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LED Roadway Luminaires Evaluation - Final Report

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LED Roadway Luminaires Evaluation

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MoDOT

Report Prepared for Missouri Department of Transportation
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LED Roadway Luminaires Evaluation (TRyy1101)
Final Report

Prepared for
Missouri Department of Transportation
Organizational Results

by

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Executive Summary

Nationally, there is considerable interest in moving to the use of LED roadway luminaires. This sustainable solution, much like the LED traffic signal indication solution implemented over the past ten plus years, provides the following benefits:

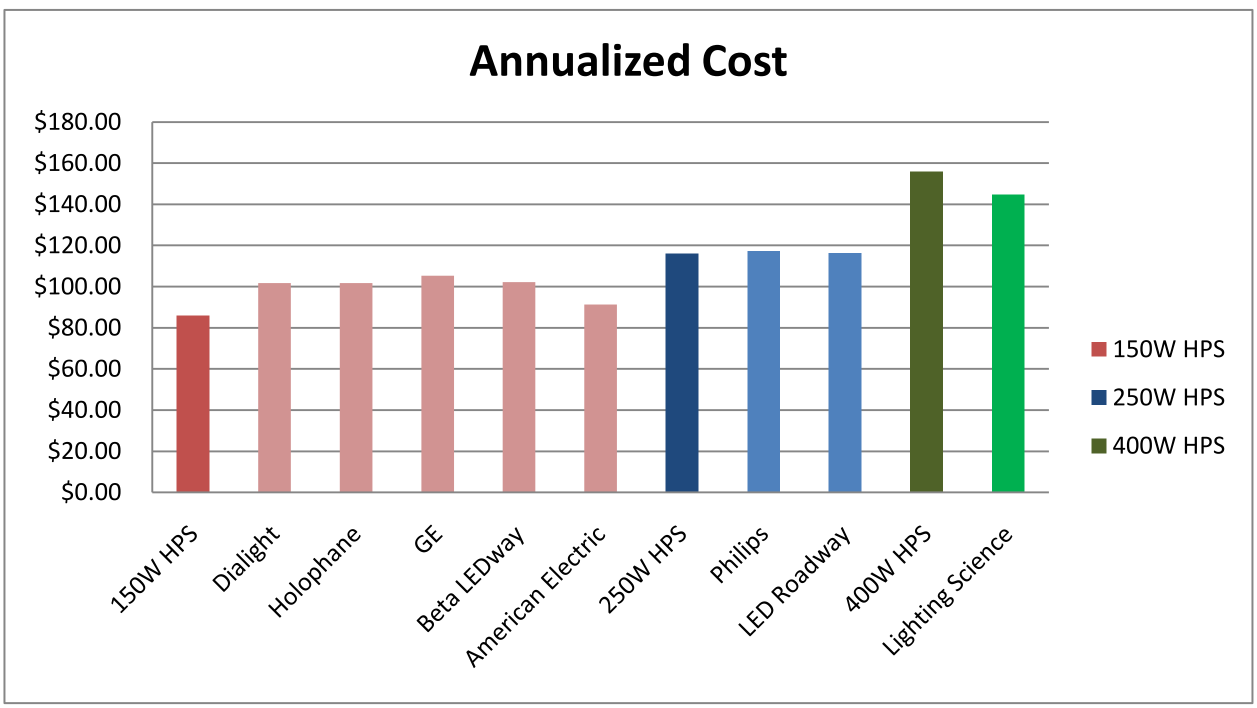
- Longer life roadway luminaires
- Reduced maintenance and operation cost
- Low energy cost
- Less impact to the environment

The Missouri Department of Transportation (MoDOT), like other local agencies across Missouri and our nation, understands and realizes the potential benefits of LED roadway luminaires. This evaluation was conducted to assist MoDOT in making an informed decision on whether or not they should pursue the transition from their current standard of using high pressure sodium (HPS) to using LED roadway luminaires.

LED roadway luminaires research and development has lagged behind the proven LED signal indicator technology for various reasons, however, over the past several years the LED roadway luminaire industry has invested significant research and development efforts in producing a quality product that is very comparable to HPS roadway luminaires.

Table 1 below shows the cost comparison between the three different HPS luminaires currently used by MoDOT and their equivalent counterpart LED luminaires. For the most part, they are very close in annual cost when evaluated over the expected 12-year LED luminaire life (based on a 50,000 hour LED luminaire life expectancy with an annual usage rate of 4000 hours).

Figure 1: Annualized Cost of HPS Equivalent LED Luminaires



Two potential variables not calculated in the annual cost were discount pricing for large annual acquisition (i.e. 2000 luminaires per year for 10-year replacement program) and the potential reduction in price experienced as the economy of manufacturing (or economy of scale) is achieved. For example, based on increased demand, LED traffic signal indicators experienced a 40 to 50% reduction in initial cost.

Although only select LED luminaires are a break even solution when compared to HPS (see Figure 1), LED technology is changing rapidly and additional products are expected to offer cost effective solutions in the near future. The following are other factors that should also be considered in determining future direction for roadway lighting:

- **Maintenance Cost** - labor and equipment costs are major components under the HPS luminaire scenario. There are four HPS installation/maintenance responses required compared to one for the LED luminaire scenario over the 12-year life expectancy for LED luminaires. Based on a comprehensive literature research of national evaluations, a three-year life expectancy for HPS was predominately used.
- **Safety –** workers and roadway users will experience less exposure to maintenance activities along major corridors with LED luminaires.
- **Demand -** the national interest by the Department of Energy (DOE), other local and state agencies and the lighting industry demonstrates a strong trend towards LED roadway luminaires and away from HPS roadway luminaires.
- **Previous technology transition -** in the 1980's, a similar transition from mercury vapor roadway luminaires to HPS roadway luminaires was made. This transition was completed over a ten year period and was implemented due to power cost savings (luminaire's cost and lifecycle were about the same) and concerns with the disposal of mercury, a hazardous material.

Two prevailing issues surfaced in our evaluation – cost effectiveness and performance. Based on previous trends in LED technologies, the LED roadway luminaires should experience a reduction in cost based on the economy of increased manufacturing. This fact will make LED roadway luminaires a more cost effective solution.

Performance was a major issue in early development of LED roadway luminaires. Most manufacturers invested in product development to ensure that LED roadway luminaires performed at similar or higher performance levels as the HPS roadway luminaires. These initial investments were focused at 30 foot mounting height luminaires and have in the recent past moved towards mounting heights of 40 feet or higher. Based on factors mentioned above and information contained in this report, we would recommend MoDOT consider the development of a future transition program from HPS to LED roadway luminaires when both cost and performance stabilizes.

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Table of Contents

List of Figures

List of Tables

Introduction

LED roadway luminaires are being evaluated and considered across our nation by many local and state agencies. Major evaluations are being conducted in Kansas City, St. Louis and Springfield regions in conjunction with the Department of Energy (DOE). LED roadway luminaires have been installed on state highways in the Central, Southeast and St. Louis Districts for initial evaluations.

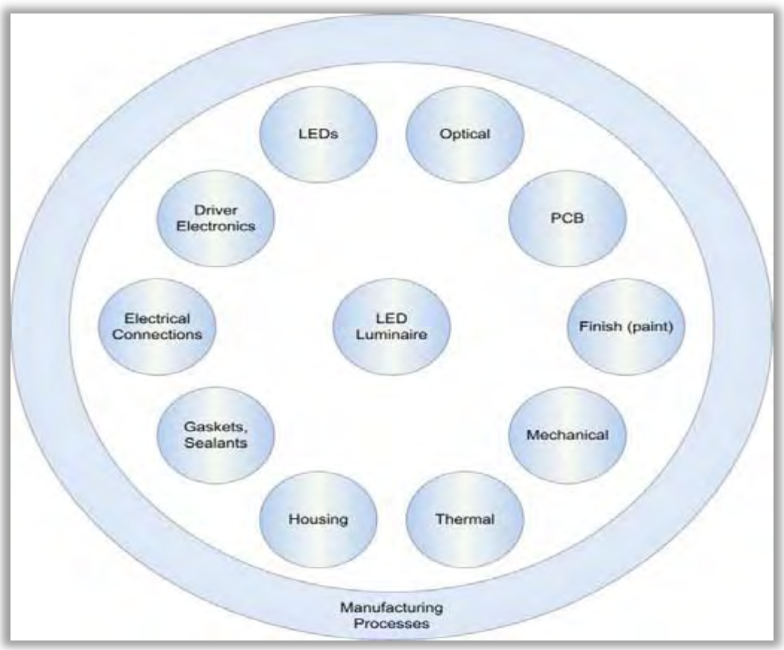
These initial evaluations are being conducted on several different generations of LED luminaire technologies. The LED roadway luminaire manufacturers are working closely with the DOE and public agencies in advancing technologies that meets and exceeds lighting standards. The national independent organization, Municipal Consortium, is a great example of this cooperative effort.

Figure 2 below reflects the various reliability factors that have driven the LED luminaire industry development of producing a high quality roadway luminaire over the past several years.

These factors have resulted in the development of several generations (between 2 to 4 manufacturer specific generations) of luminaires. With each generation, a higher quality luminaire was developed. Performance enhancements addressed luminaire heat dissipation, luminaire mounting heights and spacing, LED arrays, electrical drivers, and other concerns.

These cooperative efforts have and will continue to help guide the LED luminaire industry. In this report, the reader will notice these generation changes. It also points to an important factor that each manufacturer's generation brings improvements that need to be validated within the agency's acquisition process.

Figure 2: Total System Luminaire Reliability[2]



The roadway luminaire industry is moving towards a more sustainable roadway lighting solution that could be cost effective to both state and local agencies. This report provides information on recent past performance on LED roadway luminaires, a feasibility study and a potential program to transition from HPS to LED roadway luminaires.

