). For purposes of a pilot project, it was not necessary that all of the selected products meet all of the specified criteria to still provide value in the study. The selected products did offer the best performance out of those submitted for consideration, however.

A primary concern in terms of meeting required lighting levels often involves future, or maintained, levels rather than initial levels. However, there is no currently recommended method for calculating the lamp lumen depreciation (LLD) light loss factor that accounts for differences in lumen maintenance for LED luminaires—the Illuminating Engineering Society (IES) Lighting Handbook, 10th Ed. simply recommends that all LED luminaires incorporate an LLD of not greater than 0.70. In this case, based on the city's preference, the evaluation incorporated cumulative light loss factors of 0.63 (LLD = 0.7, lumen dirt depreciation [LDD] = 0.9) for the residential sites (100 W replacements) and 0.56 (LLD = 0.7, LDD = 0.8) for commercial/industrial sites which is their standard practice for conventional luminaires. Applying these light loss factors to the initial measured data meant that five of the LED products (types A, C, D, F, and H) and the HPS luminaires at two of the sites (C and D) were predicted to eventually not meet the specified mean illuminance over time (see Table ES.2).

In keeping with the noted emphasis on safe streets, however, KCMO closely monitors their illuminance and requires active compliance with the stated design criteria. This effectively means that the HPS lamps at sites C and D, for example, will be replaced at some point *before* the calculated maintained illuminance is reached in those locations. Presumably, a similar situation would apply to LED products as well; any product reaching the specified average maintained illuminance will be replaced at that time rather than being allowed to operate below the required level. The net effect is that some LED products will be replaced sooner than their claimed lifetime, just as the HPS lamps will be in locations C and D.

Table ES.2. Maintained illuminance values for the roadway, predicted from measured initial values

Site Label	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Category	**150**	**100**	**250**	**250**	**400**	**400**	**150**	**250**	**100**
Design Criteria									
E_{avg} (lux)	6.3	4.4	12.0	12.0	17.0	17.0	6.3	12.0	4.4
$E_{avg/min}$	6:1	6:1	2.9:1	2.9:1	2.5:1	2.5:1	6:1	2.9:1	6:1
LED									
Total LLF	0.56	0.63	0.56	0.56	0.56	0.56	0.56	0.56	0.63
Minimum (lux)	3.7	4.0	2.4	2.3	4.9	3.6	4.9	4.2	2.3
Mean (lux)	6.0[(a)]	6.2	7.5	10.2	16.6	8.8	10.3	10.0	5.5
Maximum (lux)	9.6	11.7	21.4	24.5	37.6	17.8	21.8	20.4	9.5
Avg/Min	1.6:1	1.6:1	3.1:1	4.5:1	3.4:1	2.4:1	2.1:1	2.4:1	2.4:1
Max/Min	2.6:1	3.0:1	8.9:1	10.8:1	7.6:1	4.9:1	4.5:1	4.9:1	4.1:1
HPS									
Total LLF	0.68	0.68	0.54	0.54	0.54	0.54	0.68	0.54	0.68
Minimum (lux)	2.2	2.9	3.0	2.5	7.0	7.2	3.0	3.6	1.0
Mean (lux)	12.6	7.3	10.5	11.2	18.7	16.7	9.8	9.2	5.3
Maximum (lux)	36.2	18.2	38.4	38.9	56.4	52.5	23.3	31.6	15.6
Avg/Min	5.6:1	2.6:1	3.5:1	4.4:1	2.7:1	2.3:1	3.3:1	2.5	5.6:1
Max/Min	16.3:1	6.4:1	12.7:1	15.3:1	8.0:1	7.3:1	7.8:1	11.3:1	16.4:1

(a) Red values did not meet the specification.

Note, however, that the specific point in time that a given LED product reaches the corresponding minimum illumination may be well into the distant future (as much as 30 years after installation according to the different manufacturer specification sheet estimates). The challenge is that, in contrast with HPS products, at present there is no long-term field data for LED products to confirm the validity of these projections. Moreover, failure to meet the specified lighting levels is not strictly a product failure per se, but rather a consequence of an undersized luminaire. These luminaires likely could be sized in output to meet the specified levels over their entire projected lifetimes, although doing so would also increase cost and energy use, neither of which was estimated here. A more practical approach for a given investment might be to select a desired lifetime (e.g., 12 or 15 years) and determine whether the illumination levels from each product are expected to meet the specification at that point.

An interesting finding from the continuing series of illuminance readings is the apparent relative influence of seasonal variables such as temperature and foliage on luminaire output and/or measured illuminance. Figure ES.1 compares measured illuminance to ambient temperature over time for the LED luminaires. The illuminance measurements have been converted to relative values (i.e., percent of their initial values), determined from the mean of the roadway points that were measured at every interval.[1] The hours of operation listed below the chart are approximate; precise measurement dates were determined by local weather conditions, being occasionally delayed by rain or snow. The initial value for luminaire type F was excluded because one of the luminaires was not operating at full power at the time of initial measurement and was ultimately replaced; in this instance, values were instead normalized to the measurement at 3,000 hours, when the ambient temperature was most similar to the initial reading.

For most of the luminaire types over this period of measurement, it appears that seasonal variables such as temperature and foliage drive as much as a 20% swing in measured illuminance, and the effect appears as high as 40% for one product. The latter site was also found to have contributions from spill light of up to 25% of the measured illuminance when no leaves were present on the neighboring trees, significant portions of which may be blocked during other times of the year. In any case, it appears that the influence of seasonal fluctuations on measured illuminance may significantly outweigh any temporal lumen or dirt depreciation, at least during the early stages of product life. [2]

[1] All values following Time 0 are based on measurements from a subset of eight points at each site.
[2] It must also be noted that ambient temperature has some influence on the light meter detector head and thus the readings obtained from it; the individual contributions from these two factors (meter temperature sensitivity and varying luminaire output) cannot be determined from the recorded data.

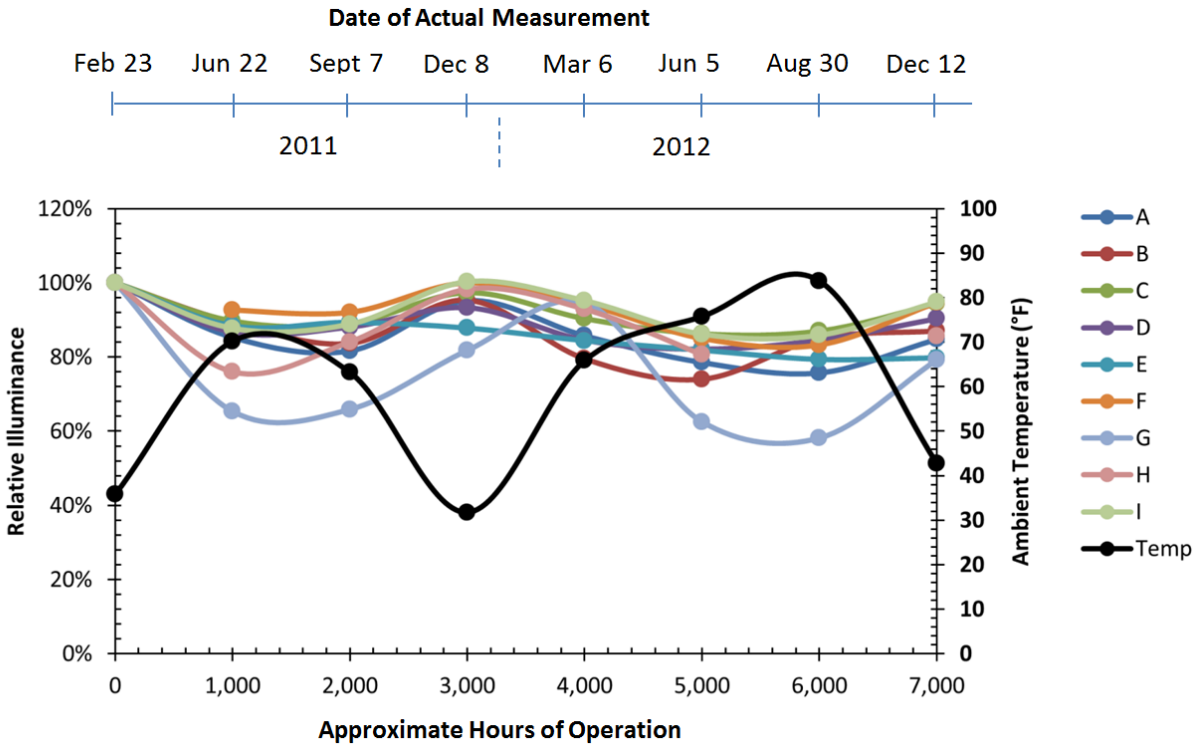

Figure ES.1. Relative illuminance over time versus to ambient temperature at the time of measurement[1]

The marked variations in the figure underscore the importance of taking multiple measurements under a variety of seasonal conditions. Decisions or conclusions drawn from any single set of the readings above would clearly risk neglecting the "full picture" of operation. Readers are advised to keep such real-world influences in mind when conducting similar investigations of their own, and moreover to remember that field measurements are only one component of a more comprehensive performance assessment.

[1] The connecting lines in the graph are included only for convenience in following individual data sets (including temperature) and may or may not reflect actual values during the periods between the measured points.

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Acronyms and Abbreviations

BUG	backlight, uplight, and glare
CALiPER	Commercially Available Light-Emitting Diode Product Evaluation and Reporting
CCT	correlated color temperature
cd	candela(s)
CRI	color rendering index
DOE	U.S. Department of Energy
EPRI	Electric Power Research Institute
fc	footcandle(s)
HPS	high-pressure sodium
IES	Illuminating Engineering Society of North America
K	kelvin
KCMO	City of Kansas City, Missouri
KCP&L	Kansas City Power & Light
LDD	luminaire dirt depreciation
LED	light-emitting diode
LLD	lamp lumen depreciation
LLF	light loss factor
lm	lumen(s)
lm/W	lumen(s) per watt
MSSLC	Municipal Solid-State Street Lighting Consortium
SSL	solid-state lighting

Table of Contents

Preface iii
Executive Summary v
Acknowledgements x
Acronyms and Abbreviations xi
1.0 Introduction 1.1
2.0 Site Description 2.1
3.0 Luminaires 3.1
3.1 Design Specifications 3.1
3.2 LED Product Selection 3.1
3.3 Comparison of Manufacturer Data and Independent LM-79 Test Data 3.3
3.4 Illuminance Calculated from Manufacturers' Submissions 3.5
4.0 Field Measurements 4.1
4.1 Measured Illuminance 4.1
4.2 Measured Luminance 4.3
5.0 Discussion 5.1
5.1 Comparisons Between Measurement Methods 5.1
5.2 Comparisons Between Measured and Calculated Illuminance 5.3
5.3 Comparison of Performance over Time 5.5
5.4 Performance Evaluation and Product Comparisons 5.7
5.5 Light Loss Factors and Design Life 5.9
6.0 Conclusions 6.1
7.0 References 7.1
Appendix A Measurement Graphics of Each Street, Including Photos A.1
Appendix B Kansas City Luminaire Performance Tables for Each of the Evaluated Subject Wattages B.1
Appendix C Complete Set of Metrics Including Sidewalks C.1
Appendix D Meter Data D.1

Figures

Figure ES.1. Relative illuminance over time versus to ambient temperature at the time of measurement ix
Figure 2.1. Residential street lighting demonstration sites 2.1
Figure 2.2. Commercial/industrial street lighting demonstration sites 2.2
Figure 3.1. Comparison of measured and rated lumen output 3.5
Figure 5.1 The Pushey illuminance meter device 5.2
Figure 5.2 Scotty 5.2
Figure 5.3. Large contributions from spill light evident for site G 5.5
Figure 5.4. Relative illuminance over time versus to ambient temperature at the time of measurement 5.6
Figure 5.5. HPS spill light sources and trees causing seasonal variation at site G 5.7

Tables

Table ES.1. Comparison of LED and HPS initial performance at the nine demonstration sites vi
Table ES.2. Maintained illuminance values for the roadway, predicted from measured initial values vii
Table 3.1. Kansas City streetlight illumination specifications 3.1
Table 3.2. Kansas City LED pilot project locations and detail 3.2
Table 3.3. Selected demonstration products, including existing HPS and new LED 3.2
Table 3.4. Manufacturer data obtained from IES-format files (output and distribution information) or specification sheets (color information) 3.3
Table 3.5. Performance data for one sample of each product tested by independent testing lab 3.4
Table 3.6. Calculated initial and maintained illuminance values for the roadway 3.6
Table 4.1. Measured initial illuminance values for the roadway 4.2
Table 4.2. Maintained illuminance values for the roadway, predicted from measured initial values 4.3
Table 4.3. Measured initial luminance values for the roadway 4.4
Table 4.4. Maintained luminance values for the roadway, predicted from measured initial values 4.4
Table 5.1. Example variations in lighting measurements from different handheld meters, using the same measurement points 5.3
Table 5.2. Example variations in illuminance measurements from different meters and different measurement methodologies 5.3
Table 5.3. Comparison of measured and calculated performance using estimated field conditions 5.4
Table 5.4. Relative illuminance over time compared to ambient temperature 5.6
Table 5.5. Comparison of LED and HPS performance at the nine demonstration sites 5.8

1.0 Introduction

This report discusses the results from a street lighting demonstration conducted in Kansas City, MO, under the auspices of the U.S. Department of Energy (DOE) Municipal Solid-State Street Lighting Consortium (MSSLC). The evaluation was conducted via support of the GATEWAY Solid-State Lighting Technology Demonstration Program.

The subject demonstration entailed the installation and evaluation of nine different light-emitting diode (LED) products that had been selected by the City of Kansas City, Missouri (KCMO) and its consultant, Kauffmann Consulting, LLC, from a larger group offered by manufacturers for the study's use. Selection followed a set of pre-analysis calculations to determine if each of the products adequately met the required performance criteria based on manufacturer-provided photometric files. For purposes of a pilot project, it was not necessary that all of the selected products meet all of the specified criteria to still be of value in the study, although the selected products did offer the best performance out of those submitted for consideration. Installation occurred in February 2011; field measurements were taken initially and have continued at roughly 1,000-hour operating intervals since then.

Multiple organizations participated in the demonstration, including in the product and site selection and in taking measurements. MSSLC members also contributed.

As this study progressed, more sources of variation in the numerous measurements obtained were identified and documented to the greatest extent possible. These additional findings have served to stimulate ancillary discussion of the effectiveness of field measurements in general. A number of such observations accompany the reported values throughout the document.

2.0 Site Descriptions

Public safety is a primary consideration for KCMO. From 1997 to 2001 the city purchased and upgraded their streetlighting system to provide a safer environment for its citizens. Poles and luminaires were moved and supplemented to provide a streetlighting system with maintained lighting levels, uniformities, and glare control exceeding minimum recommended levels. As a result, conditions were notably uniform and predictable with regard to parameters such as pole spacing and consistency of luminaire performance, making the city an excellent candidate for a pilot demonstration project.

A number of potential areas were initially identified based on their proximity to the KCMO public works facility, which facilitated access for work related to the evaluation. Several streets within those areas were then pre-screened to identify candidates with conditions favorable for measurement and comparison, including low night traffic, relatively low levels of vegetation, uniform elevations with little geographic variation, and lower contributions of spill light from other sources. The nine streets that best met the desired conditions were then selected for the demonstration project.

The final selections included a variety of residential and collector roads, as illustrated in Figure 2.1 and Figure 2.2. The letter identifiers attached to each location correspond to the tabulated values provided throughout this report. Graphics and photos of each street are included in Appendix A.