Objectives

The purpose of this evaluation study was to determine the feasibility of transitioning from a high pressure sodium (HPS) roadway luminaire to LED roadway luminaire on the MoDOT maintained highway system. This study included performance evaluations, a feasibility analysis and a potential transition replacement program.

Present Conditions

LED roadway luminaires are being evaluated and installed across our country by various state and local agencies and utility companies. The benefits of longer life roadway luminaires; reduced future maintenance and operation cost; low energy cost; and less impact to the environment have driven installations across our nation. These similar factors drove the replacement of traffic signal indications with LEDs.

There is an orchestrated effort between manufacturers, governmental agencies and utilities to produce a very high quality LED roadway luminaire. These efforts have produced two to three generations of LED roadway luminaires that continue to address concerns and makes enhancements to LED roadway luminaire.

Initial cost of LED roadway luminaires is a factor that is similar to any new technology deployment. It was observed when LED signal indications were installed with higher initial costs. It will drive any potential transitional roadway luminaire replacement program. Manufacturer cost should reduce as demand and production are increased.

Results and Discussion (Evaluation)

Task 1: Identification and evaluation of the performance of eight (8) commercial LED roadway luminaires based on the following:

LED Luminaire Data Collection Methodology

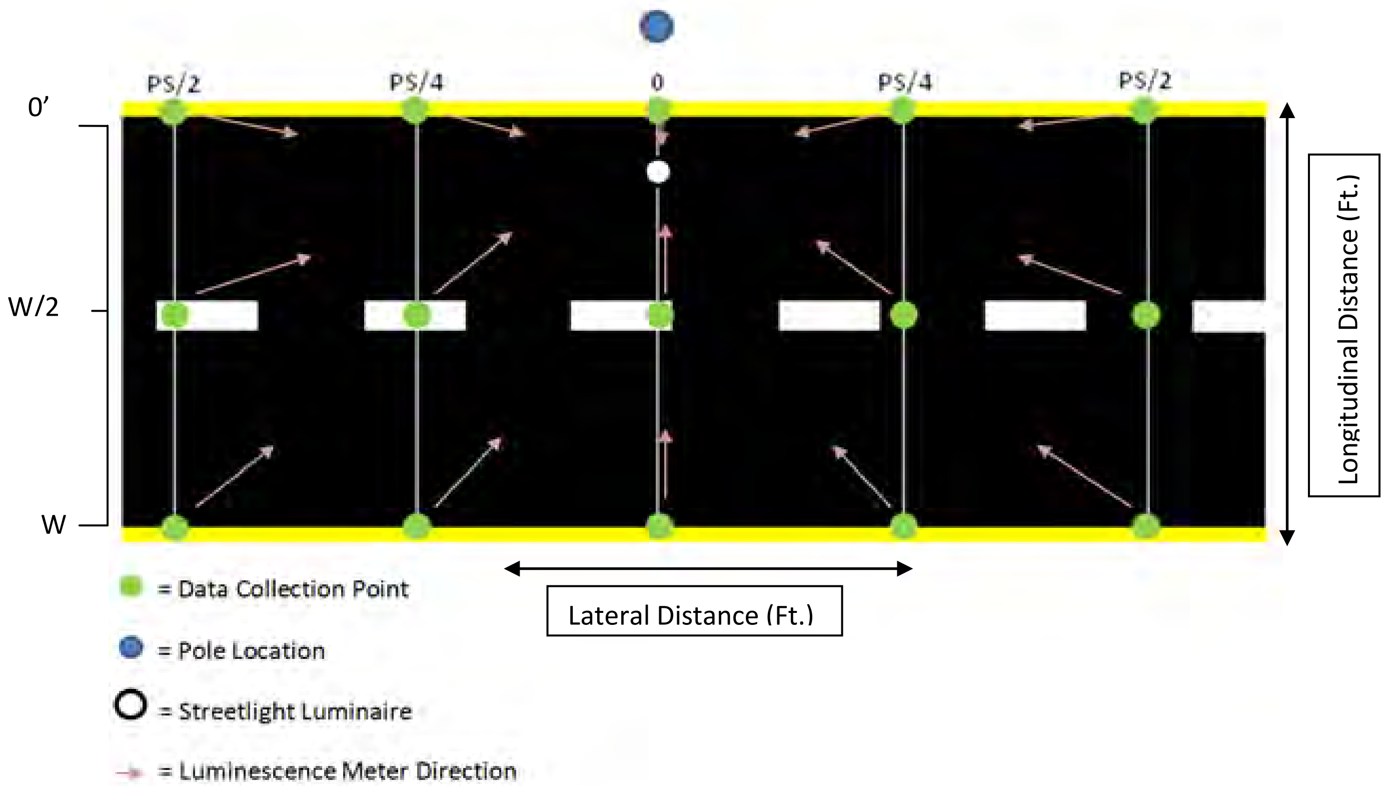
Illumination readings were collected for LED luminaires throughout the state of Missouri. The luminaires studied are currently used on roadways throughout Missouri. These readings were collected for LEDs produced by several manufacturers at varying power levels. The four requested manufacturers of LED streetlight luminaires (Dialight, GE, Phillips, Holophane), in addition to four others (Beta LEDway, American Electric, LED Roadway and Lighting Science Group), are included in the collected data.

Data collection locations were based on a function of the pole spacing between luminaires and the width of the traffic lane at the location of the luminaire. In order to minimize the effect of other nearby luminaires, luminescence readings were collected such that the reading is collected specifically for one luminaire. Data collection intervals in the direction parallel to the road are equal to one quarter of the pole spacing, the distance between two luminaires. Perpendicular data collection intervals along the road were collected in intervals equal to one lane of traffic.

A total of 31 readings were collected for each luminaire. These readings included 15 readings at ground level and 15 readings elevated 18 inches above ground level in addition to one ambient reading collected in a non-illuminated area near the luminaire. Ambient readings were collected in order to determine the impact of light sources naturally occurring outside of the studied luminaire, such as nearby outdoor area lighting. These ambient readings were subtracted from the field readings to calculate adjusted field readings, which were then used to compare to each luminaire's IES file data. Figure 3, shown below, indicates the locations used for data collection as well as the direction of the luminescence meter.

Once data collection was completed, the luminescence readings were compared to each luminaire's IES file to validate the manufacturer's claims. Initially, GE's ALADAN software was used for IES data, but the program did not contain the requisite depth and flexibility for this analysis. Therefore, the IES files were analyzed using Visual's Roadway Lighting Tool. The variation between the field data and each manufacturer's claim was analyzed.

Figure 3: LED Field Testing Locations



Field Data Evaluation and Assessment

Figure 4 - Holophane (Generation 1) Illumination Difference

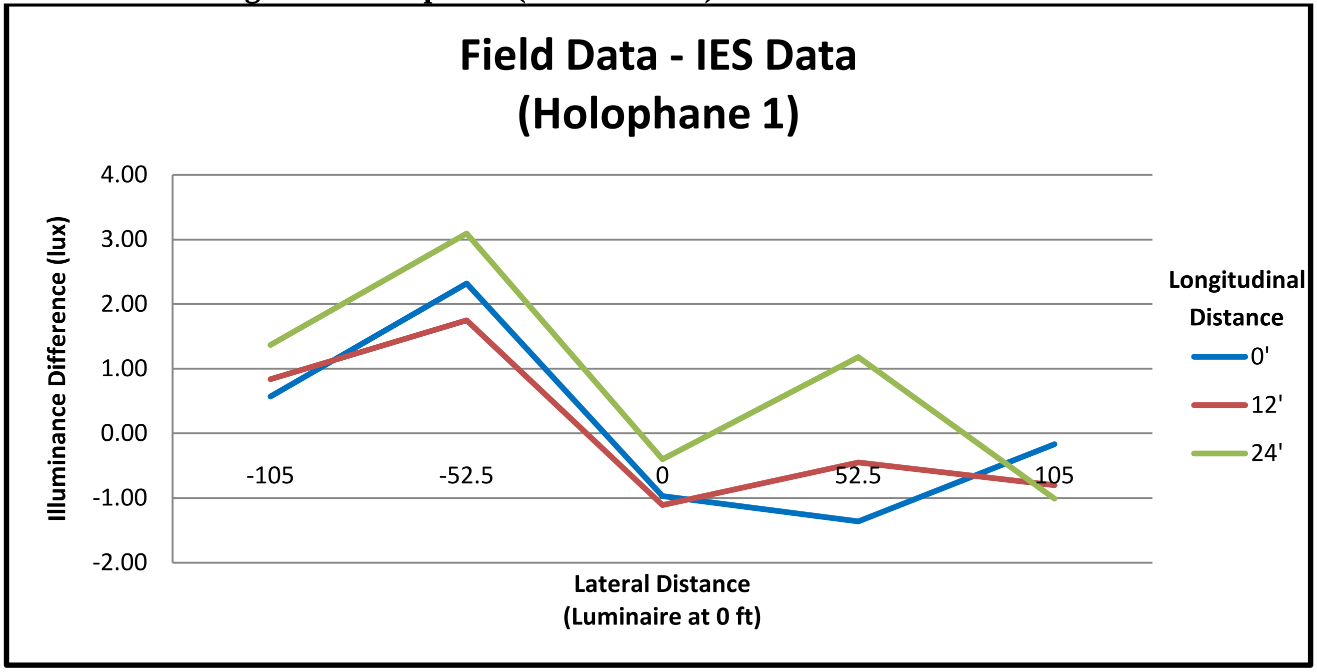


Table 1: Holophane (Generation 1) Illuminance Ratios

	Field Data (lux)	IES File Data (lux)	IES Standard
Max	9.20	10.30	----
Min	0.63	0.80	----
Avg	4.98	4.65	> 13.0
Max/Min	14.60	12.88	< 6.0
Avg / Min	7.90	5.82	< 3.0

*Red text denotes not meeting IES specifications

The first generation of Holophane products does not meet any of the Illumination Engineering Society's (IES) standards set in RP-08. Using IES standards, neither the field readings nor the IES data come close to meeting the IES standard of a minimum average of 13.0 lux (this standard is for moderately busy, major roads with R3 asphalt classification). The desired Average: Minimum uniformity ratio for such a road is 3.0 and a Maximum: Minimum uniformity ratio of 6.0. The first generation of LED luminaires by Holophane does not meet these standards.