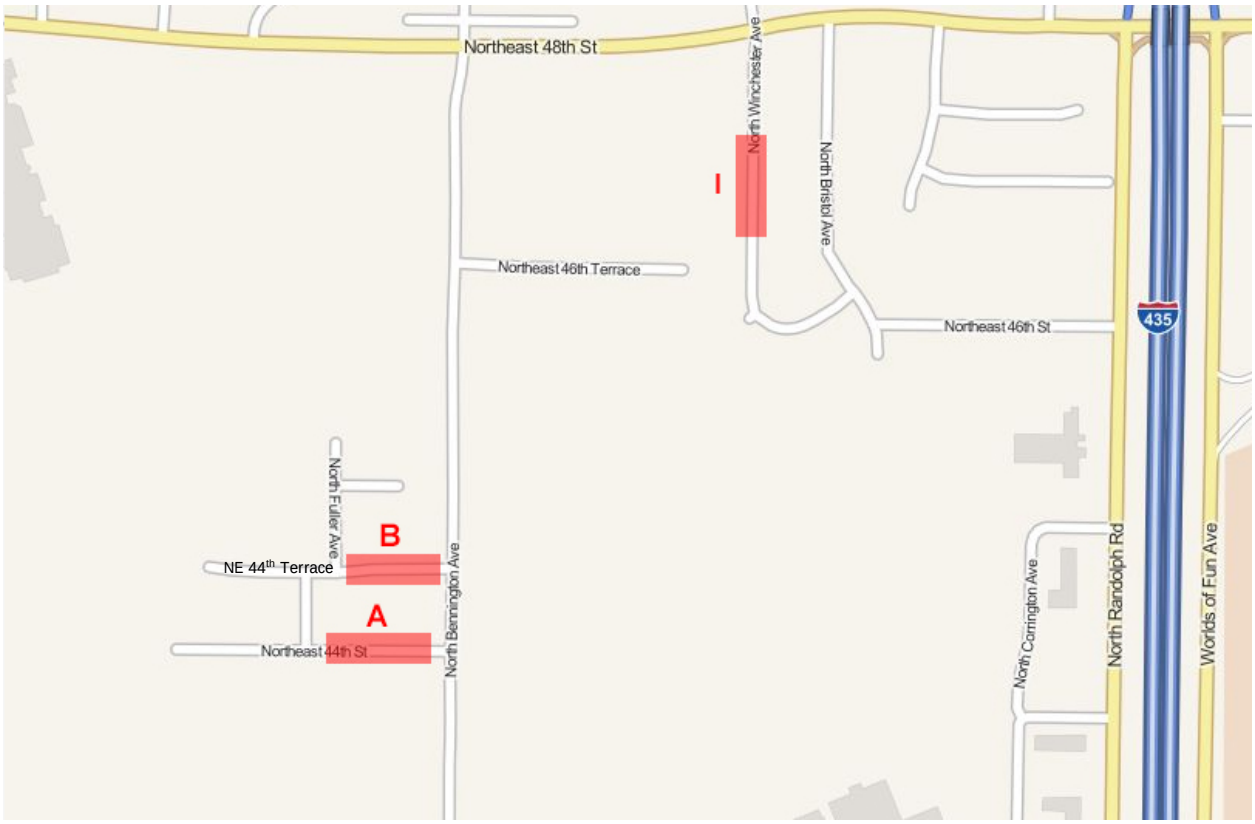

Figure 2.1. Residential street lighting demonstration sites

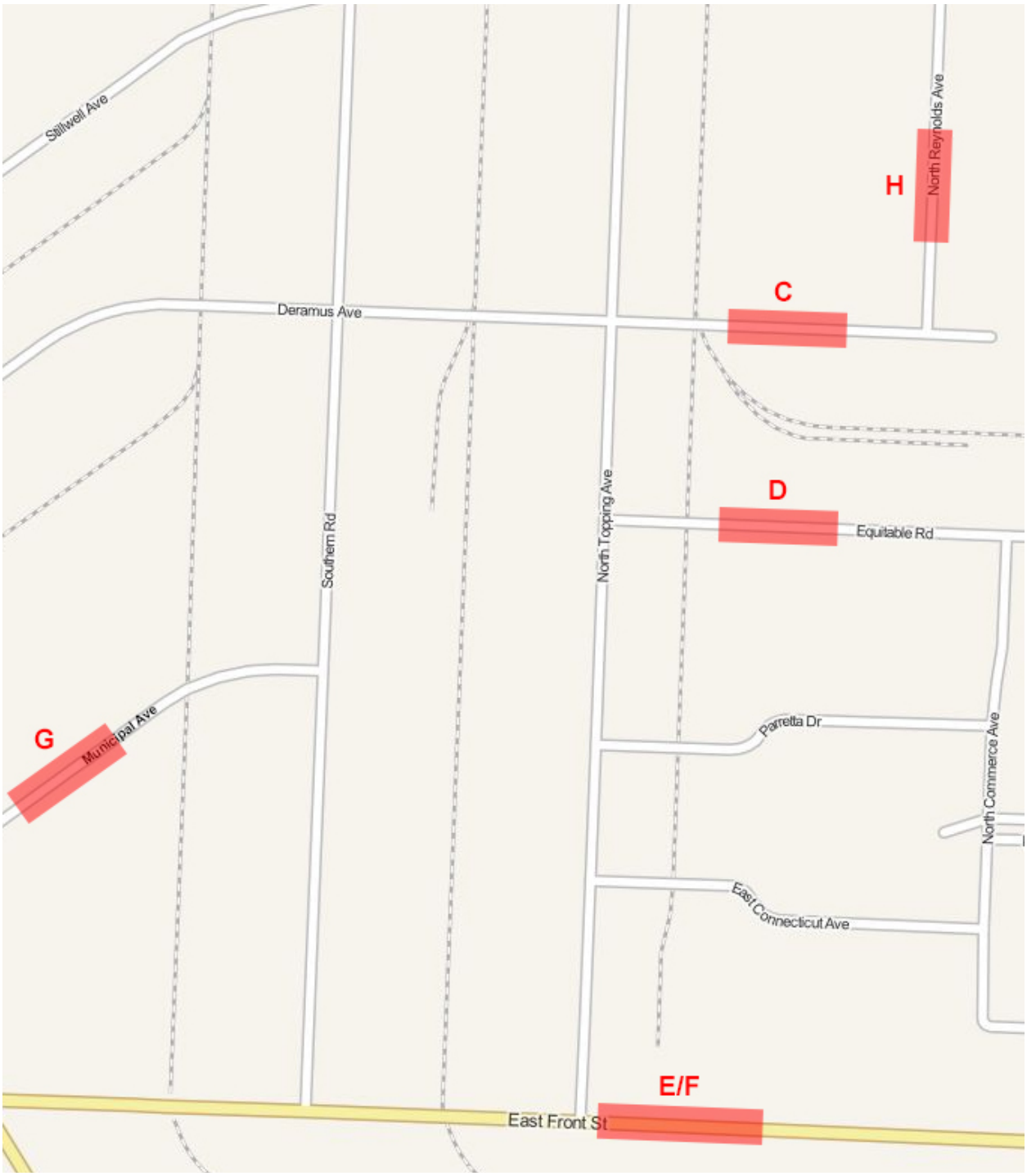

Figure 2.2. Commercial/industrial street lighting demonstration sites

3.0 Luminaires

This project set out to investigate LED replacement products across the various wattages representative of the incumbent high-pressure sodium (HPS) streetlights used in Kansas City's system (100 to 400 W). An intent of the project plan was to demonstrate no more than one LED product from each manufacturer across the applications evaluated, thus maximizing the number of different manufacturers and products reviewed. From an MSSLC demonstration perspective, this level of variety also enabled a potentially broader set of comparisons and conclusions while undertaking the investigation.

3.1 Design Specifications

Kansas City designs its street lighting to specifications it publishes in the form of luminaire performance tables. Table 3.1 summarizes the specifications used in this study. The complete luminaire performance table for each of the evaluated subject wattages is provided in Appendix B.

Table 3.1. Kansas City streetlight illumination specifications

Site Type	IES	LLF	Luminaire Distribution	Nominal Spacing (ft)	Mounting Height (ft)	Road E_{avg} (lux)	Road $E_{avg:min}$	Sidewalk E_{avg} (lux)	Sidewalk $E_{avg:min}$
100 W HPS	R3	0.63	B2-U3-G1	156	27.50	4.4	6.0:1	1.8	7.0:1
150 W HPS	R3	0.56	B2-U3-G2	165	29.75	6.3	6.0:1	2.0	5.3:1
250 W HPS	R3	0.56	B3-U3-G3	180	35.00	12.0	2.9:1	5.7	2.7:1
400 W HPS	R3	0.56	MCO III	180	35.00	17.0	2.5:1	9.0	2.7:1

IES is Illuminating Engineering Society; LLF is light loss factor.

Concurrent with this demonstration, the MSSLC was developing the *Model Specification for LED Roadway Luminaires* (MSSLC 2013) and had prepared a first draft that was still untested in an actual installation. The Kansas City demonstration served as a useful pilot of the specification and yielded valuable preliminary feedback to the development team.

Kansas City's luminaire performance requirements were clear and made for a very straightforward process of adapting the MSSLC model specification. Kansas City preferred to substitute its own quality assurance section into the document, but otherwise made only minor edits beyond inserting the necessary illumination and electrical values from their relevant performance requirements.

3.2 LED Product Selection

Existing HPS systems on the selected streets were divided into four groups based on nominal input power: 100 W, 150 W, 250 W, and 400 W. LED luminaires meeting the specification for a given wattage HPS luminaire (i.e., deemed a suitable replacement) were then assigned to individual street locations, based on a one-for-one replacement using existing poles and arms.

The existing HPS luminaires at nine sites were replaced with LED products, with each site entailing five complete luminaire cycles (i.e., five poles on a side). Of these sites, two were 100 W HPS installations, two were 150 W HPS, three were 250 W HPS, and two were 400 W HPS. Installation of the

LED luminaires proceeded smoothly with no significant issues. Incumbent luminaire wattages and other details of the specific streets selected for this evaluation are provided in Table 3.2, along with site labels that correspond to the maps provided in section 2.0. Details on the installed products and their corresponding locations are included in Table 3.3.

Table 3.2. Kansas City LED pilot project locations and detail

Site Label	Street	Vehicle Lane(s)	Sidewalk(s)	Actual Pole Spacing (ft)	Actual Pole Height (ft)	Existing Luminaire
A	NE 44th Street	2 × 16 ft	2 × 5 ft (6 ft offset)	147	30.00	150 W HPS
B	NE 44th Terrace	2 × 16 ft	2 × 5 ft (6 ft offset)	115	30.00	100 W HPS
C	Deramus Ave	2 × 16 ft	2 × 5 ft (6 ft offset)[(b)]	173	32.75	250 W HPS
D	Equitable Ave	2 × 16 ft	2 × 5 ft (6 ft offset)[(b)]	180	32.75	250 W HPS
E	Front Street Eastbound	2 × 16 ft	1 × 5 ft (6 ft offset)[(b)]	179	34.75	400 W HPS[(a)]
F	Front Street Westbound	2 × 16 ft	1 × 5 ft (6 ft offset)[(b)]	171	34.75	400 W HPS
G	Municipal Ave	4 × 11 ft	2 × 5 ft (6 ft offset)[(b)]	144	32.75	150 W HPS
H	Reynolds Ave	2 × 16 ft	2 × 5 ft (6 ft offset)[(b)]	175	32.75	250 W HPS
I	N. Winchester Ave	2 × 12 ft	2 × 4 ft (5 ft offset)[(b)]	154	27.75	100 W HPS

(a) One of the luminaires in this location was a 250 W HPS.
(b) Although the specification includes sidewalks, there were no physical sidewalks at these sites. Corresponding measurements were made in grass.

Table 3.3. Selected demonstration products, including existing HPS and new LED

Site Label	Manufacturer	Product Family	Model Number
A	BetaLED	LEDway	STR-LWY-2M-HT-10-C-UL-SV-350-R-43K
B	Philips Roadway Lighting	Roadstar	GPLS-65W49LED4K-LE2
C	GE Lighting Solutions	Evolve	ERMC-0-C3-43-A-2-GRAY
D	LED Roadway	Satellite	S96M-0-R-GS-2-NN-G3-GBQ-B1G-LF
E	Cooper Lighting	Streetworks Ventus	VSTA12LEDEUT2SBZ
F	Lighting Science Group	Prolific	DBR2 CW R3 MVOLT 4B
G	American Electric Lighting	Series LEDR	LEDR 15LED E35 MVOLT AR3
H	Philips Roadway Lighting	Roadstar	GPLS-180W98LED4K-LE2
I	Sunovia/Evolucia	SCHX5	SCHX5/65-43/PAL/T2/277/LG
A; 150 HPS-GE	GE Lighting Solutions	M250A2 Powr/Door	M2AC-15S3M1GMC21F + LU150/H/ECO
B; 100 HPS-GE	GE Lighting Solutions	M250A2 Powr/Door	M2AC-15S3M1GMC21F + LU100/H/ECO
I; 100 HPS-AEL	American Electric Lighting	Roadway Series 115	115 13S + LU100/H/ECO
G; 150 HPS-AEL	American Electric Lighting	Roadway Series 115	115 14S + LU150/H/ECO
C/D/H; 250 HPS-AEL	American Electric Lighting	Roadway Series 115	115 25S + LU250/H/ECO
E/F; 400 HPS-AEL	American Electric Lighting	Roadway Series 115	115 40S + LU400/H/ECO

3.3 Comparison of Manufacturer Data and Independent LM-79 Test Data

Manufacturer data, derived from specification sheets and IES-format files, provided by the product manufacturers as part of their submittal packages, are shown in Table 3.4. It is important to emphasize that product submittals were based on meeting the design criteria (provided in Table 3.1) rather than achieving equivalent lumen output to the HPS product being replaced. Notable differences between the HPS and LED products in any given bracket should therefore be expected when reviewing the data.

One sample of each product was sent to an independent testing laboratory to verify performance. The testing was performed using absolute photometry for both LED and HPS products. Testing results are shown in Table 3.5, and Figure 3.1 compares graphically the measured values of lumen output with those listed by the manufacturers. Two of the LED products (B and G) had measured lumen outputs that varied by more than 10% from the listed value. In both cases, the measured luminaire emitted fewer lumens than claimed, although both were also accompanied by commensurate reductions in input power.

Table 3.4. Manufacturer data obtained from IES-format files (output and distribution information) or specification sheets (color information)

Tag or Site Label	Input Power (W)	Lamp Output (lm)	Luminaire Efficiency (%)	Luminaire Output (lm)	Luminaire Efficacy (lm/W)	CCT (K)	CRI	Distribution	BUG Rating
100 HPS-AEL	120	9,500	84	7,983	67	2000	30	Type 3 Medium	B1 U3 G2
150 HPS-GE	183	16,000	67	10,645	58	2000	30	Type 3 Medium	
B	73	-	-	6,048	83	4000	70	Type 2 Short	B2 U0 G1
I	64	-	-	5,389	85	4300	70	Type 2 Short	B1 U0 G1
150 HPS-AEL	175	16,000	84	13,445	77	2000	30	Type 3 Medium	B2 U3 G3
100 HPS-GE	120	9,500	67	6,320	53	2000	30	Type 3 Medium	
A	122	-	-	7,732	63	4300	70	Type 2	B2 U2 G2
G	149	-	-	9,650	65	4900	70	Type 2 Medium	B2 U1 G2
250 HPS-AEL	285	27,500	80	21,990	77	2000	30	Type 3 Medium	B3 U3 G3
C	157	-	-	10,200	65	4300	70	Type 3 Medium	B3 U0 G3
D	201	-	-	11,986	60	5000	88	Type 3 Short	B2 U0 G2
H	200	-	-	13,974	70	4000	70	Type 2 Medium	B2 U0 G2
400 HPS-AEL	400	50,000	80	39,982	100	2000	30	Type 3 Medium	B4 U4 G5
E	299	-	-	20,549	69	4000	70	Type 2 Short	B3 U0 G2
F	300	-	-	22,712	76	5000	70	Type 3 Short	B3 U0 G3

BUG is backlight, uplight, and glare; CCT is correlated color temperature; CRI is color rendering index; K is kelvin; lm/W is lumens per watt.

In contrast, all four of the tested HPS luminaires emitted substantially fewer lumens—and hence had lower efficacies—than the value listed in the corresponding manufacturer information. A likely contributor to this difference is the fact that GATEWAY tested the luminaires using *absolute* photometry to enable direct comparisons of performance with the LED luminaires, whereas standard industry practice for conventional luminaires employs *relative* photometry, which measures lamps and fixtures

independently. Differences between absolute and relative photometry have been noted in other DOE publications.[1]

Table 3.5. Performance data for one sample of each product tested by independent testing lab[(a),(b)]

Tag	Input Power (W)	Luminaire Output (lm)	Luminaire Efficacy (lm/W)	CCT (K)	CRI	Distribution	BUG Rating
100 HPS-AEL	128	6,432[(c)]	50.1	1989	12	Type 2 Medium	B2 U3 G2
B	68	5,391	79.5	4193	69	Type 2 Short	B1 U1 G1
I	63	5,304	84.6	4522	75	Type 2 Medium	B1 U1 G2
150 HPS-AEL	189	12,227	64.9	2112	15	Type 3 Medium	B4 U2 G4
A	122	7,698	63.3	4397	81	Type 2 Medium	B2 U2 G2
G	130	8,455	65.2	4807	68	Type 2 Medium	B2 U1 G2
250 HPS-AEL	296	19,573	66.0	2000	23	Type 3 Short	B3 U1 G3
C	146	10,277	70.4	4547	75	Type 3 Short	B3 U1 G3
D	206	11,952	58.1	5018	69	Type 2 Short	B2 U2 G2
H	195	14,021	72.1	4261	70	Type 2 Medium	B3 U2 G2
400 HPS-AEL	446	32,020	71.8	2078	13	Type 3 Medium	B2 U3 G2
E	291	21,739	74.6	4187	68	Type 2 Short	B3 U2 G2
F	284	21,413	75.4	5013	68	Type 2 Short	B3 U2 G3

(a) All data obtained using absolute photometry.
(b) No laboratory measurements were made of GE HPS luminaires; thus, they do not appear in the table.
(c) Red values indicate variation of more than 10% from values reported in manufacturers' literature (see Table 3.4).