Figure 5 - Holophane (Generation 2) Illumination Difference

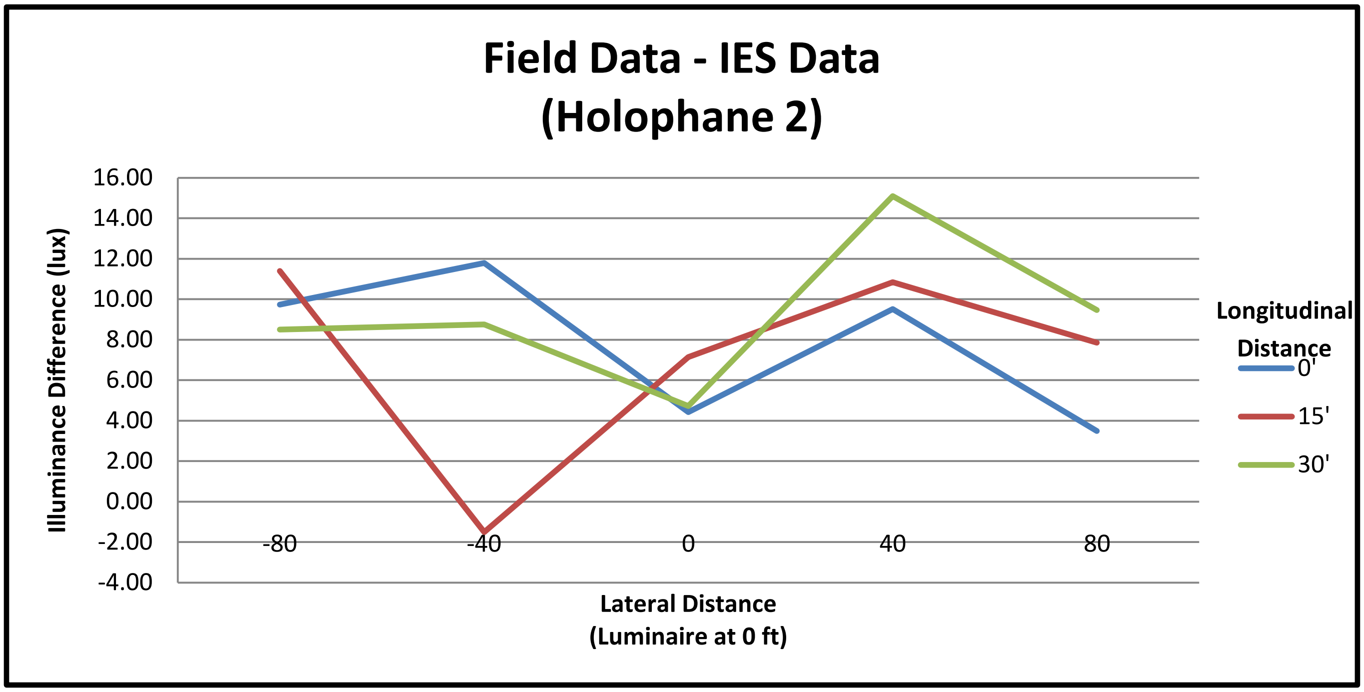


Table 2 - Holophane (Generation 2) Illumination Ratios

	Field Data (lux)	IES Data (lux)	IES Standard
Max	32.74	25.30	----
Min	7.99	2.40	----
Avg	20.07	11.99	> 13.0
Max/Min	4.10	10.54	< 6.0
Avg/Min	2.51	5.00	< 3.0

*Red text denotes not meeting IES specifications

Based on photometrics, the 2nd generation of Holophane LED luminaires appears to be a very strong candidate for replacing 150 watt HPS luminaires. Outside of one reading [(15,-40)], the collected field data is consistently above the IES data by six or more lux. The Maximum: Minimum Uniformity ratio is 4.1, which is less than the recommended 6.0 ratio. The Average: Minimum Uniformity ratio is less than 2.51, which is less than the IES recommended ratio of 3.0. In addition, the average illuminance is 20.07 lux, which is significantly higher than the recommended 13.0 lux. The uniformity ratios are below the IES recommendations and the average illuminance exceeds the IES recommended illuminance.

Due to the consistently higher field data, it appears the luminaire may be being driven above the IES file specifications and maybe above the recommended manufacturer’s settings. Monitoring electrical power usage and comparing them to manufacturer’s recommendations could clarify this potential issue. Overdriving luminaires negatively impacts the luminaire’s lifetime as well as lifetime energy consumption. A LED array’s life expectancy is based on a driver’s electrical current input to the array. Overdriving the electrical current to the LED array will increase lighting output; however, it will reduce the life of the LED array and increase power consumption.

Figure 6 - Philips Illumination Difference

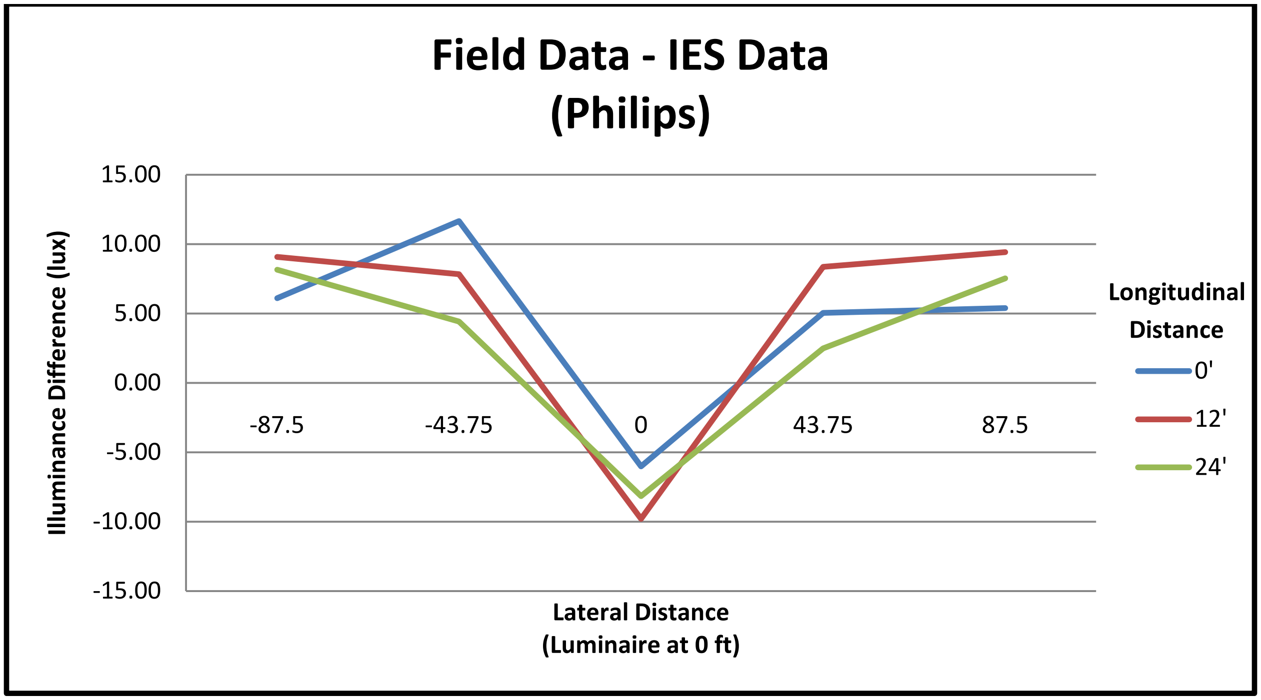


Table 3: Philips Illuminance Ratios

	Field Data (lux)	IES Data (lux)	IES Standard
Max	38.58	44.6	----
Min	9.79	4.4	----
Avg	18.79	14.69	> 13.0
Max/Min	3.94	10.14	< 6.0
Avg / Min	1.92	3.34	< 3.0

*Red text denotes not meeting IES specifications

Based on photometrics, the Philips LED luminaire appears to be a strong candidate for implementation. The field data gathered shows the Philips luminaire meets and exceeds the recommended IES standards in each area. The field data collected for this luminaire exceeds the IES data by an average of 4.3 lux. This discrepancy may be due to interference from a separate light source.