In the case of LED products, several reasons might explain a given difference between manufacturer-listed and laboratory-tested values. For instance, in this case the GATEWAY laboratory test involved only one sample. All lighting products exhibit some variation from one sample to the next, and the tested version might fall anywhere within the expected distribution. Differences may also stem from minor product updates that are not immediately reflected in the available marketing literature. Additionally, some variation among tests from different laboratories is not uncommon, though generally small among accredited testing laboratories. In the present example, all of the measured products are likely within a reasonable tolerance of the manufacturers' rated values.

One clear trend evident in Figure 3.1 is that the LED luminaires all emitted markedly fewer lumens than the HPS products they replaced. However, the LED luminaires still meet the design specification because the LED luminaires generally have better optical systems that provide superior distributions. This allows a more even illuminance distribution over the road surface, eliminating previously wasted lumens that achieved little more than over-lighted areas—or hot spots—directly beneath the incumbent HPS luminaires.

[1] For example, see related discussion of relative versus absolute photometry in http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led_energy_efficiency.pdf.

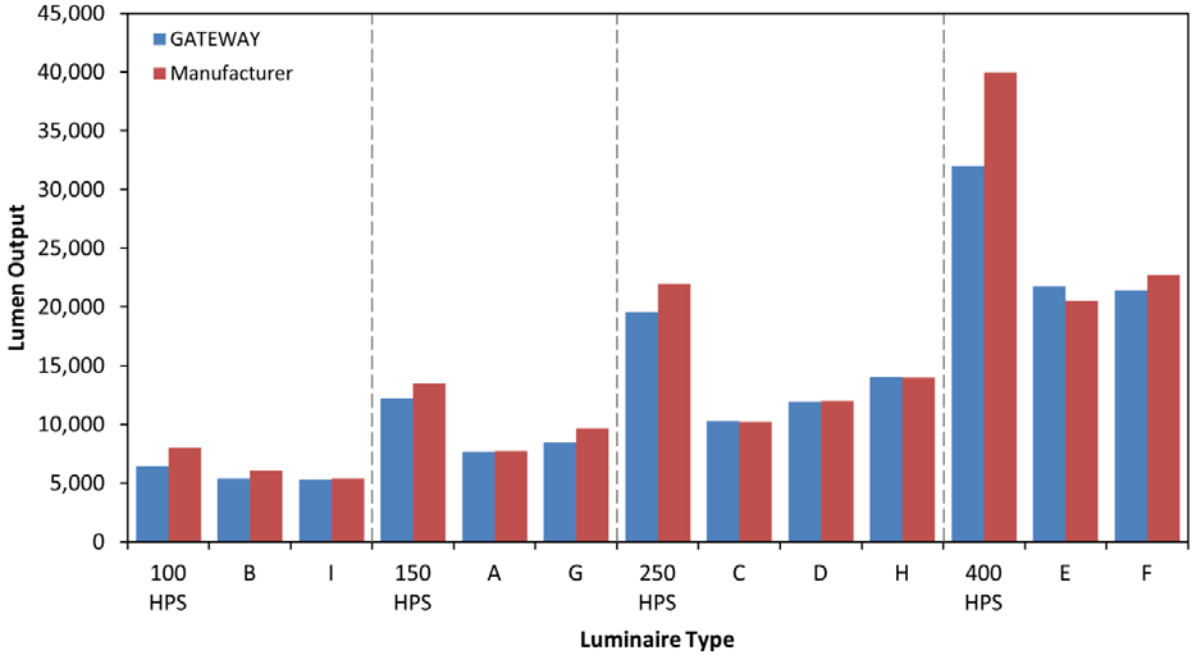

Figure 3.1. Comparison of measured and rated lumen output

3.4 Illuminance Calculated from Manufacturers' Submissions

Roadway and sidewalk illuminance levels were first calculated for each prospective luminaire type using the physical conditions established in the project specifications (Table 3.1). Manufacturer-supplied IES-format files were used as the basis for these calculations. This allowed for comparison of the expected performance versus the specification, but not against the measured illuminance because specific site conditions can vary markedly from the dimensions in the specification, as can results between listed and measured performance.

Table 3.6 lists the initial calculated values for the roadway, along with maintained illuminance values that are based on the LLF shown in the table—0.63 for 100 W replacements and 0.56 for the other types.[1] Currently, there is no recommended method for calculating the lamp lumen depreciation (LLD) light loss factor that accounts for differences in lumen maintenance for LED luminaires—the IES simply recommends that all LED luminaires incorporate an LLD of not greater than 0.70 (IES 2011, p13.8). Unfortunately, such generalizations limit the ability to accurately compare different luminaires' expected performance over time.[2] Nonetheless, estimating maintained illuminance can help identify immediate concerns about future performance.

Eight of the nine products selected for inclusion in this GATEWAY project did not strictly meet all of the requirements in the specification. Results of additional metrics are shown in Appendix C. Six of the

[1] Kansas City uses HPS light loss factors of 0.7 LLD × 0.9 luminaire dirt depreciation (LDD) = 0.63 in residential locations and 0.7 LLD × 0.8 LDD = 0.56 in commercial/industrial locations. The city wanted to use the same factors for the LED replacements.

[2] Note that the values assumed for LLF above do not consider the timeframes in which such levels might be reached. Manufacturer specification sheets in this project claimed a range of expected periods to reach an LLD of 0.7 from 50,000 hours to 121,000 hours, or 12.2 years to 29.5 years at 4,100 hours per year operation.

products did not meet the roadway illuminance criteria using the specified maintained mean illuminance calculation (types A, C, D, E, F, and G). Only product type B met all of the specified criteria, and product types H and I only fell slightly short on the sidewalk criteria (and note these sites do not actually have sidewalks present.)

The lower-wattage products tended to meet more of the criteria, and at least one product met the roadway mean illuminance criterion but not the luminance criterion. For comparison, four of the six HPS products met all of the criteria, and the two that did not missed on only two of the nine criteria.

Table 3.6. Calculated initial and maintained illuminance values for the roadway

Site Label	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Category	**150**	**100**	**250**	**250**	**400**	**400**	**150**	**250**	**100**
Design Criteria									
E_{avg} (lux)	6.3	4.4	12	12	17	17	6.3	12	4.4
$E_{avg/min}$	6:1	6:1	2.9:1	2.9:1	2.5:1	2.5:1	6:1	2.9:1	6:1
LED (Initial)									
Minimum	3.39	2.78	5.77	6.00	10.02	15.68	3.93	11.39	2.75
Mean	8.18	8.84	15.29	18.70	27.71	22.20	10.41	21.96	7.65
Maximum	14.07	21.49	36.32	37.46	51.66	33.66	25.16	34.52	16.05
Avg/Min	2.41:1	3.18:1	2.65:1	3.12:1[(a)]	2.77:1	1.42:1	2.65:1	1.93:1	2.79:1
Max/Min	4.15:1	7.74:1	6.30:1	6.24:1	5.16:1	2.15:1	6.40:1	3.03:1	5.84:1
LED (Maintained)									
Total LLF	0.56	0.63	0.56	0.56	0.56	0.56	0.56	0.56	0.63
Minimum	1.90	1.75	3.23	3.36	5.61	8.78	2.20	6.38	1.73
Mean	4.58	5.57	8.56	10.47	15.52	12.43	5.83	12.30	4.82
Maximum	7.88	13.54	20.34	20.98	28.93	18.85	14.09	19.33	10.11
Avg/Min	2.41:1	3.18:1	2.65:1	3.12:1	2.77:1	1.42:1	2.65:1	1.93:1	2.79:1
Max/Min	4.15:1	7.74:1	6.30:1	6.24:1	5.16:1	2.15:1	6.40:1	3.03:1	5.84:1

(a) Red values do not meet the applicable specification.

It is relevant to note here again that despite not meeting some of the criteria, particularly with regard to the specified future or maintained lighting levels, the products represented in the table were selected as the best candidates from among those submitted for consideration in this project. The importance of strictly meeting the maintained mean illuminance criteria, at least for initial purposes of product selection, is discussed in Section 5.5.

4.0 Field Measurements

For a variety of reasons, data measured in the field frequently differ from calculated or laboratory-measured values. In general, field measurements are less precise than laboratory measurements because there is little control over the ambient environment and related factors like site geometry, and because portable measurement equipment is typically less precise than laboratory equipment. Nonetheless, field measurements are taken because they can offer constructive insight into the effectiveness of a given installation and also help in identifying apparent problems or issues.

4.1 Measured Illuminance

Prior to the initial illuminance survey, all measurement points were marked using temporary paint. The measurement points were determined according to IES RP-8-00, Annex A procedures: vehicular travel lanes were each marked with two parallel rows of grid points at the quarter point of the lane, with each row containing 10 or 11 points. The measurements were taken between each pair of poles at the center of the string of a specific luminaire type. Each sidewalk had a single row of measurement points at the center of the path. For sites without a sidewalk, measurement points were marked down the center of the area where the sidewalk would be.

The existing HPS luminaires were cleaned and re-lamped in the weeks leading up to evaluation, and illuminance measurements taken February 21–22, 2011. The LED products were then substituted and field measurements of their corresponding initial illuminance values were taken February 22–23, 2011. The temperature and other environmental conditions varied from one illuminance survey to the next, as did the person taking the measurements and the equipment used; see section 5.0 for further discussion.

Table 4.1 compares initial measured values, using a handheld illuminance meter for the LED and HPS products at each site. Field conditions were somewhat different from the dimensions used in the submittal process, which had relied on generalized layouts for each wattage category. Thus, some differences between expected and measured performance are inevitable. This is a routine challenge for street lighting, where pole spacing and other dimensions often vary across a region; in general, the expediency of calculating performance for a representative situation outweighs the gain in accuracy that could be achieved by a full calculation (i.e., including the specifics of all sites within a region).

Table 4.1. Measured initial illuminance values for the roadway

Site Label	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Category	**150**	**100**	**250**	**250**	**400**	**400**	**150**	**250**	**100**
Design Criteria									
E_{avg} (lux)	6.3	4.4	12.0	12.0	17.0	17.0	6.3	12.0	4.4
$E_{avg:min}$	6:1	6:1	2.9:1	2.9:1	2.9:1	2.9:1	6:1	2.9:1	6:1
LED (Initial)									
Minimum (lux)	6.5	6.3	4.3	4.0	8.8	6.5	8.8	7.4	3.7
Mean (lux)	10.7	9.9	13.3	18.2	29.7	15.6[(b)]	18.3	17.9	8.8
Maximum (lux)	17.1	18.6	38.3	43.7	67.2	31.7	39.0	36.5	15.0
Avg/Min	1.6:1	1.6:1	3.1:1[(a)]	4.5:1	3.4:1	2.4:1	2.1:1	2.4:1	2.4:1
Max/Min	2.6:1	3.0:1	8.9:1	10.8:1	7.6:1	4.9:1	4.5:1	4.9:1	4.1:1
HPS (Initial)									
Minimum (lux)	3.3	4.2	5.6	4.7	13.0	13.3	4.4	6.6	1.4
Mean (lux)	18.5	10.8	19.4	20.8	34.6	30.9	14.4	17.1	7.8
Maximum (lux)	53.3	26.8	71.2	72.0	104.5	97.3	34.3	58.5	22.9
Avg/Min	5.6:1	2.6:1	3.5:1	4.4:1	2.7:1	2.3:1	3.3:1	2.5:1	5.6:1
Max/Min	16.3:1	6.4:1	12.7:1	15.3:1	8.0:1	7.3:1	7.8:1	11.3:1	16.4:1

(a) Red values did not to meet the specification.
(b) One luminaire was not properly functioning at the time of initial LED measurement at site F. The mean illuminance at 1,000 hours—after the problem was resolved—was 20.6 lux, which satisfies the design criterion.

At only three sites (G, H and I) did the LED luminaires provide a higher initial mean illuminance than the HPS luminaires they replaced. At one site (F), the LED luminaire did not meet even the initial mean illuminance criterion—of particular note given that this criterion is supposed to be met over the entire life cycle of the product. However, further inspection revealed that one of the luminaires in the measured pole cycle was malfunctioning, resulting in its replacement. At the later, 1,000-hour measurement, the mean illuminance at site F was measured at 20.6 lux, satisfying the design criterion. As for the other criteria, three of the LED products (types C, D, and E) did not meet the specified average-to-minimum ratio, although the HPS luminaires at sites C and D also showed the same issue. Importantly, in six of the nine cases, the LED product had a more favorable average-to-minimum ratio, and in all nine cases a more favorable maximum-to-minimum ratio, compared with the original HPS lighting.

Applying LLFs to the initial measured data makes it possible to estimate future performance—and thus to assess whether a product is likely to meet the design specifications over time. When this was done using the data in Table 4.1, five of the LED products (types A, C, D, F, and H) and the HPS luminaires at two of the sites (C and D) were predicted to not meet the specified mean illuminance over time (see Table 4.2).

Table 4.2. Maintained illuminance values for the roadway, predicted from measured initial values

Site Label	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Category	**150**	**100**	**250**	**250**	**400**	**400**	**150**	**250**	**100**
Design Criteria									
E_{avg} (lux)	6.3	4.4	12.0	12.0	17.0	17.0	6.3	12.0	4.4
$E_{avg/min}$	6:1	6:1	2.9:1	2.9:1	2.5:1	2.5:1	6:1	2.9:1	6:1
LED									
Total LLF	0.56	0.63	0.56	0.56	0.56	0.56	0.56	0.56	0.63
Minimum (lux)	3.7	4.0	2.4	2.3	4.9	3.6	4.9	4.2	2.3
Mean (lux)	6.0[(a)]	6.2	7.5	10.2	16.6	8.8	10.3	10.0	5.5
Maximum (lux)	9.6	11.7	21.4	24.5	37.6	17.8	21.8	20.4	9.5
Avg/Min	1.6:1	1.6:1	3.1:1	4.5:1	3.4:1	2.4:1	2.1:1	2.4:1	2.4:1
Max/Min	2.6:1	3.0:1	8.9:1	10.8:1	7.6:1	4.9:1	4.5:1	4.9:1	4.1:1
HPS									
Total LLF	0.68	0.68	0.54	0.54	0.54	0.54	0.68	0.54	0.68
Minimum (lux)	2.2	2.9	3.0	2.5	7.0	7.2	3.0	2.8	1.0
Mean (lux)	12.6	7.3	10.5	11.2	18.7	16.7	9.8	6.8	5.3
Maximum (lux)	36.2	18.2	38.4	38.9	56.4	52.5	23.3	31.1	15.6
Avg/Min	5.6:1	2.6:1	3.5:1	4.4:1	2.7:1	2.3:1	3.3:1	2.5	5.6:1
Max/Min	16.3:1	6.4:1	12.7:1	15.3:1	8.0:1	7.3:1	7.8:1	11.3:1	16.4:1

(a) Red values did not meet the specification.

Measurements were also taken on the sidewalks, or in locations where a sidewalk would typically be found, in accordance with the site drawings that were used in the submittal process. This measurement data is available in Appendix D.

4.2 Measured Luminance

Many believe that, compared with illuminance, luminance better represents what a typical driver or other user experiences in terms of visual performance, and as a result the IES recommended practice is moving toward an emphasis on luminance metrics in its associated guidance (Kauffman 2013). However, measuring luminance is generally more complicated and prone to errors, requires more expensive equipment, and is less familiar to most street lighting personnel than illuminance measurements. Questions exist as to the possible rate of transition and potential design impacts from this forthcoming change in practice; therefore, related measurements were undertaken in hopes of contributing useful information to the discussion.

Roadway luminance was measured at four of the sites (A, C, H, and I). Table 4.3 compares the results to Kansas City's published design specifications. All measured sites meet the specifications; although when LLFs are applied (Table 4.4), the luminaire at site C is expected to not meet this criterion, which matches the prediction based on illuminance. In contrast, the luminaire at site H is expected to pass the mean *luminance* criterion in the future but not the *illuminance* criterion based on the field measurements. Although the underlying sample size is small, it demonstrates a potential concern associated with using different metrics. In this case, the difference between meeting and not meeting the performance criterion—for the same product in the same location—is solely determined by the means used for measurement.

Table 4.3. Measured initial luminance values for the roadway

Site Label	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Category	**150**	**100**	**250**	**250**	**400**	**400**	**150**	**250**	**100**
Design Criteria									
L_{avg} (cd/m^2)	0.4	0.35	0.8	0.8	1.2	1.2	0.4	0.8	0.35
$L_{avg:min}$	3.3:1	3.15:1	3.2:1	3.2:1	2.1:1	2.1:1	3.3:1	3.2:1	3.15:1
$L_{max:min}$	7.2:1	6.5:1	4.8:1	4.8:1	2.9:1	2.9:1	7.2:1	4.8:1	6.5:1
LED (Initial)[(a)]									
Minimum (cd/m^2)	0.8	-	0.7	-	-	-	-	1.1	0.5
Mean (cd/m^2)	1.1	-	1.3	-	-	-	-	1.7	0.9
Maximum (cd/m^2)	1.5	-	1.9	-	-	-	-	2.6	1.3
Avg/Min	1.4:1	-	1.9:1	-	-	-	-	1.5:1	1.6:1
Max/Min	1.9:1	-	2.8:1	-	-	-	-	2.3:1	2.5:1
HPS (Initial)[(a)]									
Minimum (cd/m^2)	1.0	-	1.0	-	-	-	-	0.9	0.3
Mean (cd/m^2)	1.8	-	2.1	-	-	-	-	2.1	0.7
Maximum (cd/m^2)	3.1	-	3.5	-	-	-	-	4.1	1.4
Avg/Min	1.7:1	-	2.1:1	-	-	-	-	2.3:1	2.6:1
Max/Min	3.0:1	-	3.4:1	-	-	-	-	4.5:1	4.9:1

cd is candela.
(a) Luminance measurements were only taken for the four sites indicated.

Table 4.4. Maintained luminance values for the roadway, predicted from measured initial values

Site Label	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Category	**150**	**100**	**250**	**250**	**400**	**400**	**150**	**250**	**100**
Design Criteria									
L_{avg} (cd/m^2)	0.4	0.35	0.8	0.8	1.2	1.2	0.4	0.8	0.35
$L_{avg:min}$	3.3:1	3.15:1	3.2:1	3.2:1	2.1:1	2.1:1	3.3:1	3.2:1	3.15:1
$L_{max:min}$	7.2:1	6.5:1	4.8:1	4.8:1	2.9:1	2.9:1	7.2:1	4.8:1	6.5:1
LED									
Total LLF	0.56	-	0.56	-	-	-	-	0.56	0.63
Minimum (cd/m^2)	0.4	-	0.4	-	-	-	-	0.6	0.3
Mean (cd/m^2)	0.6	-	0.7	-	-	-	-	1.0	0.5
Maximum (cd/m^2)	0.8	-	1.0	-	-	-	-	1.4	0.8
Avg/Min	1.4	-	1.9	-	-	-	-	1.5	1.6
Max/Min	1.9	-	2.8	-	-	-	-	2.3	2.5
HPS									
Total LLF	0.68	-	0.54	-	-	-	-	0.54	0.68
Minimum (cd/m^2)	0.7	-	0.6	-	-	-	-	0.5	0.2
Mean (cd/m^2)	1.2	-	1.2	-	-	-	-	1.1	0.5
Maximum (cd/m^2)	2.1	-	1.9	-	-	-	-	2.2	0.9
Avg/Min	1.7	-	2.1	-	-	-	-	2.3	2.6
Max/Min	3.0	-	3.4	-	-	-	-	4.5	4.9

5.0 Discussion

Because of the broad scope and time scale of the task, photometric measurements were taken by a variety of staff (and one remote-controlled vehicle) and different meters. While reasonable effort was made to achieve consistency between these methods, myriad factors introduced inherent variation into the measured data. Although no systematic procedure was followed in quantifying the differences between measurements, the limited anecdotal data provides some indication of the relative precision of these and other street lighting measurements. Comparisons of the values obtained among the various procedures and equipment are discussed in this section.

5.1 Comparisons Between Measurement Methods

This project presented the opportunity to review a variety of measurement methods in addition to the measurements themselves. These included the variability between:

- different handheld illuminance meters[1] on the same street (e.g., see Figure 5.1)
- a handheld illuminance meter and a GPS-enabled, radio-guided remote-controlled mobile illuminance measurement system developed by the Electric Power Research Institute (EPRI) and known as *Scotty* (Figure 5.2)
- the results indicated by employing *illuminance* measurements versus *luminance* measurements taken on the same street
- a reference luminance meter and a standard luminance meter more likely to be purchased by a typical streetlight owner (such as in this case, by Kansas City).

While budget and time limitations prevented complete coverage of the demonstration sites by each individual method (e.g., Scotty was only run on two streets), some representative overlap between methods was used for calibration among methods. In some cases one team repeated measurements at a given location, in other cases multiple teams repeated measurements. For example, manual readings were taken with a handheld meter and then repeated using Scotty to compare those methods. Luminance readings were taken at the same points that illuminance readings were taken at four sites.

Because many of these initial readings were taken by different personnel using different meters at different times of night (and at different temperatures), some amount of variability in the results is to be expected even before the range in characteristics of each site are taken into account. Table 5.1 compares two different pairs of measurements, involving sites A and G, where the meter and operator taking the readings both varied but the grid and measurement procedures were similar. Both cases show a fair degree of variation.

As for the luminance comparison, IES LM-50-99[2] requires a luminance meter with a 2 minute arc (i.e., 2/60ths of a degree) field of view. The reference PR-810L has this plus it also has an adjustable field of view angle. The less expensive LS-100 has a fixed 1° arc field of view. One consequence of using the latter instrument is that the observer position must be adjusted to yield an equivalent measurement. The

[1] Meter information can be found in Appendix D.
[2] Presently withdrawn by the IES while under revision.

9% difference achieved is actually quite small considering this fact, and may represent a better result than typically expected from using such lower cost meters.

Figure 5.1 The Pushey illuminance meter device[1] developed by Kauffmann Consulting, LLC

Figure 5.2 Scotty

In addition to the contrasts highlighted in Table 5.1, two sites were measured using Scotty over a tightly spaced (4 by 4 ft) grid, supplementing the measurements made with handheld illuminance meters

[1] The *Pushey* device was developed to facilitate the process of multiple readings. It has one platform near the ground to hold the detector and another near the operator for the meter. Bubble levels are located on each platform to facilitate consistent leveling with the ground surface. Note: readings are not being recorded in this photo.

and the typical grid prescribed by IES RP-8-00. Scotty employs a Solar Light PMA1130 illuminance meter. In Table 5.2, the Scotty measurements are compared to the results obtained using two different handheld meters. The LED luminaire measurements were taken on the same night, but at different times and by different staff. Two comparisons show little difference, but one showed a 20% average difference. Reasons underlying the latter could include differences in calibration, different temperature sensitivities or response curves of the meters, different meter operators, or other issues. As with other sources of variation, selection of a particular handheld meter could potentially result in passing or failing the same luminaire in the same installation (with regard to mean illuminance in this instance), and thus should not be the sole means employed for evaluating a luminaire's effectiveness in any given situation.

Table 5.1. Example variations in lighting measurements from different handheld meters, using the same measurement points

Site	Comparison (Meter 1 vs. Meter 2)	Measurement Type	1	2	Difference
A	Photo Research PR-810L vs. Minolta LS-100	Luminance (cd/m^2)	0.77	0.70	9%
G	Minolta T-1 vs. Solar Light PMA2200	Illuminance (lux)	18.31	15.69	14%

Table 5.2. Example variations in illuminance measurements from different meters and different measurement methodologies

Site	Comparison (Meter 1 vs. Meter 2)	Measurement Type	1	2	Difference
G	Minolta T-1 vs. Scotty	Illuminance (lux)	18.31	14.71	20%
G	Solar Light PMA2200 vs. Scotty	Illuminance (lux)	15.69	14.71	6%
H	Solar Light PMA2200 vs. Scotty	Illuminance (lux)	13.43	12.70	5%[(a)]

(a) The adjacent site lighting (spill light) happened to be turned off during the readings on this particular evening.

5.2 Comparisons Between Measured and Calculated Illuminance

Calculations are used to predict current and future performance, but cannot account for many environmental or geometric factors, or inherent variation in the measurement procedures or equipment as reported above. Common sources of variation at any given point include differences between the geometry assumed and actual field conditions, and spill light from neighboring sources not accounted for in the model.

Table 5.3 compares field and calculated values. To provide an appropriate comparison, the tabulated values are based on different calculations than those used to evaluate each of the LED luminaires against the design specification. The calculations for the design specification assumed a generalized layout that does not reflect the actual conditions at any of the demonstration sites, whereas the new set of calculations attempted to incorporate the actual field conditions measured at each location. As expected, when incorporated into the model, the real-world variations in pole spacing, height, setback, lane width, and other features lead to additional differences between calculated and measured values. However, the new calculations continue to markedly diverge from the field measurements, especially for sites C, D, G, and H.

One of the most frequent contributors to differences between field measurements and calculated performance is spill light, which was present at a number of the Kansas City locations. Contributions

from adjacent site luminaires were specifically noted at sites G and H, as visible in the photo in Figure 5.3. On the streets measured by Scotty, one run was made across the grid to capture total light, and a second run was made with the subject luminaires turned off to measure spill light. Comparative measurements at site H showed a 25% reduction in illuminance when the adjacent lighting was turned off. (The cause of the other large discrepancies at sites C and D could not be determined.)

In total, seven of the nine sites had measured illuminance values above their corresponding calculated values, suggesting a more widespread underlying factor. Cold temperatures at the time of initial measurement may partially explain this trend—LED products generally are more efficacious at lower ambient temperatures. In this case, the temperature was approximately 36 °F, considerably lower than the temperature used for the LM-79 measurement-based values (approximately 77 °F). Ambient temperatures during field measurements influence LED products substantially—affecting both lumen output and to a lesser degree power draw—which increases the uncertainty of calculations.

Table 5.3. Comparison of measured and calculated performance using estimated field conditions[(a)]

Site Label	**A**	**B**	**C**	**D**	**E**	**F[(b)]**	**G**	**H**	**I**
Category	**150**	**100**	**250**	**250**	**400**	**400**	**150**	**250**	**100**
Road E_{avg} Initial									
Measured	10.7	9.9	13.3	18.2	29.7	15.6	18.3	17.9	8.8
Calculated	10.6	10.5	10.1	11.4	27.9	15.9	11.9	13.9	8.0
Difference	0%	-6%	32%	60%	6%	-2%	53%	29%	10%
Sidewalk E_{avg} Initial									
Measured	6.1	4.9	6.2	6.0	11.9	12.8	11.1	-[(c)]	3.8
Calculated	6.1	4.9	4.4	6.3	11.6	12.6	3.2	7.7	3.7
Difference	-1%	0%	40%	-5%	2%	2%	252%	-	3%
Input Power									
Field	130	68	154[(d)]	201	299	212	156	197	66
Lab Test	122	68	146	206	291	284	130	195	63
.IES (Calc)	116	73	157	201	299	300	134	200	64
Lumen Output									
Lab Test	7,698	5,391	10,277	11,952	21,739	21,413	8,455	14,021	5,304
.IES (Calc)	7,732	6,048	10,200	11,986	20,549	22,712	9,000	13,974	5,389

(a) For this comparison, calculations were performing using the geometry from the actual field conditions, rather than the generic sites used in the submittal process.
(b) One of the two luminaires was not operating properly at the time of measurement, as evidenced by a substantial reduction in power consumption—listed values are the average of the two poles nearest the measurement points. Illuminance readings were considerably lower than expected for half of the points.
(c) No illuminance measurements were made at the sidewalk location for site H.
(d) Actual recorded measurement was twice the value listed in the table. Measurement is believed to have been taken between incorrect legs of the three-phase power line. Adjustment was made post-hoc.

Figure 5.3. Large contributions from spill light evident for site G

5.3 Comparison of Performance over Time

Kansas City is the first GATEWAY street lighting demonstration site where performance has been actively tracked over time. Illuminance measurements continue to be recorded at roughly 1,000-hour intervals as allowed by local weather conditions. Full measurements are taken every 4,000 hours while only a subset of eight representative points is measured at the intermediate readings, most taken by the same team using the same meter. Although this effort was originally intended to track lumen maintenance, it has also illustrated the influence of ambient temperature on the LED product and, in general, the influence of environmental conditions on field measurements.

Figure 5.4 shows a plot of illuminance versus temperature over time for the LED luminaires, with the underlying data provided in Table 5.4. The illuminance measurements have been converted to relative values (i.e., percent of their initial values), determined from the mean of the subset of eight roadway points that were measured at every interval. The initial value for luminaire type F was excluded because one of the luminaires was malfunctioning at the time of initial measurement; in this instance, values were instead normalized to the measurement at 3,000 hours, when the temperature was most similar to the initial reading. For most of the luminaire types over this period of measurement, seasonal variables like temperature and foliage appeared to drive as much as a 20% swing in measured illuminance, and the effect appears as high as 40% for one product (site G, see Figure 5.5). It thus appears that the influence of

seasonal fluctuations may significantly outweigh any temporal lumen or dirt depreciation, at least during the early stages of product life.[1]

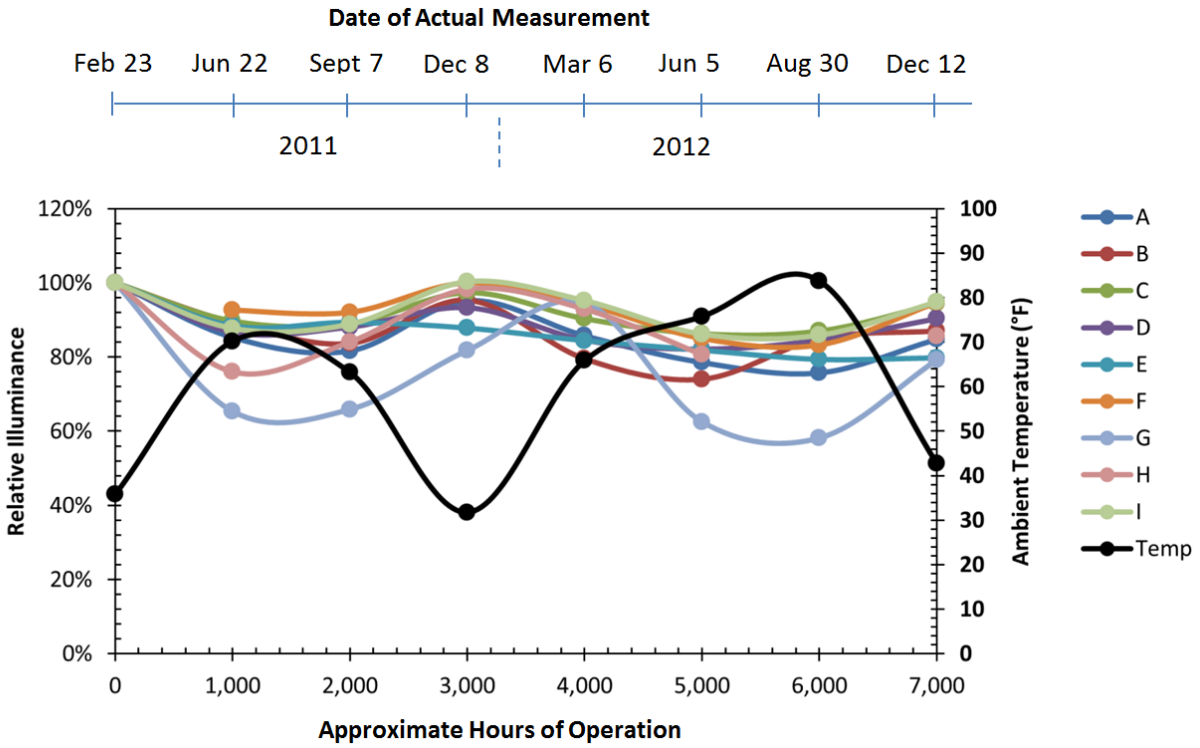

Figure 5.4. Relative illuminance over time versus to ambient temperature at the time of measurement[2]

Table 5.4. Relative illuminance over time compared to ambient temperature

Hours	**0**	**1,000**	**2,000**	**3,000**	**4,000**	**5,000**	**6,000**	**7,000**
Temp (°F)	**35.8**	**70.2**	**63.2**	**31.8**	**65.9**	**75.8**	**83.8**	**42.8**
A	1.00	0.85	0.82	0.95	0.86	0.79	0.76	0.85
B	1.00	0.89	0.84	0.95	0.80	0.74	0.85	0.87
C	1.00	0.90	0.89	0.97	0.90	0.86	0.87	0.94
D	1.00	0.87	0.88	0.93	0.85	0.82	0.85	0.90
E	1.00	0.88	0.89	0.88	0.84	0.82	0.79	0.80
F	-	0.93	0.92	1.00	0.94	0.85	0.83	0.95
G	1.00	0.65	0.66	0.82	0.95	0.63	0.58	0.79
H	1.00	0.76	0.84	0.98	0.93	0.81	-	0.86
I	1.00	0.88	0.89	1.00	0.95	0.86	0.86	0.95

[1] It must also be noted that ambient temperature has some influence on the light meter detector head and thus the readings obtained from it; the individual contributions from these two factors (meter temperature sensitivity and varying luminaire output) cannot be determined from the recorded data.
[2] The connecting lines in the graph are included only for convenience in following individual data sets (including temperature) and may or may not reflect actual values during the periods between the measured points.

Figure 5.5. HPS spill light sources and trees potentially causing seasonal variation at site G. LED street lighting at right.

In contrast with site G, site E has shown little seasonal variation, although the illuminance values appear to have decreased to about 80% of their initial values at 7,000 hours. In general, some lumen depreciation would be expected over this measurement period, though relatively small compared to the changes due to ambient temperature and other influences. The consistent decline for site E appears to be more directly related to luminaire output, and suggests that the luminaire will not reach its rated lifetime if the decline continues.