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Figure 7 - GE Illumination Difference

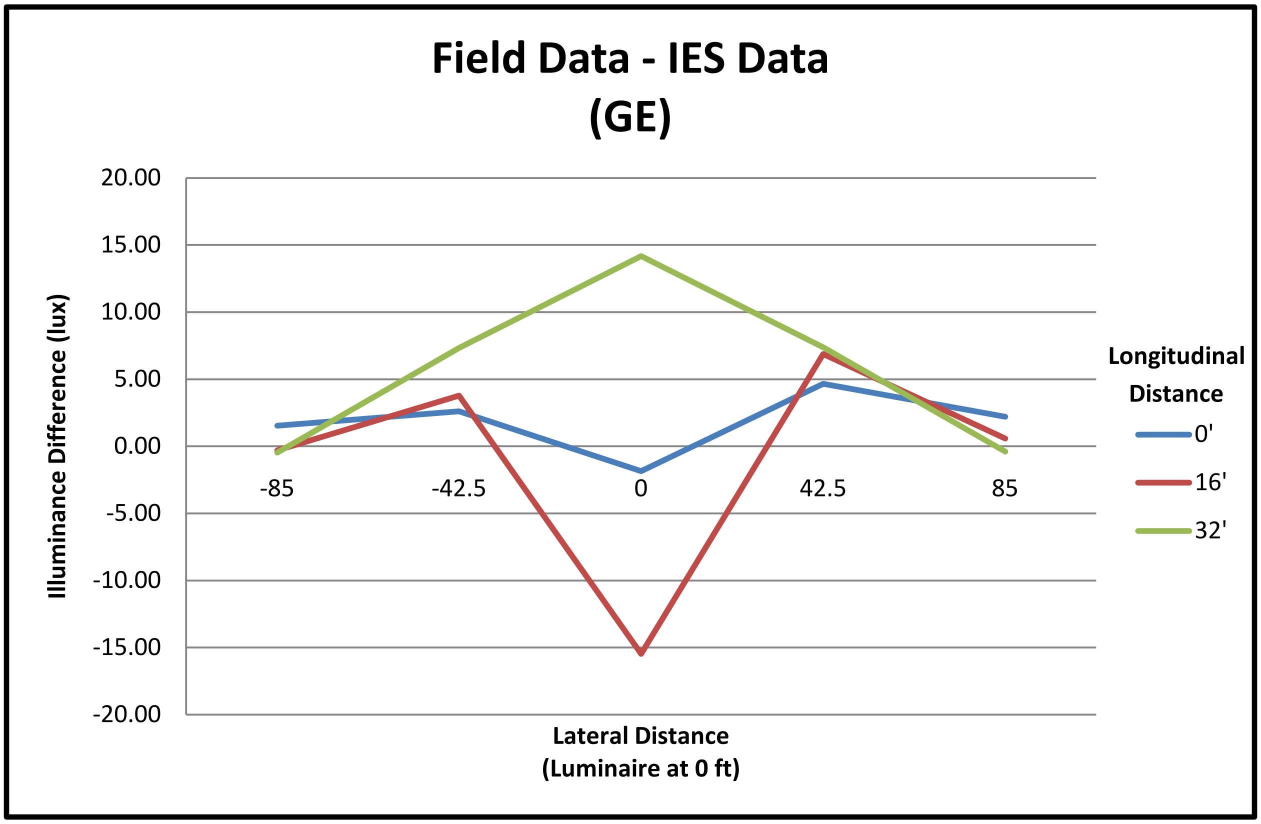

Table 4: GE Illuminance Ratios

	Field Data (lux)	IES Data (lux)	IES Standard
Max	33.53	49	----
Min	4.04	2.5	----
Avg	11.58	9.40	> 13.0
Max/Min	8.30	19.60	< 6.0
Avg / Min	2.87	3.76	< 3.0

*Red text denotes not meeting IES specifications

Using the recommended IES standards for roadway illumination, the GE luminaire is not satisfactory for use as a replacement for HPS luminaires. The GE LED luminaire does not meet the minimum average of 13.0 lux, nor does the luminaire satisfy the desired uniformity ratios, except for the average/minimum uniformity ratio for the field data.

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Figure 8 - Beta LEDway Illuminance Difference

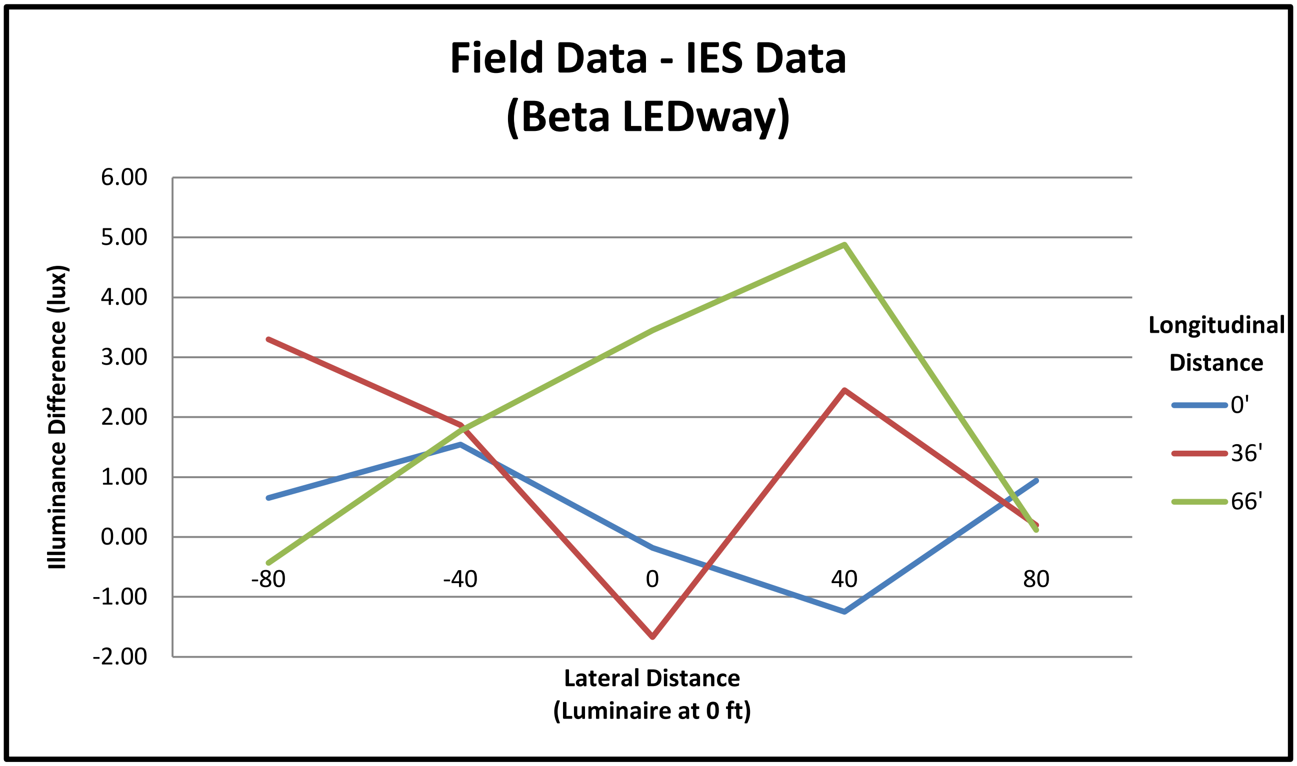

Table 5: Beta LEDway Illuminance Ratios

	Field Data (lux)	IES Data (lux)	IES Standard
Max	8.94	9.4	----
Min	1.97	2.4	----
Avg	5.60	4.23	> 13.0
Max/Min	4.54	3.92	< 6.0
Avg / Min	2.84	1.76	< 3.0

*Red text denotes not meeting IES specifications

The field data for this particular Beta LEDway luminaire is greater than or equivalent to the related IES file. Although the field data matches the IES file, the average illuminance for this Beta LEDway luminaire is not sufficient to meet the suggested recommendations by the Illumination Engineering Society. The IES recommendation requires an average minimum of 13.0 lux, which is significantly greater than the 5.6 lux from the collected field data.

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Figure 9 - American Electric Illuminance Difference

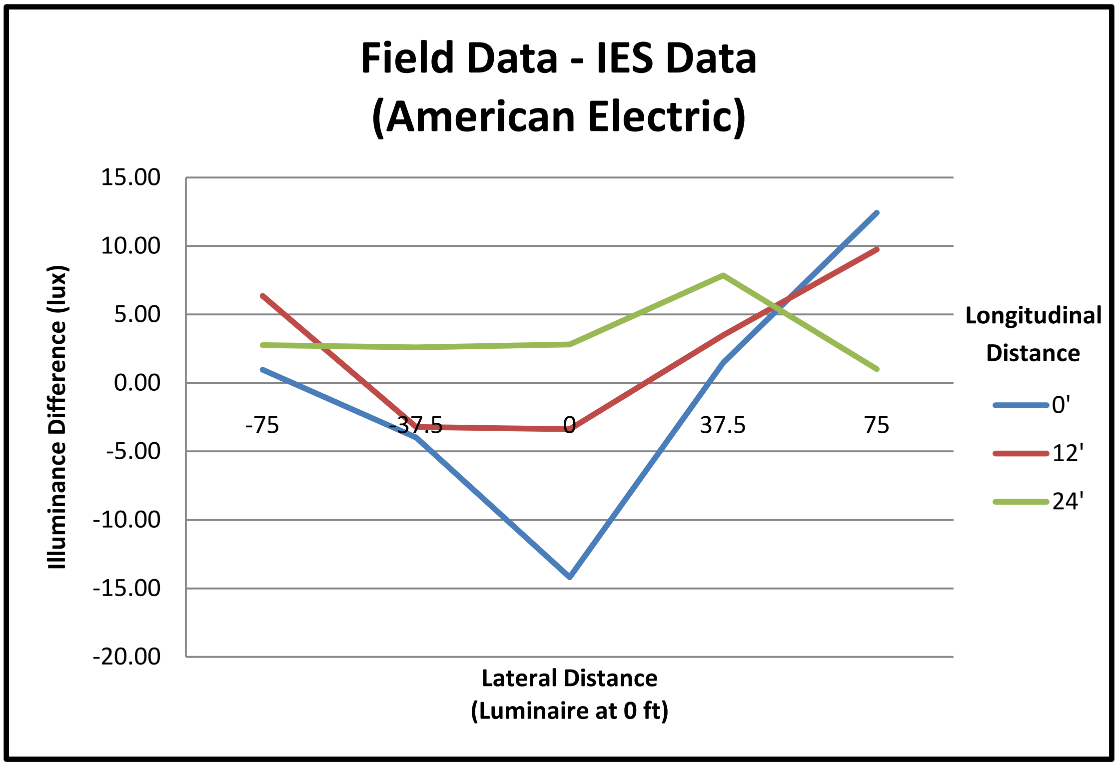

Table 6: American Electric Illuminance Ratios

	Field Data (lux)	IES Data (lux)	IES Standard
Max	30.51	30.00	----
Min	7.06	6.10	----
Avg	16.53	14.75	> 13.0
Max/Min	4.32	4.92	< 6.0
Avg / Min	2.34	2.42	< 3.0

*Red text denotes not meeting IES specifications

For this American Electric LED luminaire, the minimum, maximum, and average values of the field data lines up with the IES files. Based on the difference between the IES values and the field values, there may be interference, or error, within the field data collected. The average illuminance of the IES data and the field data exceed the minimum average illuminance recommended by IES for major, moderately traveled roads. In addition, the uniformity ratios of the field and IES data are within range of IES recommendations. Therefore, from a lighting design perspective, this LED luminaire is feasible to implement.

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Figure 10 - LED Roadway Illuminance Difference

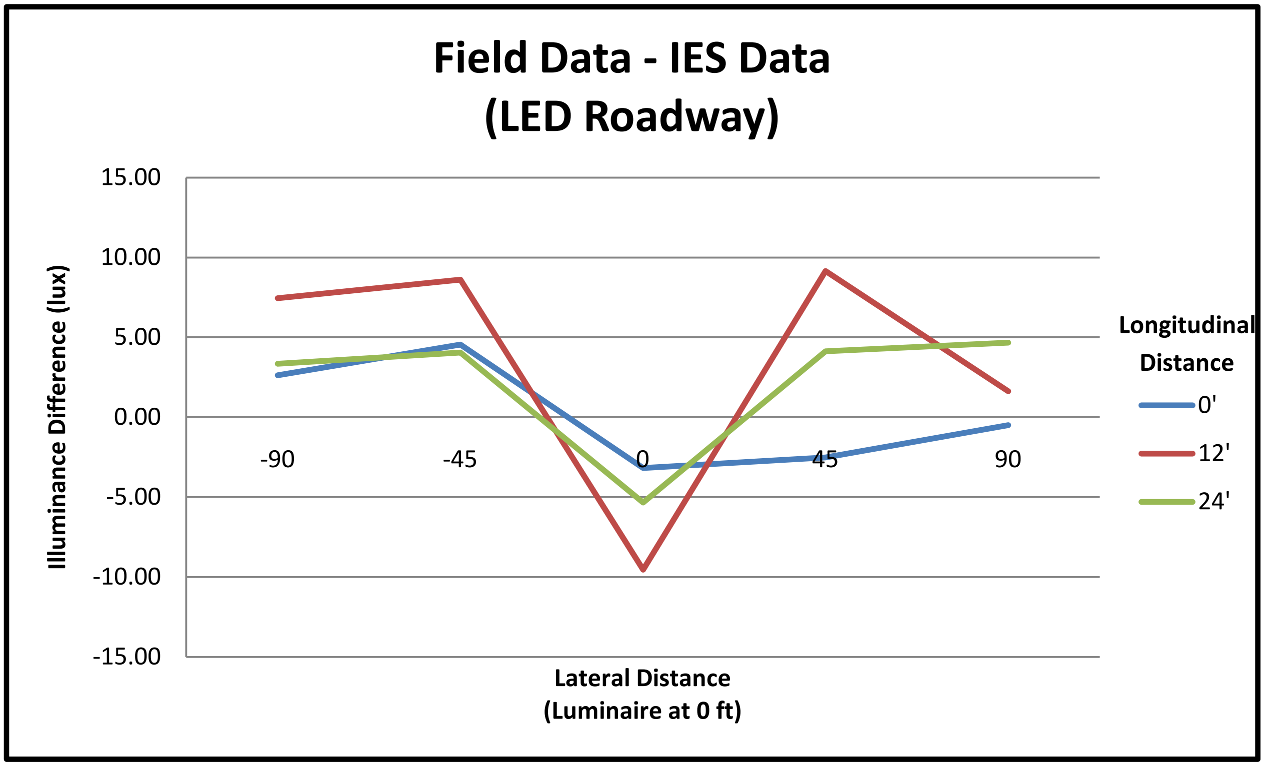

Table 7: LED Roadway Illuminance Ratios

	Field Data (lux)	IES Data (lux)	IES Standard
Max	30.51	30.00	----
Min	7.06	6.10	----
Avg	16.53	14.75	> 13.0
Max/Min	4.32	4.92	< 6.0
Avg / Min	2.34	2.42	< 3.0

The LED Roadway luminaire appears to be promising for implementation. The LED Roadway luminaire meets the IES recommendations for minimum average illuminance, maximum/ average uniformity ratio, and average/minimum uniformity ratio. In addition, the minimum, maximum, and average field values match the IES data.

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Figure 11 - Dialight Illuminance Difference

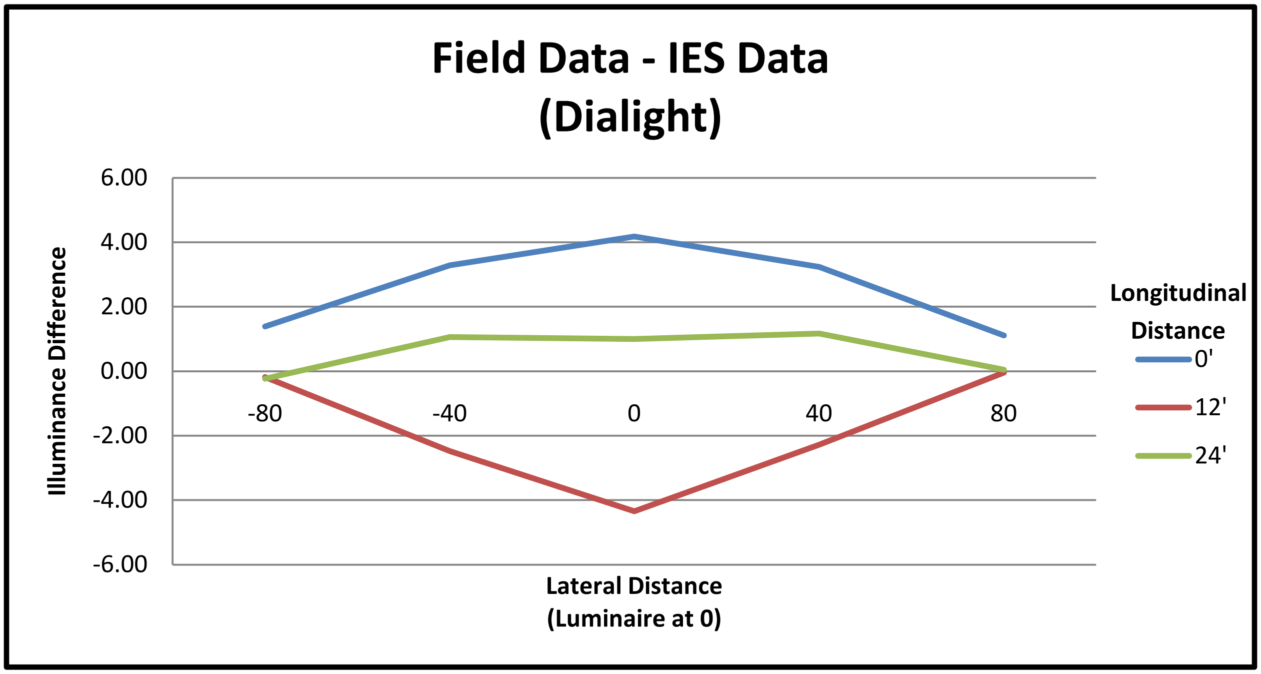

Table 8: Dialight Illuminance Ratios

	Field Data (lux)	IES Data (lux)	IES Standard
Max	12.78	12.10	----
Min	4.17	3.20	----
Avg	7.21	7.19	> 13.0
Max/Min	3.06	3.78	< 6.0
Avg/Min	1.73	2.25	< 3.0

*Red text denotes not meeting IES specifications

The Dialight LED luminaire was the only luminaire tested at a 45 foot mounting height. This greatly impacts the acceptability of the luminaire. Although the luminaire meets the recommended uniformity ratios and the IES data matches the data collected in the field, the minimum average illuminance of 13.0 lux was not met. This luminaire simply was not providing enough light to properly light the roadway at a 45 foot mounting height. This luminaire is not acceptable to use at a 45 foot mounting height. A manufacturer current production generation at 30 foot mounted height should be tested. An earlier generation was used in Cape Girardeau at a 30 foot mounting height is no longer in production and may not be desirable to be tested based on future availability.