5.4 Performance Evaluation and Product Comparisons

Table 5.5 compares the performance attributes of the LED luminaires to the HPS luminaires that were previously installed. The table includes normalized metrics such as application efficacy and delivery efficiency, which to some degree allow for more effective before-and-after comparisons. Application efficacy and delivery efficiency both account for the distribution of emitted light, along with the total output and input power. However, these metrics should be restricted to comparisons of luminaires installed at the same site (i.e., the original HPS and its replacement LED) rather than to rank products across different sites because of the different geometries and other site conditions that these values do not take into account. **Moving a given luminaire to another site would almost certainly alter the corresponding values reported in the table.**

Table 5.5. Comparison of LED and HPS performance at the nine demonstration sites

Site Label	**LED A**	**LED B**	**LED C**	**LED D**	**LED E**	**LED F**	**LED G**	**LED H**	**LED I**
Category	**150**	**100**	**250**	**250**	**400**	**400**	**150**	**250**	**100**
Lab Measured Input Power (W)	122	68	146	206	291	284	130	195	63
Lab Measured Output (lm)	7,698	5,391	10,277	11,952	21,739	21,413	8,455	14,021	5,304
Lab Measured Efficacy (lm/W)	63.3	79.5	70.4	58.1	74.6	75.4	65.2	72.1	84.6
Measured Road Illuminance (fc)	0.99	0.92	1.24	1.69	2.76	1.45	1.70[(a)]	1.66	0.81
Pole Spacing (ft)	147	115	173	180	179	171	144	175	154
Area of Roadway (ft^2)	4,704	3,680	5,536	5,760	5,728	5,472	6,336	5,600	3,696
Delivered Lumens	4,674	3,379	6,864	9,759	15,785	7,952	10,782[(a)]	9,307	3,006
Delivery Efficiency[(b)]	61%	63%	67%	82%	73%	37%	128%[(a)]	66%	57%
Application Efficacy (lm/W)[(c)]	38.4	49.8	47.0	47.4	54.2	28.0	83.1[(a)]	47.9	48.0

Site Label	**HPS A**	**HPS B**	**HPS C**	**HPS D**	**HPS E**	**HPS F**	**HPS G**	**HPS H**	**HPS I**
Category	**150**	**100**	**250**	**250**	**400**	**400**	**150**	**250**	**100**
Lab Measured Input Power (W)	189	128	296	296	446	446	189	296	128
Lab Measured Output (lm)	12,227	6,432	19,573	19,573	32,020	32,020	12,227	19,573	6,432
Lab Measured Efficacy (lm/W)	64.9	50.1	66.0	66.0	71.8	71.8	64.9	66.0	50.1
Measured Road Illuminance (fc)	1.72	1.00	1.80	1.93	3.21	2.87	1.34	1.59	0.73
Pole Spacing (ft)	147	115	173	180	179	171	144	175	154
Area of Roadway (ft^2)	4,704	3,680	5,536	5,760	5,728	5,472	6,336	5,600	3,696
Delivered Lumens	8,098	3,678	9,958	11,135	18,396	15,704	8,495[(a)]	8,912	2,694
Delivery Efficiency[(b)]	66%	57%	51%	57%	57%	49%	69%[(a)]	46%	42%
Application Efficacy (lm/W)[(c)]	43.0	28.6	33.6	37.6	41.3	35.2	45.1[(a)]	30.1	21.0

(a) Measured value includes significant contributions from adjacent site lighting (spill light).

(b) *Delivery efficiency* is calculated as the quotient of lumens delivered to the target area (e.g., vehicular travel lanes) and the laboratory measured lumen output. **This metric should not be used to compare luminaires installed in different locations due to individual differences in site geometries and other relevant factors; i.e., comparisons in the table can be made vertically between the incumbent HPS and its replacement LED located in the same column, but such comparisons are not valid across columns.**

(c) *Application efficacy* is calculated as the quotient of total lumens delivered to the target area (e.g., vehicular travel lanes) and the laboratory measured input power of the luminaire. **This metric is subject to the same column restriction as stated in note (b).**

GATEWAY and other studies of LED installations often stress the importance of matching products to the application. The variability of applications in the real world makes this a formidable challenge for all lighting, LED and non-LED alike. The latter is illustrated even for the carefully designed HPS system in Table 5.5 in the disparity between the delivery efficiencies of sites HPS B and HPS I. Both of these sites employed the *same* HPS luminaire, but have different pole spacing and street widths that cause that luminaire's suitability to vary accordingly, at least as suggested by this particular metric.

The demonstration project as a whole—and Table 5.5 in particular—provides useful insight into the state of LED streetlights constructed circa late 2010. All of the LED products consumed less power than the HPS luminaires they replaced—with a mean difference of 39% and a range of 31% to 51%—but they also emitted 31% fewer lumens, on average. The net result is just a 15% increase in mean efficacy. Two of the LED products actually had lower efficacies than the products they replaced.

Six of the LED products also delivered a higher percentage of emitted lumens to the roadway[1] than their HPS counterparts, and had higher application efficacies as well, most likely because of the better targeted optical system allowed by LED technology. The delivery efficiency for one LED product (type G; Table 5.5) appeared to exceed 100% due to the unusually large contribution of spill light from an adjacent parking lot. Delivery efficiency and application efficacy at other sites have likely also been increased, though in less obvious fashion (note that spill light makes the same illuminance contribution to both LED and HPS measurements at any given site, but probably differs from site to site).

Sidewalks were not included in the calculations of application efficacy and overall performance, primarily because they were not present for most of the sites evaluated, despite being part of the specification. Including consideration of sidewalks could change the conclusions from this evaluation, however; doing so would likely boost the apparent performance of some products and reduce that of others according to their respective performance in those corresponding areas. Many of the LED luminaires did not meet the specifications for sidewalk illuminance.

5.5 Light Loss Factors and Design Life

The city requires the use of fairly stringent light loss factors for their HPS luminaires (as noted, 0.63 for 100 W residential replacements, and 0.56 for all other types) that are based on an established history of operation in the field, involving numerous life cycles of lamps, ballasts and fixtures. In contrast, there is no long-term field data for LED products that can confirm the validity of these values for their use with LEDs, and furthermore no distinction of *when* any particular product reaches them. The expected timeframe for LED products to reach the underlying lumen maintenance values ranges between 12 and 30 years after installation according to information provided in the various manufacturer specification sheets.

Also relevant is that not meeting the specified lighting levels in the future is not strictly a product failure per se, but is rather a consequence of an undersized luminaire. These luminaires probably could be sized in output to meet the specified levels over their entire projected lifetimes, although doing so also increases cost and energy use, not to mention significant over-lighting of the sites for most of the initial years of operation. None of these potential effects were estimated in this report, but the value of designing a system to meet light levels 15 or more years out should be seriously questioned. A more practical approach for a given street lighting investment might be to select a desired lifetime, for example 12 or 15 years, and determine whether the illumination levels from each product under consideration are expected to meet the specification at that point. Among other advantages, this approach puts luminaires with different lumen maintenance profiles on a more equivalent basis for comparison.

Applying the selected light loss factors to the initial measured data meant that five of the LED products (types A, C, D, F, and H) and the HPS luminaires at two of the sites (C and D) were predicted to eventually not meet the specified mean illuminance over time (see Table 4.2).

In keeping with the noted emphasis on safe streets, however, KCMO closely monitors their illuminance and requires continued compliance with the stated design criteria. This effectively means that the HPS lamps used at sites C and D will be replaced at some point *before* the calculated maintained illuminance is reached in those locations. Presumably, a similar situation would apply to LED products

[1] Calculated by multiplying the measured average illuminance (in footcandles) across the target area by that area (in square feet), divided by the luminaire total output (in lumens) as documented by laboratory measurement.

as well; any product reaching the specified average maintained illuminance will be replaced at that time rather than being allowed to continue operation at less than the required output. The net effect is that some LED products will be replaced sooner than their claimed lifetime, just as the HPS lamps must be in locations C and D.

6.0 Conclusions

The characteristic uncertainty in field measurements demonstrated in this study substantially complicates meaningful comparisons among products, especially when relying on very specific metrics with a fixed set of target values. Such comparisons can be very educational but should not be construed as yielding the final verdict for or against any given product. In all cases, each lighting product must be suitably matched with the correct application and evaluated across its overall suite of merits.

The luminaires evaluated in this report were installed in early 2011, and their design and manufacture extends even earlier. The performance of these nine luminaires may not be representative of the LED streetlights that are available today. Analyzing data from LED Lighting Facts[1] shows that outdoor area and roadway products listed in the first quarter of 2013 (the most recent period available as of publication) were approximately 30% more efficacious on average than those listed in the fourth quarter of 2010. Mean lumen output also increased by about 50% during this period.

With the possible exception of the luminaire installed at site E, given the other levels of variation in the measurements—from the meter used, seasonal conditions, etc.—it is still premature to draw any firm conclusions about individual lumen depreciation or expected future performance. Monitoring of the various sites is therefore planned to continue.

As a group, the LED products installed in this project tended to be slightly more efficacious, but provided a significant component of energy savings by reducing overall light levels in comparison with the original HPS products. The reduced levels met the desired performance levels in some cases but not in others (or were so predicted in calculations). However, the city's decision to base maintained illuminance requirements for LED products on light levels that are not expected until many years into the future should perhaps be revisited. As noted, a more practical approach might be to select a timeframe beyond which luminaire lifetime projections become increasingly tenuous, for example 12 to 15 years, and recalculate illuminance levels for each product at that point.

Finally, in terms of the study methodology itself, the noted variations in the different measurements and procedures and the resulting conclusions raise the question of what purpose field measurements should most appropriately serve. One fitting use is to confirm that the delivered products are what was originally ordered and are installed and operating correctly—one of the products in this study, for example, was detected as malfunctioning when its power use and illumination level were considerably below the expected values. Periodic monitoring of the relevant operating characteristics can identify similar issues that may arise in the future.

But moreover it should be recognized that even with the best design intent, and careful planning and selection, resulting numbers "on the ground" may or may not exactly conform to the original specification for reasons that go beyond the luminaire. The real world introduces a complex host of combined effects, from natural influences like temperature, foliage, and geography; to varying quality of the electricity supplying the luminaires; to technical variations among meters and to human error in documenting their readings. All of these influences were encountered in this study, and in fact, are encountered regularly in field studies of this type.

[1] http://www.lightingfacts.com/

The best approach is probably to use laboratory-tested performance values for initial design and selection of products, relying on field measurements to then ensure there are no problems or issues present in the resulting installation. To an extent, before-and-after comparisons on the same street, with poles and all other variables (including weather) equal, can provide useful field evaluations of performance. However, sole reliance on field measurements for comparing the adequacy of one product versus another installed in a different location should be largely avoided. In all cases, field measurements should only be considered one component of a much more comprehensive assessment.

7.0 References

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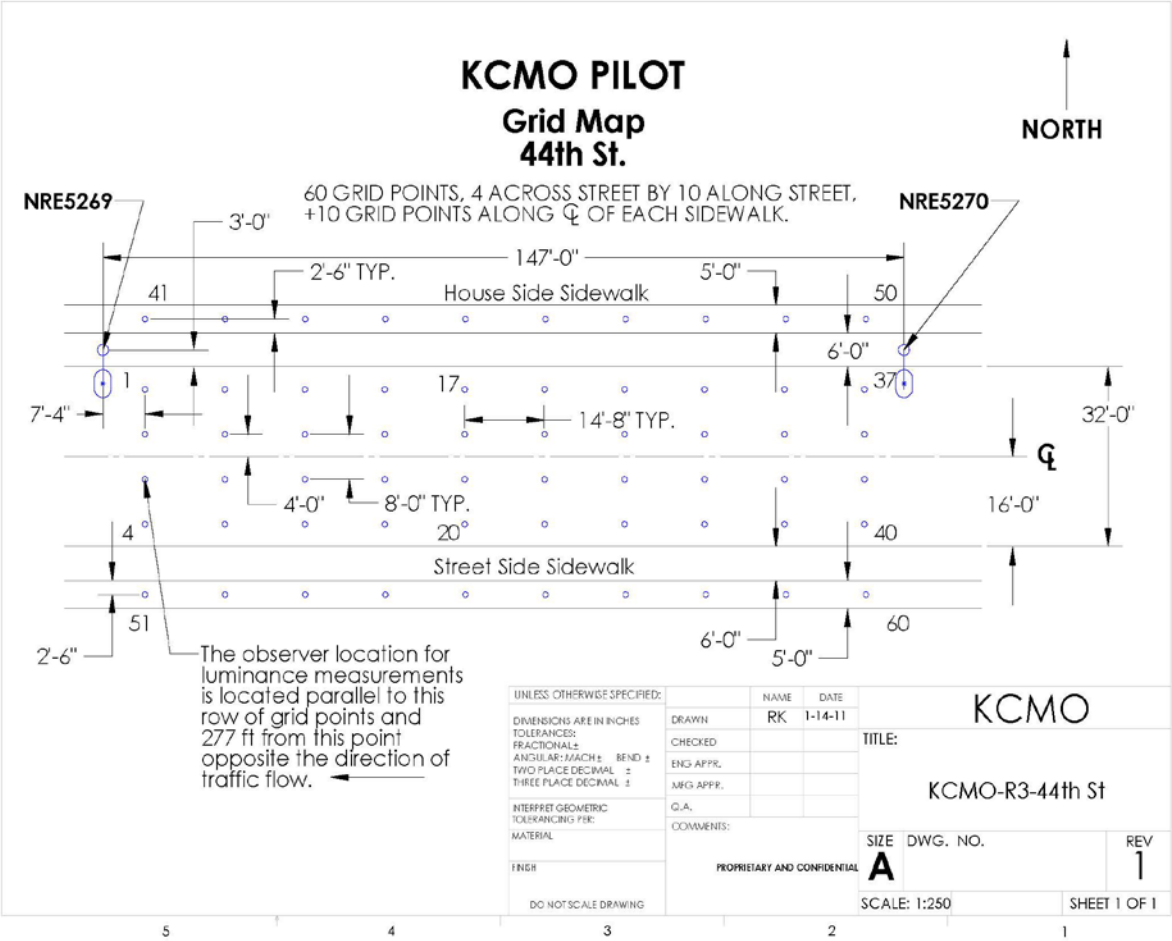
Appendix A

Measurement Graphics of Each Street, Including Photos

Site A: 44th Street

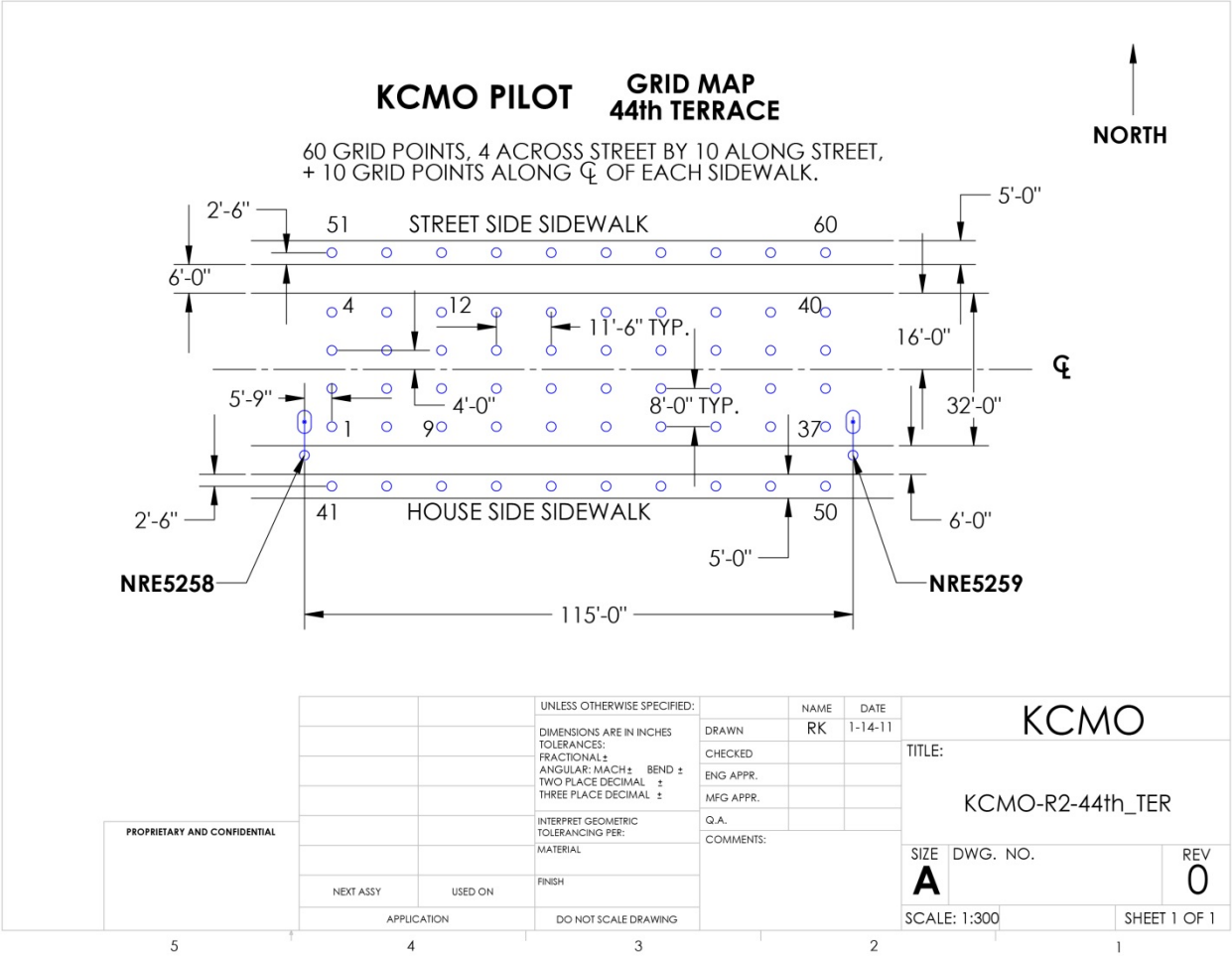


HPS

LED

[Photos should not be used to compare relative illuminance/luminance or color due to differences in the camera settings.]