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Figure 12 – Lighting Science Group Illuminance Difference

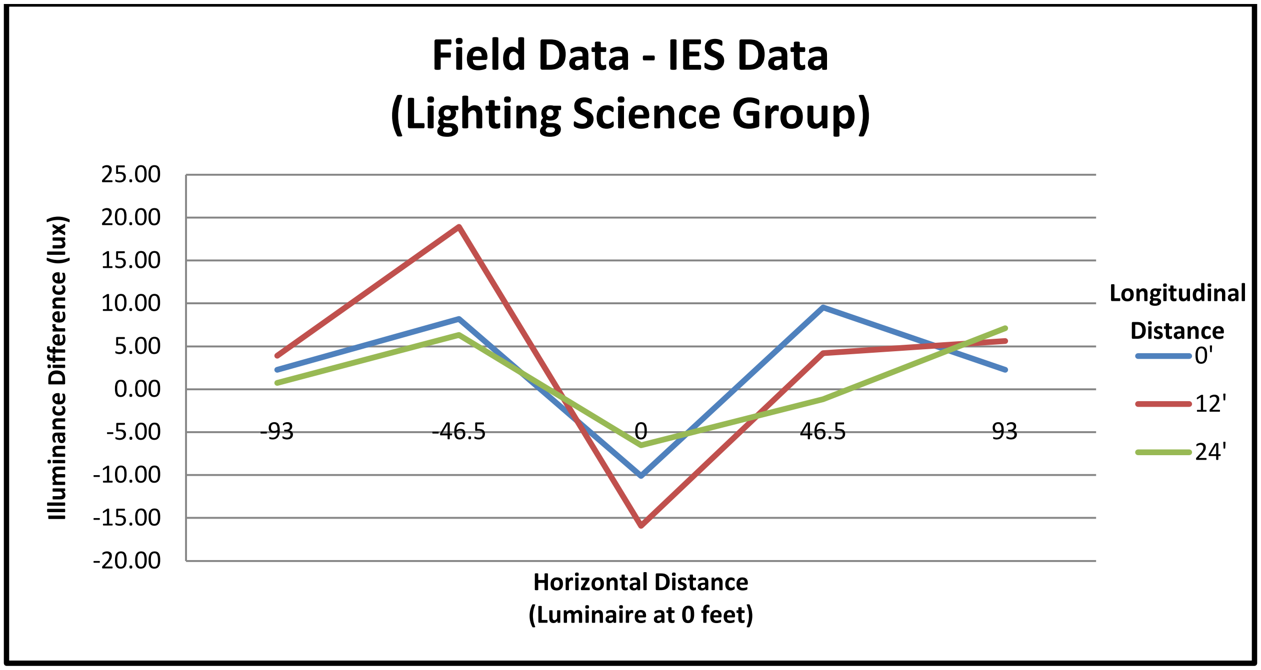

Table 9: Lighting Science Illuminance Ratios

	Field Data (lux)	IES Data (lux)	IES Standard
Max	35.11	41.4	----
Min	4.35	2.1	----
Avg	17.55	17.67	> 13.0
Max/Min	**8.07**	**19.71**	< 6.0
Av2g/Min	**4.07**	**8.42**	< 3.0

*Red text denotes not meeting IES specifications

The Lighting Science Group luminaire exceeds the uniformity ratios recommended by the IES, yet the analysis shows that the luminaire still performs strongly with respect to average illuminance output. The readings indicate the illuminance levels far exceed the required average minimum of 13.0 lux. The mounting height for this luminaire used a 30 foot with a 10 foot tenon arm, which extends the height of the pole above 30 feet. Although this luminaire's field reading results exceeds the recommended uniformity ratios by approximately 25%, the average illumination produced by this luminaire (17.55 lux) far exceeds the recommended average illumination recommended by IES (13.0 lux), which is why our research team recommends this luminaire.

Summary of Task 1 Results

Four out of the nine luminaires were deemed acceptable to use for 30 foot mounting heights. Field data was very limited for luminaires at 45 foot mounting heights. Municipalities and utilities have normally tested LED fixtures at mounting heights of 30 foot or less, since a very high percentage of luminaires are installed at these heights. Newer LED roadway luminaire generations are being designed to address the higher mounting heights.

More information on the specifics of each luminaire can be found in Table 13 of this report.

The field data collected and the IES data values can be obtained from Appendix A of this report.

Task 2: Perform economic comparison analysis of LED roadway lighting with existing light sources

The fiscal feasibility for LED luminaires is dependent upon several factors. First, luminaires must be grouped and compared to the most appropriate high pressure sodium luminaire to establish accurate equivalency. Recently, manufacturers have been producing LED luminaires that are specifically used to replace traditional high-intensity discharge (HID) lamps. This is advantageous for transportation organizations because of the possibility of directly replacing traditional luminaires with LED luminaires.

Second, the fiscal feasibility of LED luminaires rely heavily on the assumptions made pertaining to lifetime, labor hour cost, overhead, equipment costs, repair costs, discounts for ordering in large quantities, and electricity efficiency. The assumptions in this economic analysis include: replacing HPS luminaires after three years, LED luminaires remain in operation for 12 years, labor cost for relamping or retrofitting luminaires is $60, and the costs for replacing high pressure sodium lamps for 150 Watt, 250 Watt, and 400 Watt lamps is $100, $130, and $160 respectively.

The economic analysis assumes high pressure sodium luminaires are replaced every three years. This assumption can easily change to reflect a transportation agency's views of scheduling HPS replacements. The assumption of three years accounts for the reduction in luminaire lifetime due to vibration and shock, which is prevalent along bridges and overpasses, and spot replacement of HPS luminaires. In contrast, spot replacement waits until the HPS lamp fails catastrophically, which maximizes the lifetime of each luminaire.

Another key assumption is LED luminaires will remain in operation for a 12 year life expectancy. Some manufacturers claim the life of their luminaire will operate beyond 50,000 hours (approximately 12 years with an annual usage of approximately 4000 hours), however the most common claim is a 12 year lifetime, and therefore 12 years was used for the economic lifetime.

Labor cost to retrofit or relamp a light pole with an LED or a HPS luminaire was assumed to be $60 per luminaire. With lighting labor costs around $25-$35 per hour, the labor cost was averaged and doubled to $60 in order to account for overhead, equipment cost, setup, and travel time for conservative estimate labor cost.

The costs for replacing high pressure sodium luminaires vary by the wattage of the lamp being replaced. For the lowest wattage bulb, a $100 cost is used which is based on related LED luminaire analyses. The costs of 250 Watt and 400 Watt bulbs were estimated to be $130 and $160 respectively. The costs are based on the cost of the lamp being replaced, the cost of labor repairing the lamp's ballast, and the cost of vehicles and equipment to travel to and reach the luminaire.

As previously mentioned, costs may be reduced once roadway lighting demand shifts its focus solely toward LEDs. Economies of scale will then be realized, such as they were for LED traffic signal indicators, and prices of LED luminaires will decrease significantly.

Life Cycle Analysis

To determine economic feasibility of LEDs all costs incurred to install, operate, and dispose of the luminaire are included in the analysis. The installation and disposal costs are accounted for in the retrofitting and relamping labor cost. In addition, the cost of powering the luminaire was calculated based on a sample of actual energy consumption. The actual energy consumption was then extrapolated to other luminaires based on relative wattages between the luminaires which energy consumption was known and other luminaires. Energy consumption for HPS luminaires was calculated using system wattages.

In order to make a fair comparison between HPS luminaires with assumed lifetimes of 3 years and LED luminaires with expected lifetimes of 12 years, the total cost to install and operate a luminaire was annualized. This allows for a fair economic comparison between products with varying lifetimes. An expected project return of 3% was used to annualize costs.

Using information from Tables 9-11, the annualized costs of LED luminaires is equivalent to or approaching equivalency to HPS lamps. This evaluation of the luminaires was based on pricing for small purchase orders, except for American Electric, which quoted a price for orders of 1,000 or more luminaires. More information on the calculations of annualized costs can be found in Appendix B.

Replacement Period Analysis

A potential methodology to level the roadway lighting expenditures while transitioning from HPS luminaires to LED luminaires would be to slowly phase in LED luminaires. By transitioning to LEDs at a rate of the inverse of the expected lifetime of LED luminaires, the annual investment in LEDs is uniform. For example, if LEDs are rated to last for 12 years of use, then 1/12 of lamps should be replaced with LEDs every year. This allows for approximately constant replacement of LED luminaires once the transition from HPS is completed because the failure rate of the LED luminaires will be evenly distributed throughout 12 years.

It would be further recommended to replace the LED luminaires in large, continuous sections. This will allow for more consistency in overhead street lighting for long sections of road. This will prevent luminaires from constantly switching between the high pressure sodium and LED luminaires.

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Table 10: Economic Analysis of 150 Watt Equivalent Luminaires

Life Cycle Analysis (150 W Equivalents)						
Product	150W HPS	Dialight	Holophane	GE	Beta LEDway	American Electric
Price	$100.00	$695.00	$695.00	$732.00	$700.00	$592.00
Expected Lifetime (years)	3	12	12	12	12	12
Expected Project Rate of Return	3%	3%	3%	3%	3%	3%
Pole Installation Costs	0	0	0	0	0	0
Relamping/Retrofit Labor Costs	$60.00	$60.00	$60.00	$60.00	$60.00	$60.00
Initial Cost per lifecycle	$160.00	$755.00	$755.00	$792.00	$760.00	$652.00
Annual Electricity Consumption	$29.28	$25.80	$25.80	$25.80	$25.80	$25.80
Annualized Cost	**$85.84**	**$101.65**	**$101.65**	**$105.37**	**$102.15**	**$91.30**

Table 11: Economic Analysis of 250 Watt Equivalent Luminaires

Life Cycle Analysis (250 W Equivalent)			
Product	250W HPS	Philips	LED Roadway
Price	$130.00	$700.00	$712.00
Expected Lifetime (years)	3	12	12
Expected Project Rate of Return	3%	3%	3%
Pole Installation Costs	0	0	0
Relamping/Retrofit Labor Costs	$60.00	$60.00	$60.00
Initial Cost per lifecycle	$190.00	$760.00	$772.00
Annual Electricity Consumption	$48.80	$41.00	$38.80
Annualized Cost	**$115.97**	**$117.35**	**$116.36**

Table 12: Economic Analysis of 400 Watt Equivalent Luminaires

Life Cycle Analysis (400 W Equivalent)		
Product	400W HPS	Lighting Science
Price	$160.00	$800.00
Expected Lifetime (years)	3	12
Expected Project Rate of Return	3%	3%
Pole Installation Costs	0	0
Relamping/Retrofit Labor Costs	$60.00	$60.00
Initial Cost per lifecycle	$220.00	$860.00
Annual Electricity Consumption	$78.08	$58.20
Annualized Cost	**$155.86**	**$144.60**

Table 13: 150W HPS and Studied LED Substitutes

Manufacturer	150W HPS	Dialight	Holophane	GE	Beta LEDway	American Electric
Model	-	SL2C4ELGH	LEDG-120-35-6K	GE Evolve R150	STR-LWY-3M-HT-05-D-UL-SV-700	ATB1-60-E70-120-R3-5K
Wattage	150	132	129	132	116	144
Initial Fixture Lumens	16,000	6,613	9,652	7,200	8,024	12,730
Lm/W	107	50.33	75	55	69.17	66
Assumed Lifetime (hours)	12,000	50,000	50,000	50,000	50,000	50,000
Assumed Lifetime (years)	3	12	12	12	12	12

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Table 14: 250W HPS and Studied LED Substitutes

Manufacturer	250W HPS	Philips	LED Roadway
Model	-	910403890312	SAT-96M
Wattage	250	181	200
Initial Fixture Lumens	25,000	17,716	11,950
Lm/W	100	96	59
Assumed Lifetime (hours)	12,000	50,000	50,000
Assumed Lifetime (years)	3	12	12

Table 15: 400W HPS and Studied LED Substitutes

Manufacturer	400W HPS	Lighting Science
Model	-	DBR2
Wattage	400	300
Initial Fixture Lumens	40,000	22,300
Lm/W	100	74
Assumed Lifetime (hours)	12,000	50,000
Assumed Lifetime (years)	3	12

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Figure 13 - Sensitivity Analysis of 150 W HPS