Site B: 44th Terrace

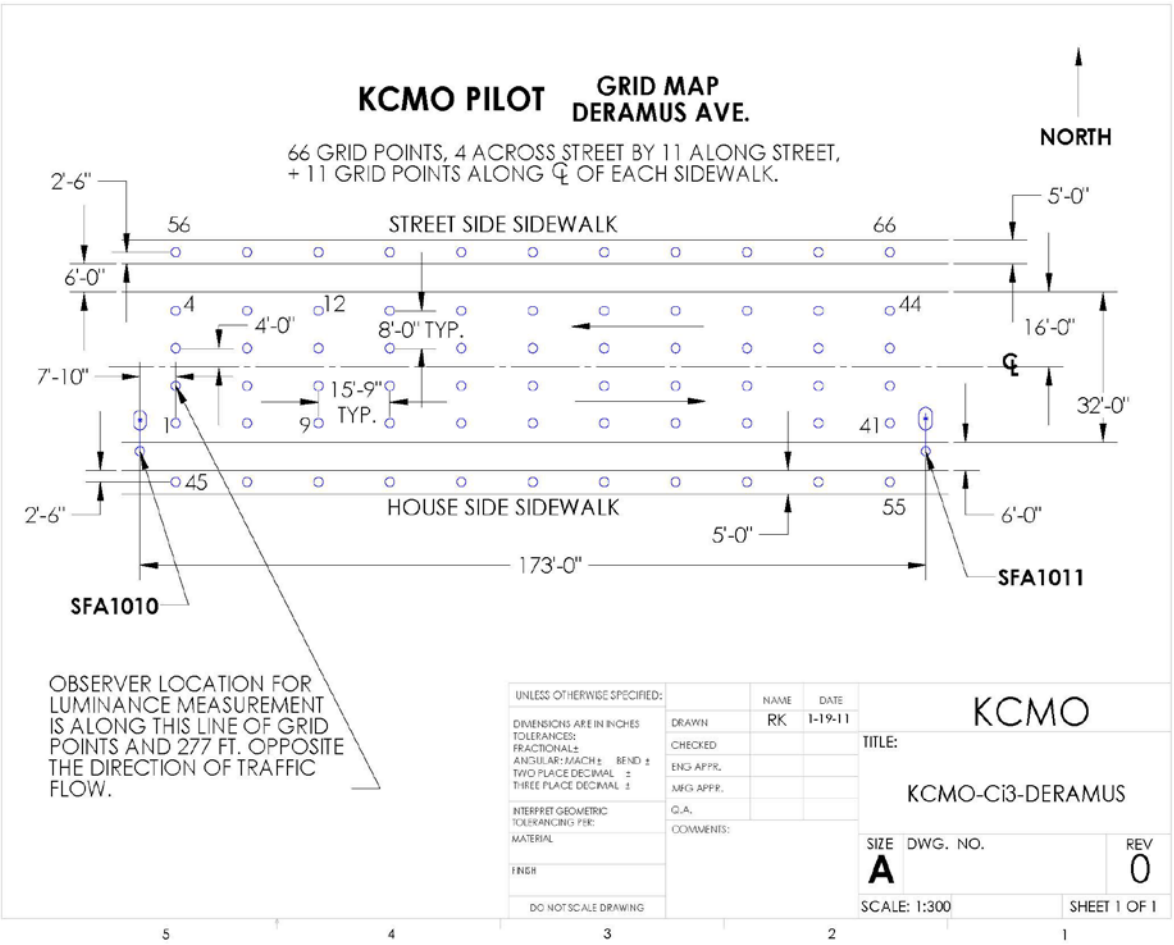


HPS

LED

[Photos should not be used to compare relative illuminance/luminance or color due to differences in the camera settings.]

Site C: Deramus Avenue

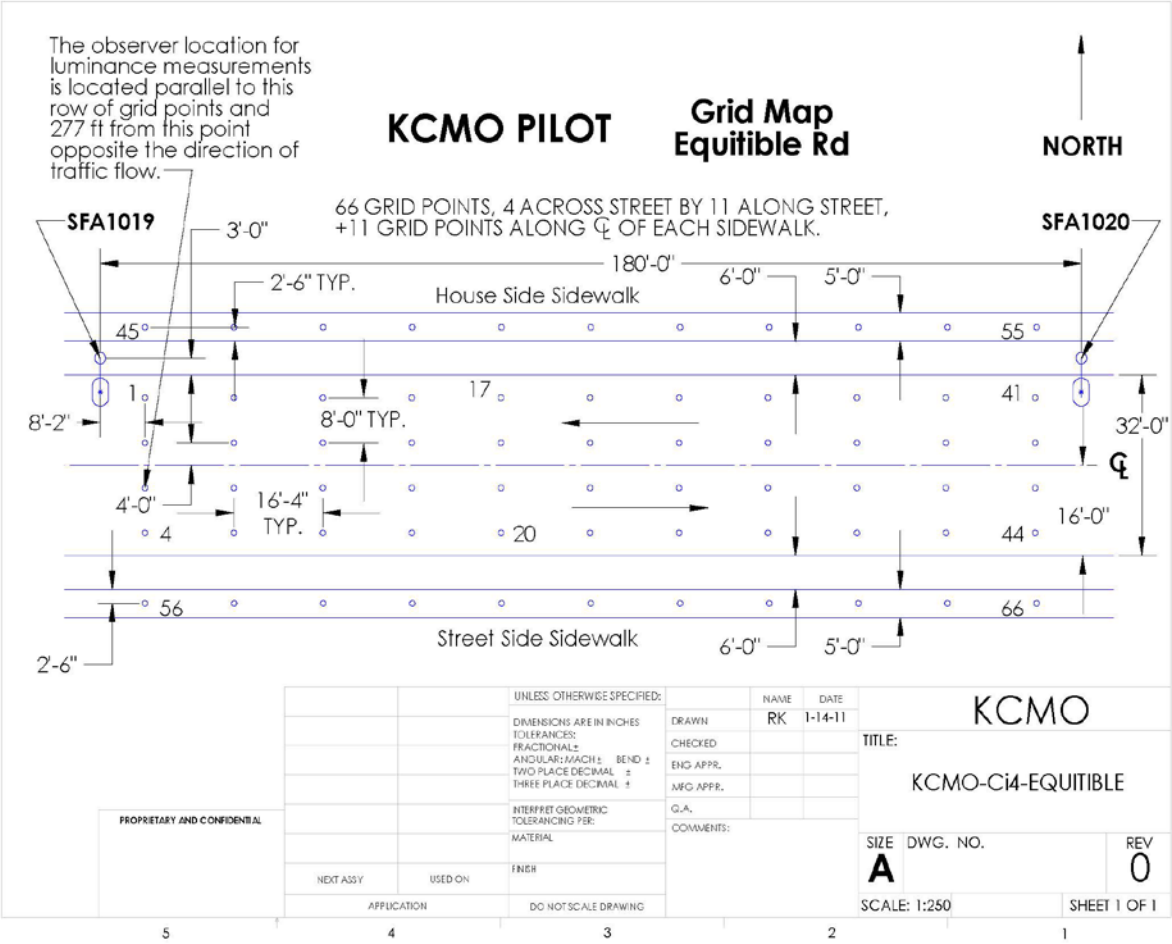


HPS

LED

[Photos should not be used to compare relative illuminance/luminance or color due to differences in the camera settings.]

Site D: Equitable Avenue

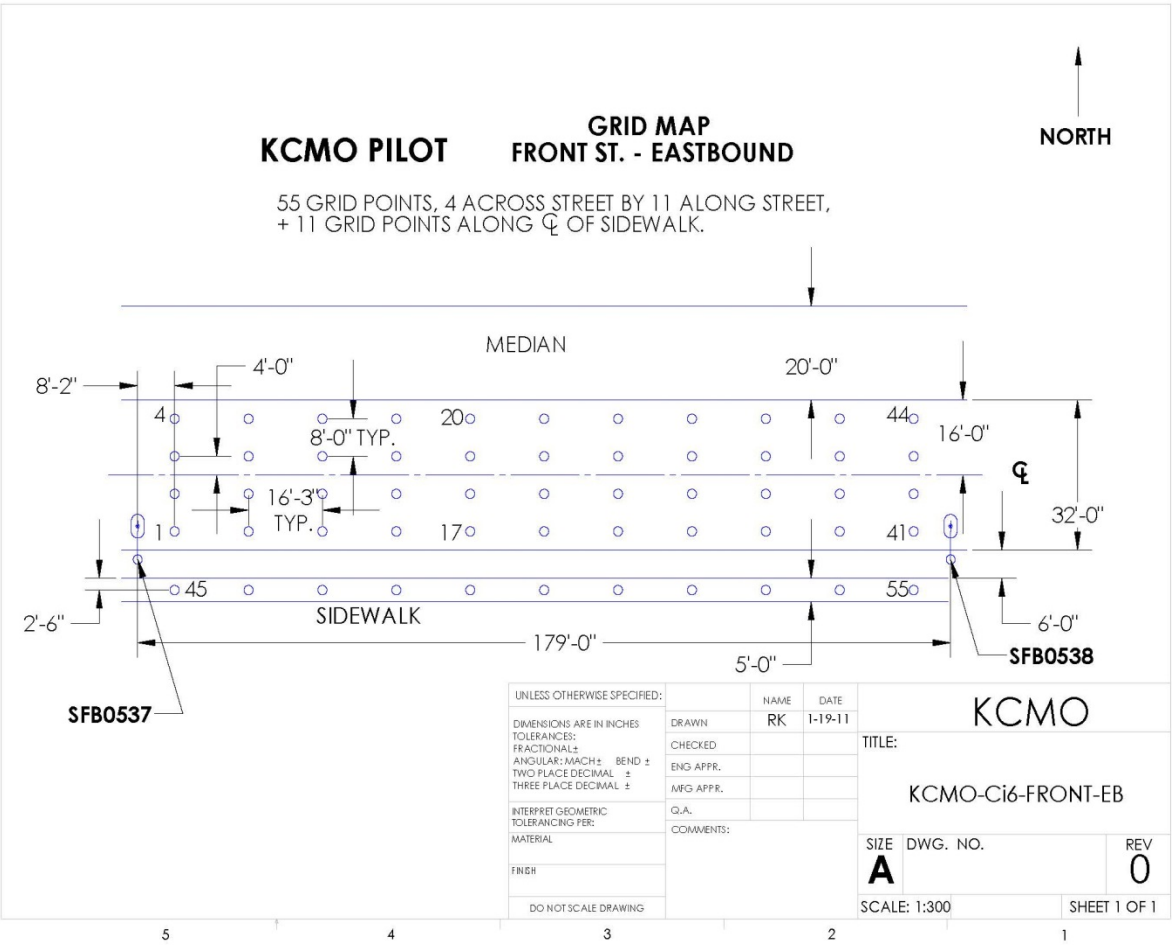


HPS

LED

[Photos should not be used to compare relative illuminance/luminance or color due to differences in the camera settings.]

Site E: Front Street Eastbound

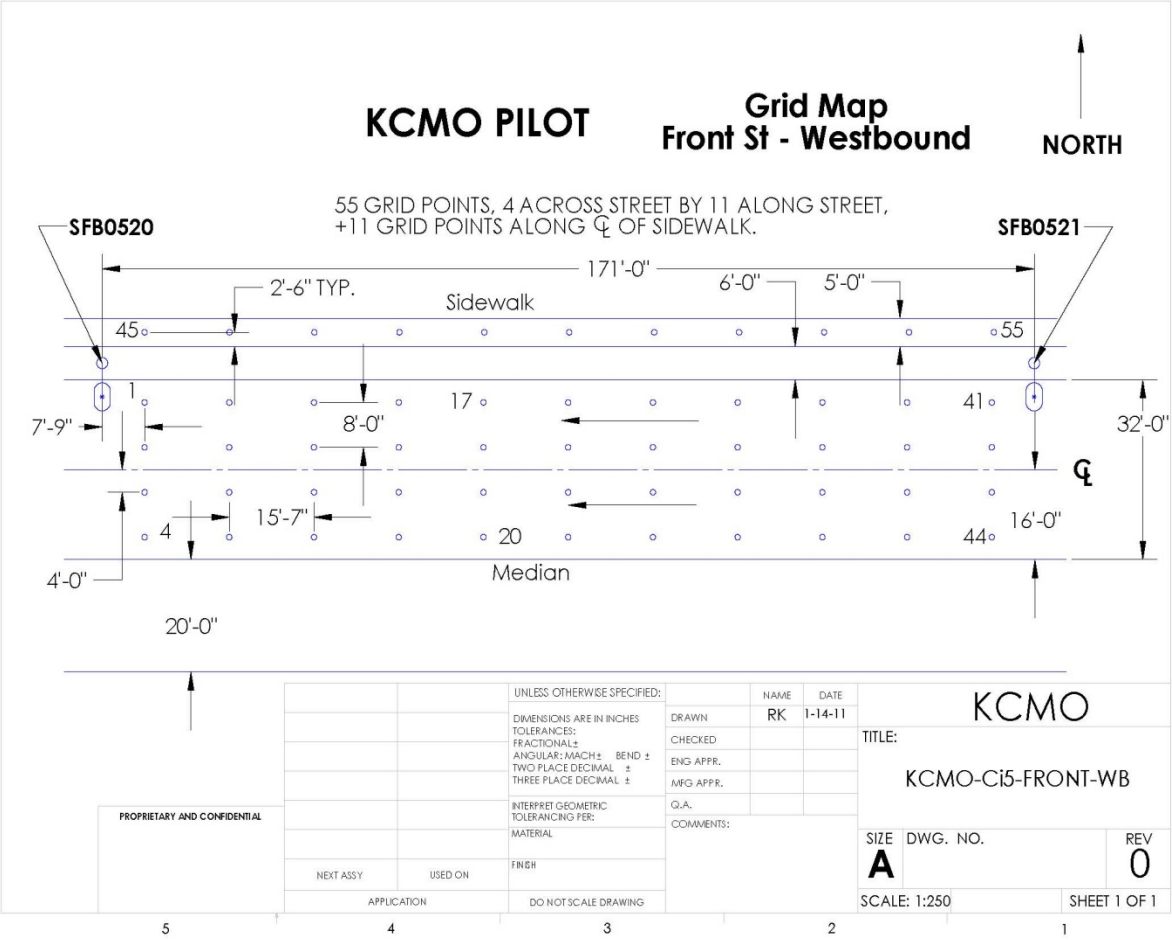


HPS

LED

[Photos should not be used to compare relative illuminance/luminance or color due to differences in the camera settings.]

Site F: Front Street Westbound

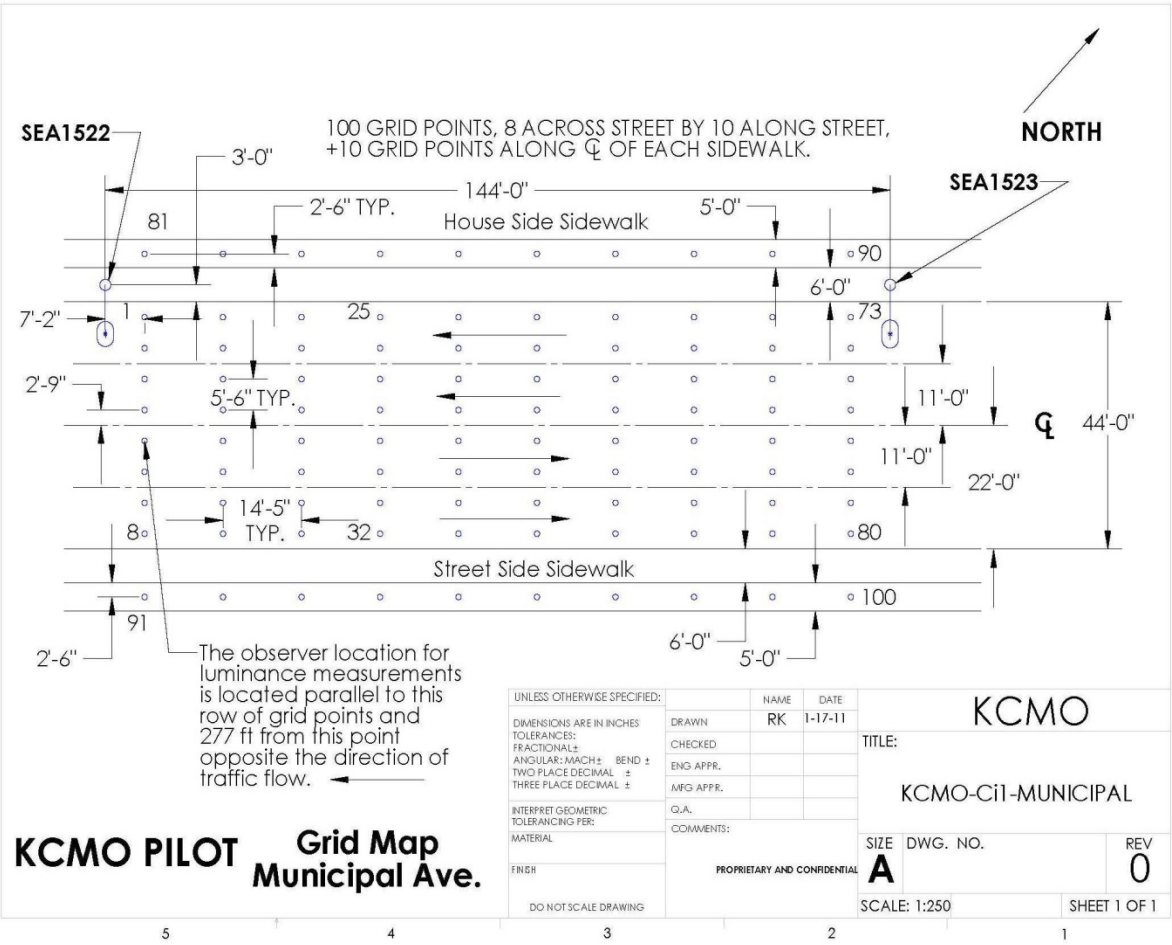


HPS

LED

[Photos should not be used to compare relative illuminance/luminance or color due to differences in the camera settings.]

Site G: Municipal Avenue

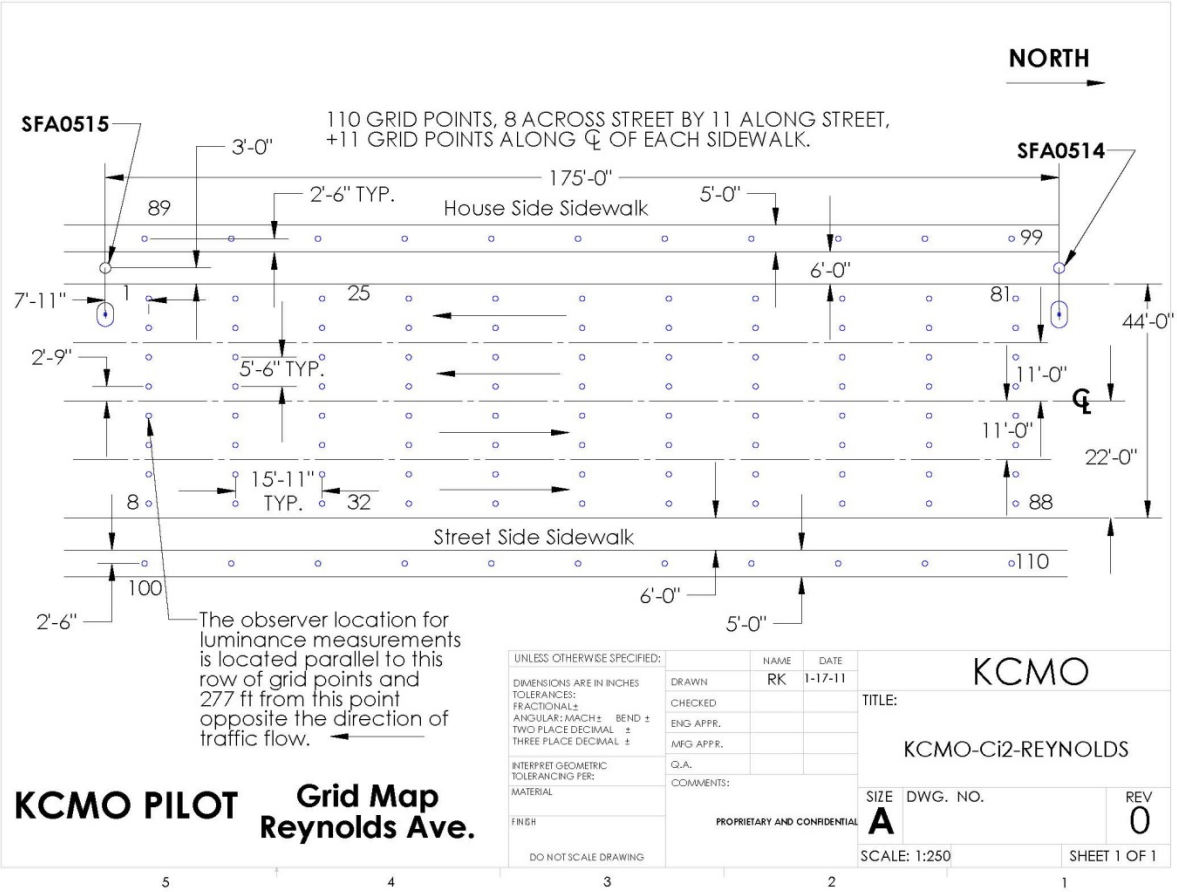


HPS

LED

[Photos should not be used to compare relative illuminance/luminance or color due to differences in the camera settings.]

Site H: Reynolds Avenue

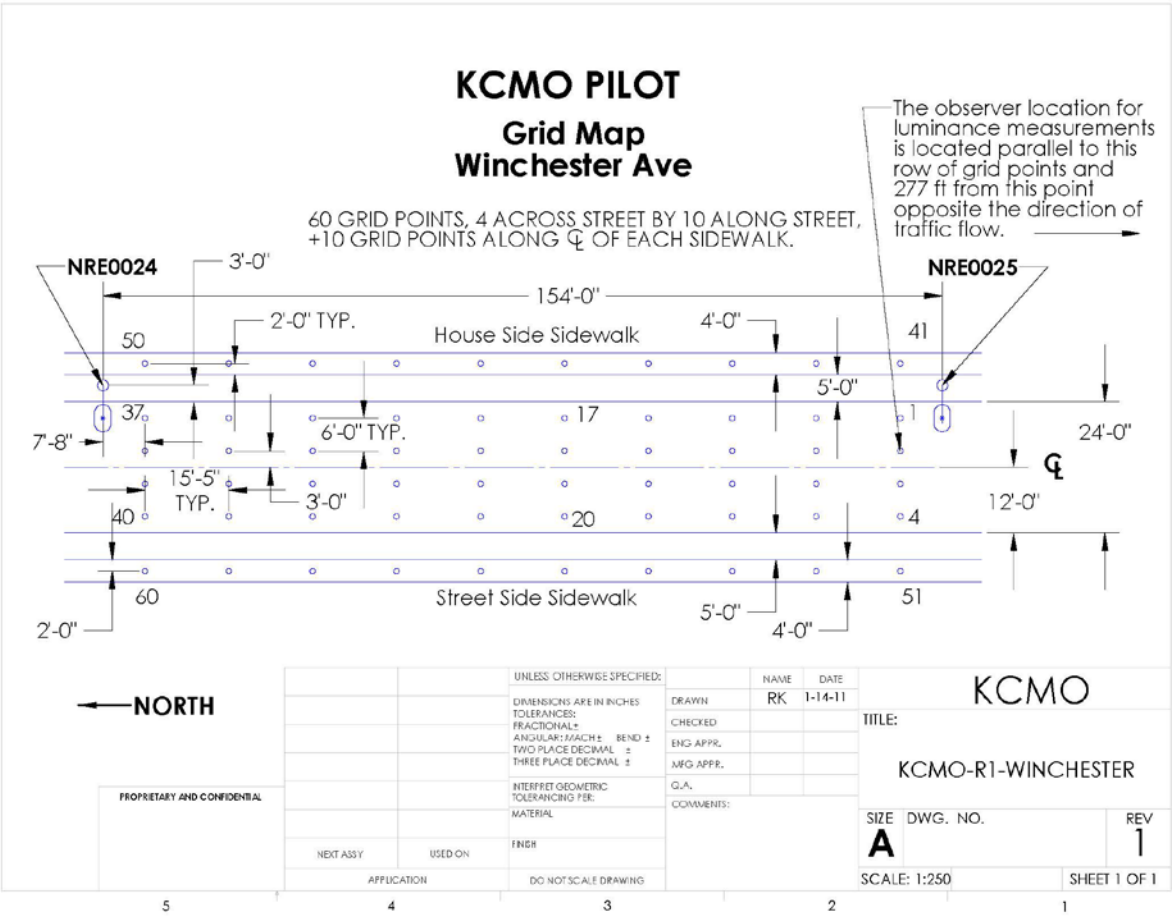


HPS

LED

[Photos should not be used to compare relative illuminance/luminance or color due to differences in the camera settings.]

Site I: Winchester Avenue



HPS

LED

[Photos should not be used to compare relative illuminance/luminance or color due to differences in the camera settings.]

Appendix B

Kansas City Luminaire Performance Tables for Each of the Evaluated Subject Wattages

KANSAS CITY MISSOURI [KCMO] PUBLIC WORKS
LUMINAIRE PERFORMANCE TABLE 100 WATT HPS

GIVEN CONDITIONS		
ROADWAY DATA:	Pavement Width	27 ft.
	Number of Lanes	2
	IES Surface Classification	R3
	Q-Zero Value	.07
SIDEWALK DATA: (5 ft. walk)	Street Side Distance from walk to far E. of P.	6 ft
	House Side Distance from walk to near E. of P.	6 ft
LIGHT POLE DATA:	Mounting Height	27.75 ft
	Mast Arm Length	6 ft
	Pole Set-back from Edge of Pavement	2 ft
LUMINAIRE DATA:	Lamp Type	100W HPS
	Lamp Lumens	9,500 L
	IES Cut-off Classification	CO or SC
	IES Distribution Pattern (see note)	MCO II or MSCII SSCII
	Total Light Loss Factor	0.68
LAYOUT DATA:	Spacing	156 ft
	Configuration	One side
	Luminaire Overhang Over-Edge	4

NOTE: Variations from the above specified IES distribution pattern may be requested and acceptance of variations will be subject to review by KCMO based on how well the performance requirements are met. IES type non-cutoff luminaires will not be accepted.

PERFORMANCE REQUIREMENTS

NOTE: These performance requirements shall be the minimum acceptable standards of photometric performance for the luminaire, based on the given conditions listed above.

ROADWAY		
ILLUMINATION:	Average Horizontal Illumination	4.4 lux
	Uniformity Ratio: *(avg/min)*	6 : 1
LUMINANCE:	Average Luminance (L_{Avg})	0.35 cd/m^2
	Uniformity Ratio *(L_{Avg}/ L_{Min})*	3.15 : 1
	(L_{Max}/ L_{Min})	6.5 : 1
	Maximum Veiling Luminance Ratio *(L_{vmax}/*	0.33 : 1
STREET OR HOUSE SIDEWALK		
	Average Horizontal Illumination	1.8 lux
	Uniformity Ratio: *(avg./min)*	7: 1

KANSAS CITY MISSOURI [KCMO] PUBLIC WORKS
LUMINAIRE PERFORMANCE TABLE 150 WATT HPS

	GIVEN CONDITIONS	
ROADWAY DATA:	Pavement Width	36 ft.
	Number of Lanes	3
	IES Surface Classification	R3
	Q-Zero Value	.07
SIDEWALK DATA: (5 ft. walk)	Street Side Distance from walk to far E. of P.	6 ft
	House Side Distance from walk to near E. of P.	6 ft
LIGHT POLE DATA:	Mounting Height	29.75 ft
	Mast Arm Length	6 ft
	Pole Set-back from Edge of Pavement	4 ft
LUMINAIRE DATA:	Lamp Type	150W HPS
	Lamp Lumens	16,000 L
	IES Cut-off Classification	CO or SC
	IES Distribution Pattern (see note)	MCO II, MSCII or III, SSCII
	Total Light Loss Factor	0.68
LAYOUT DATA:	Spacing	165 ft
	Configuration	One side
	Luminaire Overhang Over-Edge	2

NOTE: Variations from the above specified IES distribution pattern may be requested and acceptance of variations will be subject to review by KCMO based on how well the performance requirements are met. IES type non-cutoff luminaires will not be accepted.

PERFORMANCE REQUIREMENTS

NOTE: These performance requirements shall be the minimum acceptable standards of photometric performance for the luminaire, based on the given conditions listed above.

	ROADWAY	
ILLUMINATION:	Average Horizontal Illumination	6.3 lux
	Uniformity Ratio: *(avg./min)*	6 : 1
LUMINANCE:	Average Luminance (L_{Avg})	0.4 cd/m^2
	Uniformity Ratio (L_{Avg}/L_{Min})	3.3 : 1
	(L_{Max}/L_{Min})	7.2 : 1
	Maximum Veiling Luminance Ratio (L_{vmax}/L_{Avg})	0.35 : 1
	STREET OR HOUSE SIDEWALK	
	Average Horizontal Illumination	2.0 lux
	Uniformity Ratio: *(avg./min)*	5.3 : 1

KANSAS CITY MISSOURI [KCMO] PUBLIC WORKS
LUMINAIRE PERFORMANCE TABLE 250 WATT HPS

	GIVEN CONDITIONS	
ROADWAY DATA:	Pavement Width	48 ft.
	Number of Lanes	4
	IES Surface Classification	R3
	Q-Zero Value	.07
SIDEWALK DATA: (5 ft. walk)	Street Side Distance from walk to far E. of P.	10 ft
	House Side Distance from walk to near E. of P.	10 ft
LIGHT POLE DATA:	Mounting Height	35 ft
	Mast Arm Length	6 ft
	Pole Set-back from Edge of Pavement	6 ft
LUMINAIRE DATA:	Lamp Type	250W HPS
	Lamp Lumens	27,500 L
	IES Cut-off Classification	CO
	IES Distribution Pattern (see note)	MCO III
	Total Light Loss Factor	0.54
LAYOUT DATA:	Spacing	180 ft
	Configuration	Opposite
	Luminaire Overhang Over-Edge	3

NOTE: Variations from the above specified IES distribution pattern may be requested and acceptance of variations will be subject to review by KCMO based on how well the performance requirements are met. IES type non-cutoff luminaires will not be accepted.

PERFORMANCE REQUIREMENTS

NOTE: These performance requirements shall be the minimum acceptable standards of photometric performance for the luminaire, based on the given conditions listed above.

	ROADWAY	
ILLUMINATION:	Average Horizontal Illumination	12.0 lux
	Uniformity Ratio: *(avg./min)*	2.9 : 1
LUMINANCE:	Average Luminance (L_{Avg})	0.8 cd/m^2
	Uniformity Ratio (L_{Avg}/ L_{Min})	3.2 : 1
	(M_{ax}/ M_{in})	4.8 : 1
	Maximum Veiling Luminance Ratio (L_{vmax}/ L_{Avg})	0.34 : 1
	STREET OR HOUSE SIDEWALK	
	Average Horizontal Illumination	5.7 lux
	Uniformity Ratio: *(avg./min)*	2.7 : 1

KANSAS CITY MISSOURI [KCMO] PUBLIC WORKS
LUMINAIRE PERFORMANCE TABLE 400 WATT HPS

	GIVEN CONDITIONS	
ROADWAY DATA:	Pavement Width	60 ft.
	Number of Lanes	6
	IES Surface Classification	R3
	Q-Zero Value	.07
SIDEWALK DATA: (5 ft. walk)	Street Side Distance from walk to far E. of P.	10 ft
	House Side Distance from walk to near E. of P.	10 ft
LIGHT POLE DATA:	Mounting Height	41.25 ft
	Mast Arm Length	6 ft
	Pole Set-back from Edge of Pavement	3 ft
LUMINAIRE DATA:	Lamp Type	400W HPS
	Lamp Lumens	50,000 L
	IES Cut-off Classification	CO
	IES Distribution Pattern (see note)	MCO III
	Total Light Loss Factor	0.54
LAYOUT DATA:	Spacing	180 ft
	Configuration	Opposite
	Luminaire Overhang Over-Edge	3

NOTE: Variations from the above specified IES distribution pattern may be requested and acceptance of variations will be subject to review by KCMO based on how well the performance requirements are met. IES type non-cutoff luminaires will not be accepted.

PERFORMANCE REQUIREMENTS

NOTE: These performance requirements shall be the minimum acceptable standards of photometric performance for the luminaire, based on the given conditions listed above.

	ROADWAY	
ILLUMINATION:	Average Horizontal Illumination	17.0 lux
	Uniformity Ratio: *(avg./min)*	2.5 : 1
LUMINANCE:	Average Luminance (L_{Avg})	1.2 cd/m^2
	Uniformity Ratio (L_{Avg}/L_{Min})	2.1 : 1
	(L_{Max}/L_{Min})	2.9 : 1
	Maximum Veiling Luminance Ratio (L_{vmax}/L_{Avg})	0.32 : 1
	STREET OR HOUSE SIDEWALK	
	Average Horizontal Illumination	9.0 lux
	Uniformity Ratio: *(avg./min)*	3.2 : 1

Appendix C

Complete Set of Measurements Including Sidewalks

Calculated Initial Illuminance, Specification Layout

Roadway

Site Label	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Category	**150**	**100**	**250**	**250**	**400**	**400**	**150**	**250**	**100**
Design Criteria									
E_{avg} (lux)	6.3	4.4	12.0	12.0	17.0	17.0	6.3	12.0	4.4
$E_{avg/min}$	6:1	6:1	2.9:1	2.9:1	2.5:1	2.5:1	6:1	2.9:1	6:1
LED (Initial)									
Minimum	3.39	2.78	5.77	6.00	10.02	15.68	3.93	11.39	2.75
Mean	8.18	8.84	15.29	18.70	27.71	22.20	10.41	21.96	7.65
Maximum	14.07	21.49	36.32	37.46	51.66	33.66	25.16	34.52	16.05
Avg/Min	2.41	3.18	2.65	3.12	2.77	1.42	2.65	1.93	2.79
Max/Min	4.15	7.74	6.30	6.24	5.16	2.15	6.40	3.03	5.84
HPS									
Minimum	3.81	2.46	12.72	12.72	19.24	19.24	2.74	12.72	1.66
Mean	10.66	8.35	32.56	32.56	44.44	44.44	13.59	32.56	9.74
Maximum	49.75	33.72	77.43	77.43	92.74	92.74	38.32	77.43	26.01
Avg/Min	2.80	3.40	2.56	2.56	2.31	2.31	4.97	2.56	5.86
Max/Min	13.06	13.73	6.09	6.09	4.82	4.82	14.01	6.09	15.65

Street Side Sidewalk

Site Label	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Category	**150**	**100**	**250**	**250**	**400**	**400**	**150**	**250**	**100**
Design Criteria									
E_{avg} (lux)	2.0	1.8	5.7	5.7	9.0	9.0	2.0	5.7	1.8
$E_{avg/min}$	5.3:1	7:1	2.7:1	2.7:1	3.2:1	3.2:1	5.3:1	2.7:1	7:1
LED (Maintained)									
Minimum	1.48	2.46	4.52	4.02	5.18	7.41	1.54	6.00	2.78
Mean	3.09	3.65	4.80	8.05	8.80	13.46	4.00	9.18	3.60
Maximum	6.29	4.44	5.25	14.98	20.66	23.13	7.95	14.18	4.68
Avg/Min	2.08	1.48	1.06	2.00	1.70	1.82	2.60	1.53	1.30
Max/Min	4.24	1.81	1.16	3.73	3.99	3.12	5.17	2.36	1.69
HPS (Maintained)									
Minimum	2.09	2.54	5.89	5.89	10.35	10.35	4.72	5.89	4.12
Mean	2.79	3.47	12.65	12.65	19.39	19.39	5.34	12.65	5.66
Maximum	3.56	4.96	20.02	20.02	29.06	29.06	6.34	20.02	7.91
Avg/Min	1.34	1.36	2.15	2.15	1.87	1.87	1.13	2.15	1.38
Max/Min	1.70	1.95	3.40	3.40	2.81	2.81	1.34	3.40	1.92

House Side Sidewalk

Site Label	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Category	**150**	**100**	**250**	**250**	**400**	**400**	**150**	**250**	**100**
Design Criteria									
E_{avg} (lux)	2.0	1.8	5.7	5.7	9.0	9.0	2.0	5.7	1.8
$E_{avg/min}$	5.3:1	7:1	2.7:1	2.7:1	3.2:1	3.2:1	5.3:1	2.7:1	7:1
LED (Maintained)									
Minimum	1.43	1.44	4.52	4.02	5.18	7.41	1.64	6.00	1.33
Mean	3.71	4.14	4.80	8.05	8.80	13.46	2.63	9.18	2.14
Maximum	5.96	9.17	5.25	14.98	20.66	23.13	4.13	14.18	3.29
Avg/Min	2.60	2.87	1.06	2.00	1.70	1.82	1.60	1.53	1.61
Max/Min	4.18	6.35	1.16	3.73	3.99	3.12	2.51	2.36	2.46
HPS (Maintained)									
Minimum	3.03	1.49	5.89	5.89	10.35	10.35	1.78	5.89	1.04
Mean	9.60	5.38	12.65	12.65	19.39	19.39	5.96	12.65	3.37
Maximum	27.15	14.37	20.02	20.02	29.06	29.06	12.44	20.02	7.10
Avg/Min	3.17	3.62	2.15	2.15	1.87	1.87	3.35	2.15	3.23
Max/Min	8.96	9.67	3.40	3.40	2.81	2.81	6.99	3.40	6.80

Calculated Maintained Illuminance, Specification Layout

Roadway

Site Label	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Category	**150**	**100**	**250**	**250**	**400**	**400**	**150**	**250**	**100**
Design Criteria									
E_{avg} (lux)	6.3	4.4	12.0	12.0	17.0	17.0	6.3	12.0	4.4
$E_{avg/min}$	6:1	6:1	2.9:1	2.9:1	2.5:1	2.5:1	6:1	2.9:1	6:1
LED (Maintained)									
Total LLF	0.56	0.63	0.56	0.56	0.56	0.56	0.56	0.56	0.63
Minimum	1.90	1.75	3.23	3.36	5.61	8.78	2.20	6.38	1.73
Mean	4.58	5.57	8.56	10.47	15.52	12.43	5.83	12.30	4.82
Maximum	7.88	13.54	20.34	20.98	28.93	18.85	14.09	19.33	10.11
Avg/Min	2.41	3.18	2.65	3.12	2.77	1.42	2.65	1.93	2.79
Max/Min	4.15	7.74	6.30	6.24	5.16	2.15	6.40	3.03	5.84
HPS (Maintained)									
Total LLF	0.68	0.68	0.54	0.54	0.54	0.54	0.68	0.54	0.68
Minimum	2.6	1.7	6.9	6.9	10.4	10.4	1.9	6.9	1.1
Mean	7.3	5.7	17.6	17.6	24.0	24.0	9.2	17.6	6.6
Maximum	33.8	22.9	41.8	41.8	50.1	50.1	26.1	41.8	17.7
Avg/Min	2.8	3.4	2.6	2.6	2.3	2.3	5.0	2.6	5.9
Max/Min	13.1	13.7	6.1	6.1	4.8	4.8	14.0	6.1	15.7

Street Side Sidewalk

Site Label	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Category	**150**	**100**	**250**	**250**	**400**	**400**	**150**	**250**	**100**
Design Criteria									
E_{avg} (lux)	2.0	1.8	5.7	5.7	9.0	9.0	2.0	5.7	1.8
$E_{avg/min}$	5.3:1	7:1	2.7:1	2.7:1	3.2:1	3.2:1	5.3:1	2.7:1	7:1
LED (Maintained)									
Total LLF	0.56	0.63	0.56	0.56	0.56	0.56	0.56	0.56	0.63
Minimum	0.83	1.55	2.53	2.25	2.90	4.15	0.86	3.36	1.75
Mean	1.73	2.30	2.69	4.51	4.93	7.54	2.24	5.14	2.27
Maximum	3.52	2.80	2.94	8.39	11.57	12.95	4.45	7.94	2.95
Avg/Min	2.08	1.48	1.06	2.00	1.70	1.82	2.60	1.53	1.30
Max/Min	4.24	1.81	1.16	3.73	3.99	3.12	5.17	2.36	1.69
HPS (Maintained)									
Total LLF	0.68	0.68	0.54	0.54	0.54	0.54	0.68	0.54	0.68
Minimum	1.42	1.73	3.18	3.18	5.59	5.59	3.21	3.18	2.80
Mean	1.90	2.36	6.83	6.83	10.47	10.47	3.63	6.83	3.85
Maximum	2.42	3.37	10.81	10.81	15.69	15.69	4.31	10.81	5.38
Avg/Min	1.34	1.36	2.15	2.15	1.87	1.87	1.13	2.15	1.38
Max/Min	1.70	1.95	3.40	3.40	2.81	2.81	1.34	3.40	1.92

House Side Sidewalk

Site Label	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Category	**150**	**100**	**250**	**250**	**400**	**400**	**150**	**250**	**100**
Design Criteria									
E_{avg} (lux)	2.0	1.8	5.7	5.7	9.0	9.0	2.0	5.7	1.8
$E_{avg/min}$	5.3:1	7:1	2.7:1	2.7:1	3.2:1	3.2:1	5.3:1	2.7:1	7:1
LED (Maintained)									
Total LLF	0.56	0.63	0.56	0.56	0.56	0.56	0.56	0.56	0.63
Minimum	0.80	0.91	2.53	2.25	2.90	4.15	0.92	3.36	0.84
Mean	2.08	2.61	2.69	4.51	4.93	7.54	1.47	5.14	1.35
Maximum	3.34	5.78	2.94	8.39	11.57	12.95	2.31	7.94	2.07
Avg/Min	2.60	2.87	1.06	2.00	1.70	1.82	1.60	1.53	1.61
Max/Min	4.18	6.35	1.16	3.73	3.99	3.12	2.51	2.36	2.46
HPS (Maintained)									
Total LLF	0.68	0.68	0.54	0.54	0.54	0.54	0.68	0.54	0.68
Minimum	2.06	1.01	3.18	3.18	5.59	5.59	1.21	3.18	0.71
Mean	6.53	3.66	6.83	6.83	10.47	10.47	4.05	6.83	2.29
Maximum	18.46	9.77	10.81	10.81	15.69	15.69	8.46	10.81	4.83
Avg/Min	3.17	3.62	2.15	2.15	1.87	1.87	3.35	2.15	3.23
Max/Min	8.96	9.67	3.40	3.40	2.81	2.81	6.99	3.40	6.80

Measured Initial Illuminance

Roadway

ID	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Category	**150**	**100**	**250**	**250**	**400**	**400**	**150**	**250**	**100**
Design Criteria									
E_{avg} (lux)	6.3	4.4	12.0	12.0	17.0	17.0	6.3	12.0	4.4
$E_{avg/min}$	6:1	6:1	2.9:1	2.9:1	2.5:1	2.5:1	6:1	2.9:1	6:1
LED (Initial)									
Minimum	6.5	6.3	4.3	4.0	8.8	6.5	8.8	7.4	3.7
Mean	10.7	9.9	13.3	18.2	29.7	15.6	18.3	17.9	8.8
Maximum	17.1	18.6	38.3	43.7	67.2	31.7	39.0	36.5	15.0
Avg/Min	1.6	1.6	3.1	4.5	3.4	2.4	2.1	2.4	2.4
Max/Min	2.6	3.0	8.9	10.8	7.6	4.9	4.5	4.9	4.1
HPS									
Minimum	3.3	4.2	5.6	4.7	13.0	13.3	4.4	6.6	1.4
Mean	18.5	10.8	19.4	20.8	34.6	30.9	14.4	17.1	7.8
Maximum	53.3	26.8	71.2	72.0	104.5	97.3	34.3	58.5	22.9
Avg/Min	5.6	2.6	3.5	4.4	2.7	2.3	3.3	2.5	5.6
Max/Min	16.3	6.4	12.7	15.3	8.0	7.3	7.8	11.3	16.4

Sidewalks

Site Label	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Category	**150**	**100**	**250**	**250**	**400**	**400**	**150**	**250**	**100**
Design Criteria									
E_{avg} (lux)	2.0	1.8	5.7	5.7	9.0	9.0	2.0	5.7	1.8
$E_{avg/min}$	5.3:1	7:1	2.7:1	2.7:1	2.7:1	2.7:1	5.3:1	2.7:1	7:1
LED (Initial)									
Minimum	2.3	2.7	3.1	2.0	5.1	4.8	2.8	-	1.1
Mean	6.1	4.9	6.2	6.0	11.9	12.8	11.1	-	3.8
Maximum	12.4	8.3	11.7	11.8	36.1	35.5	29.4	-	6.1
Avg/Min	2.7	1.8	2.0	3.1	2.3	2.7	4.0	-	3.6
Max/Min	5.5	3.0	3.8	6.1	7.1	7.4	10.5	-	5.7
HPS									
Minimum	1.8	2.4	4.0	2.7	4.0	8.9	-	-	0.9
Mean	8.2	4.3	11.1	12.2	27.0	22.3	-	-	3.1
Maximum	22.4	11.3	34.5	34.2	71.7	57.8	-	-	8.1
Avg/Min	4.5	1.8	2.8	4.5	6.7	2.5	-	-	3.4
Max/Min	2.7	2.6	3.1	2.8	2.7	2.6	-	-	2.6

Measured/Predicted Maintained Illuminance[a]

Roadway

Site Label	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Category	**150**	**100**	**250**	**250**	**400**	**400**	**150**	**250**	**100**
Design Criteria									
E_{avg} (lux)	6.3	4.4	12.0	12.0	17.0	17.0	6.3	12.0	4.4
$E_{avg/min}$	6:1	6:1	2.9:1	2.9:1	2.5:1	2.5:1	6:1	2.9:1	6:1
LED (Initial)									
Total LLF	0.56	0.63	0.56	0.56	0.56	0.56	0.56	0.56	0.63
Minimum	3.7	4.0	2.4	2.3	4.9	3.6	4.9	4.2	2.3
Mean	6.0	6.2	7.5	10.2	16.6	8.8	10.3	10.0	5.5
Maximum	9.6	11.7	21.4	24.5	37.6	17.8	21.8	20.4	9.5
Avg/Min	1.6	1.6	3.1	4.5	3.4	2.4	2.1	2.4	2.4
Max/Min	2.6	3.0	8.9	10.8	7.6	4.9	4.5	4.9	4.1
HPS									
Total LLF	0.68	0.68	0.54	0.54	0.54	0.54	0.68	0.54	0.68
Minimum	2.2	2.9	3.0	2.5	7.0	7.2	3.0	3.6	1.0
Mean	12.6	7.3	10.5	11.2	18.7	16.7	9.8	9.2	5.3
Maximum	36.2	18.2	38.4	38.9	56.4	52.5	23.3	31.6	15.6
Avg/Min	5.6	2.6	3.5	4.4	2.7	2.3	3.3	2.5	5.6
Max/Min	16.3	6.4	12.7	15.3	8.0	7.3	7.8	11.3	16.4

Sidewalks

Site Label	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Category	**150**	**100**	**250**	**250**	**400**	**400**	**150**	**250**	**100**
Design Criteria									
E_{avg} (lux)	2.0	1.8	5.7	5.7	9.0	9.0	2.0	5.7	1.8
$E_{avg/min}$	5.3:1	7:1	2.7:1	2.7:1	2.7:1	2.7:1	5.3:1	2.7:1	7:1
LED (Initial)									
Total LLF	0.56	0.63	0.56	0.56	0.56	0.56	0.56	0.56	0.63
Minimum	1.3	1.7	1.7	1.1	2.9	2.7	1.6	-	0.7
Mean	3.4	3.1	3.5	3.4	6.6	7.2	6.2	-	2.4
Maximum	6.9	5.2	6.6	6.6	20.2	19.9	16.5	-	3.8
Avg/Min	2.7	1.8	2.0	3.1	2.3	2.7	4.0	-	3.6
Max/Min	5.5	3.0	3.8	6.1	7.1	7.4	10.5	-	5.7
HPS									
Total LLF	0.68	0.68	0.54	0.54	0.54	0.54	0.68	0.54	0.68
Minimum	1.2	1.6	2.2	1.5	2.2	4.8	-	-	0.6
Mean	5.6	2.9	6.0	6.6	14.6	12.0	-	-	2.1
Maximum	15.2	7.7	18.6	18.5	38.7	31.2	-	-	5.5
Avg/Min	4.5	1.8	2.8	4.5	6.7	2.5	-	-	3.4
Max/Min	2.7	2.6	3.1	2.8	2.7	2.6	-	-	2.6

(a) In the table, light loss factors are applied to initial measured illuminance data to estimate future performance—and thus to assess whether a product is likely to meet the design specifications over time. Five of the LED products (types A, C, D, F, and H) and the HPS luminaires at two of the sites (C and D) are predicted to not meet the specified mean illuminance over time.

Appendix D

Meter Data

Meter Type	Manufacturer	Model #	Owner	Last Calibration	Website for More Information
Illuminance	Solar Light	PMA2200	EPRI	Not reported	http://solarlight.com/product/pma2200-single-input-radiometer/
Illuminance	Solar Light	PMA1130-D (Mounted on Scotty)	EPRI	1/2011	http://solarlight.com/product/photopic-light-sensor-analog-pma1130/
Illuminance	Gigahertz-Optik	HCT-99D w/ CT-4501 Detector	KCMO	12/2010 and 5/2011	http://www.gigahertz-optik.de/29-1-HCT-99D+.html
Illuminance	Minolta	T-1	PNNL	2/2011	http://sensing.konicaminolta.us/products/t-10a-illuminance-meter/
Luminance	Photo Research, Inc.	PR-810L Pritchard / MS-75	Photo Research	2/2011	http://www.photoresearch.com/current/pr810.asp?type=2
Luminance	Minolta	LS-100	Kansas City	12/2010	http://sensing.konicaminolta.us/products/ls-100-luminance-meter/