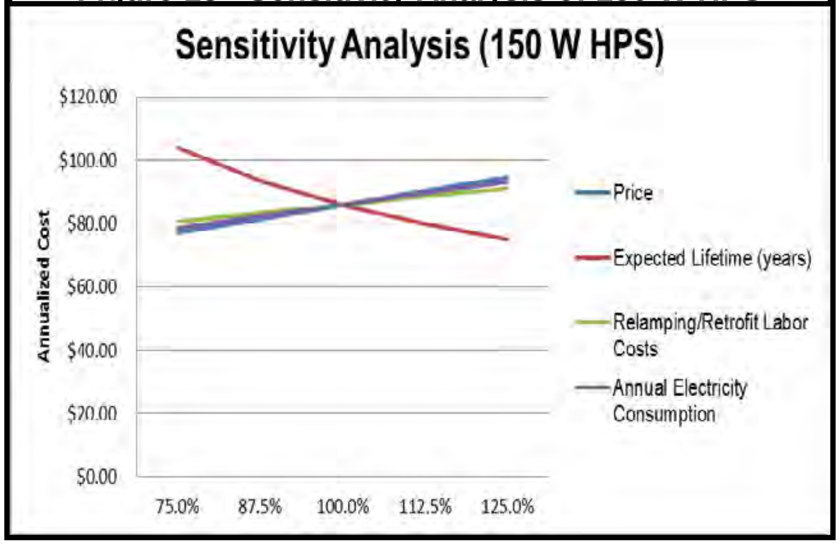


Figure 14 - Sensitivity Analysis of American Electric

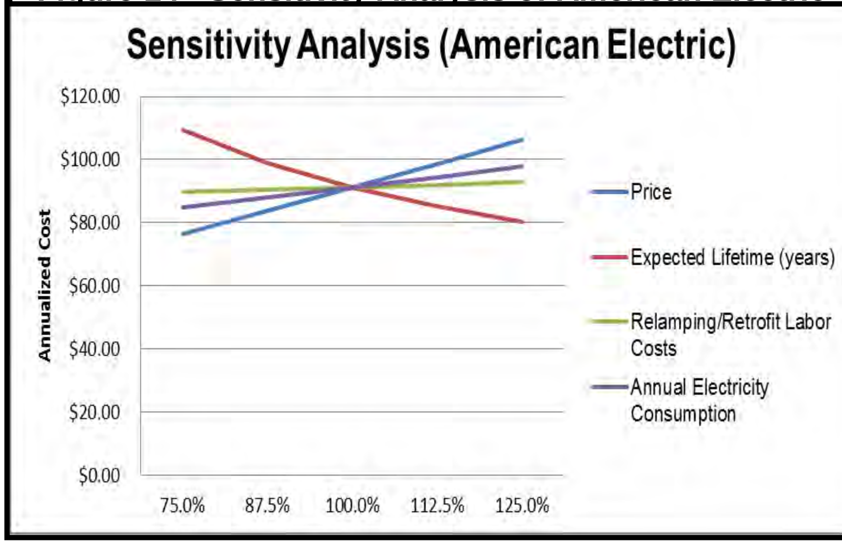


Figure 15 - Sensitivity Analysis of Holophane

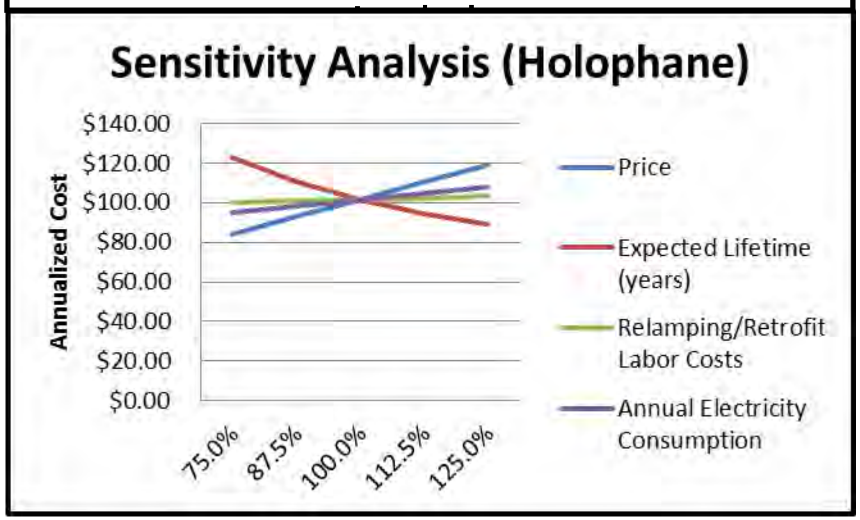


Figure 16 - Sensitivity Analysis of Beta LEDway

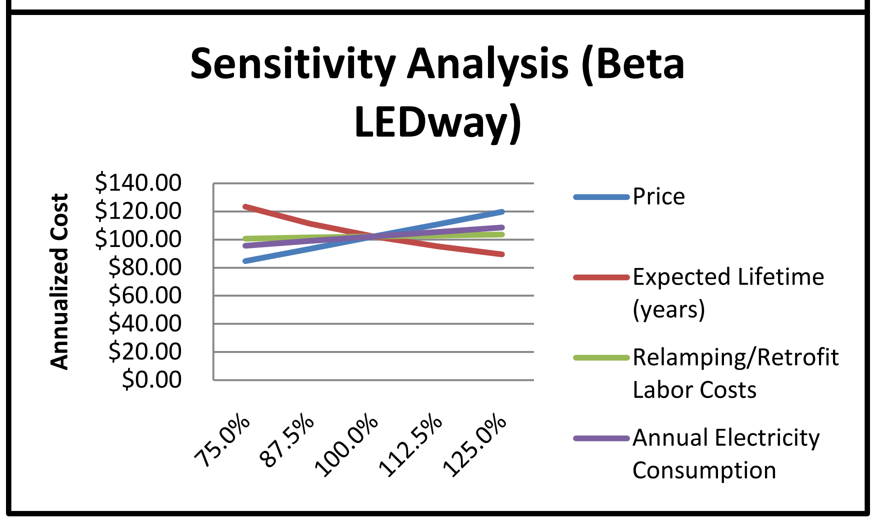


Figure 17 – Sensitivity Analysis of Philips Luminaire

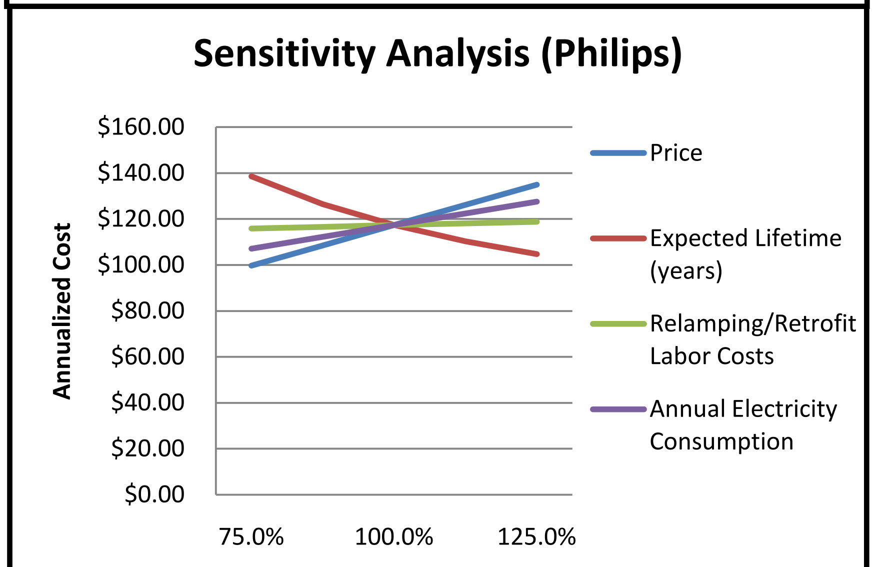


Figure 18 - Sensitivity Analysis of GE Luminaire

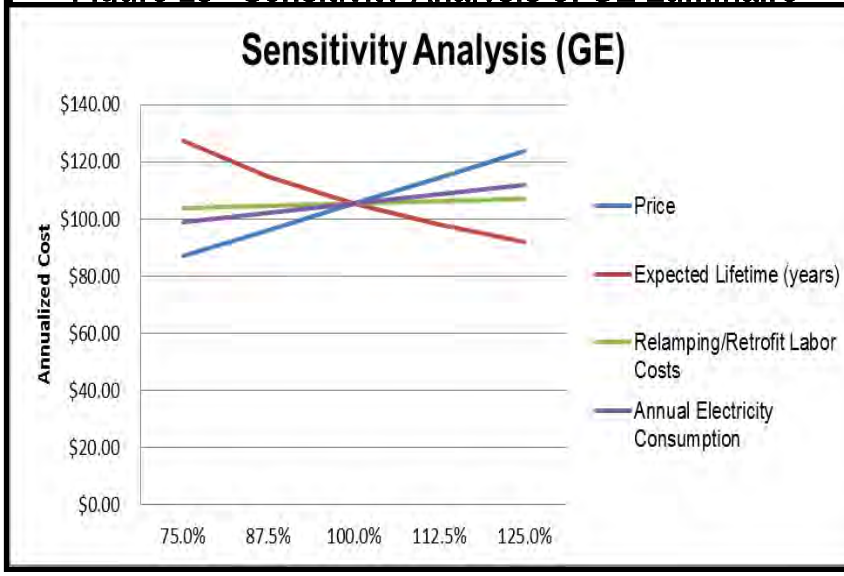


Figure 19 – Sensitivity Analysis of Dialight Luminaire

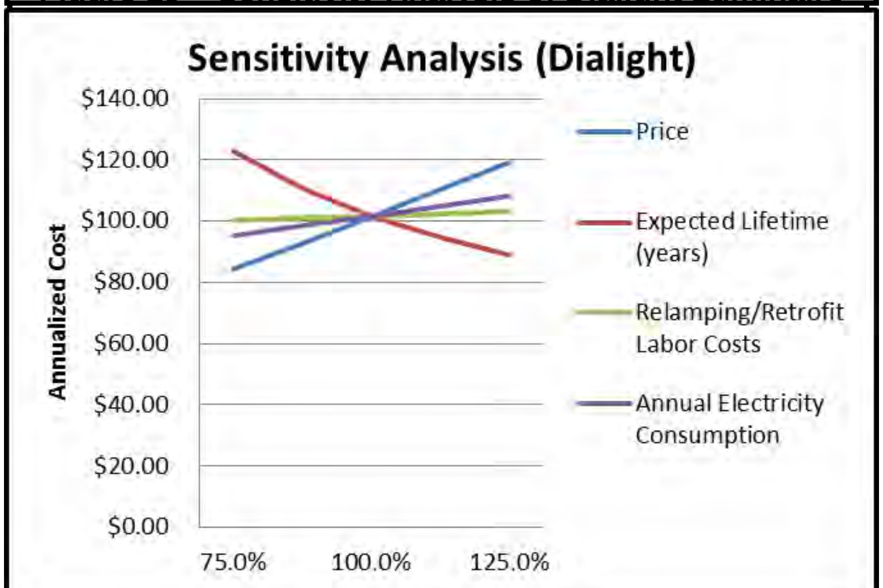


Figure 20 - Sensitivity Analysis of 250 W HPS

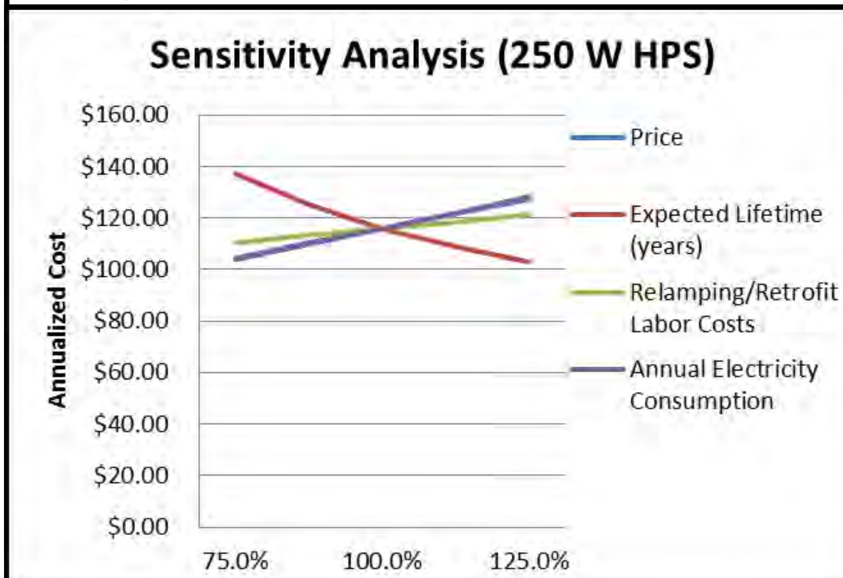


Figure 21 – Sensitivity Analysis of LED Roadway

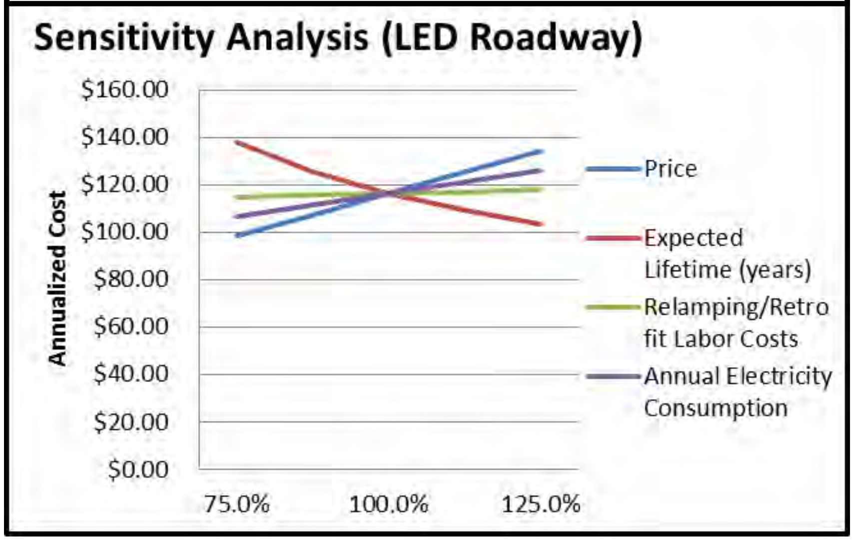


Figure 22 - Sensitivity Analysis of 400 W HPS

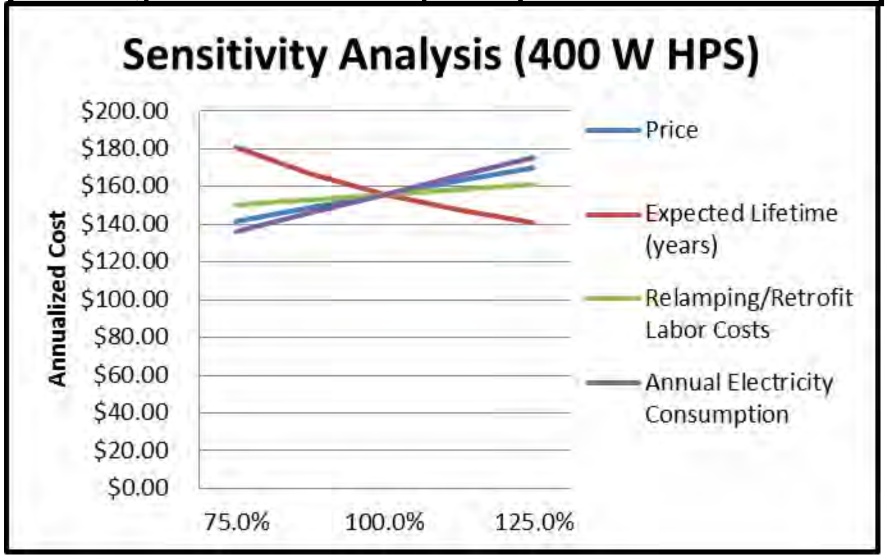
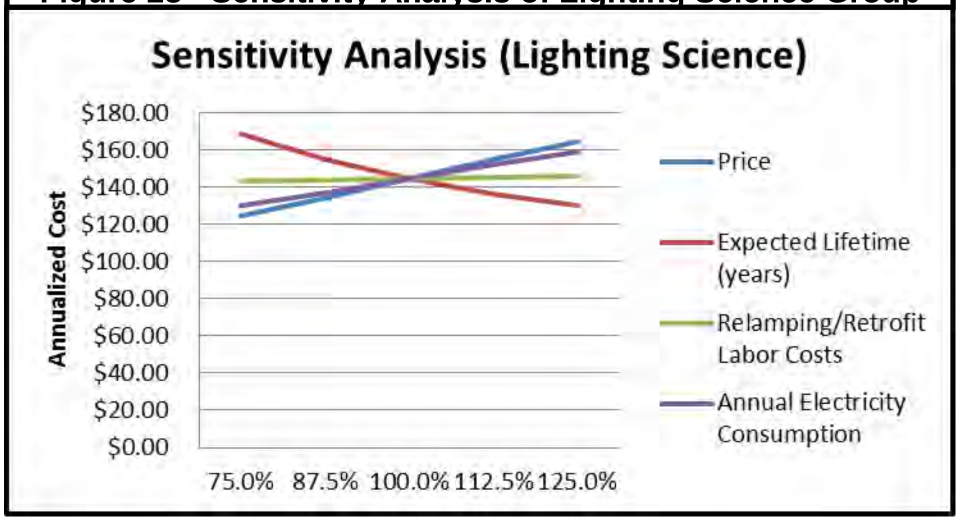


Figure 23 - Sensitivity Analysis of Lighting Science Group



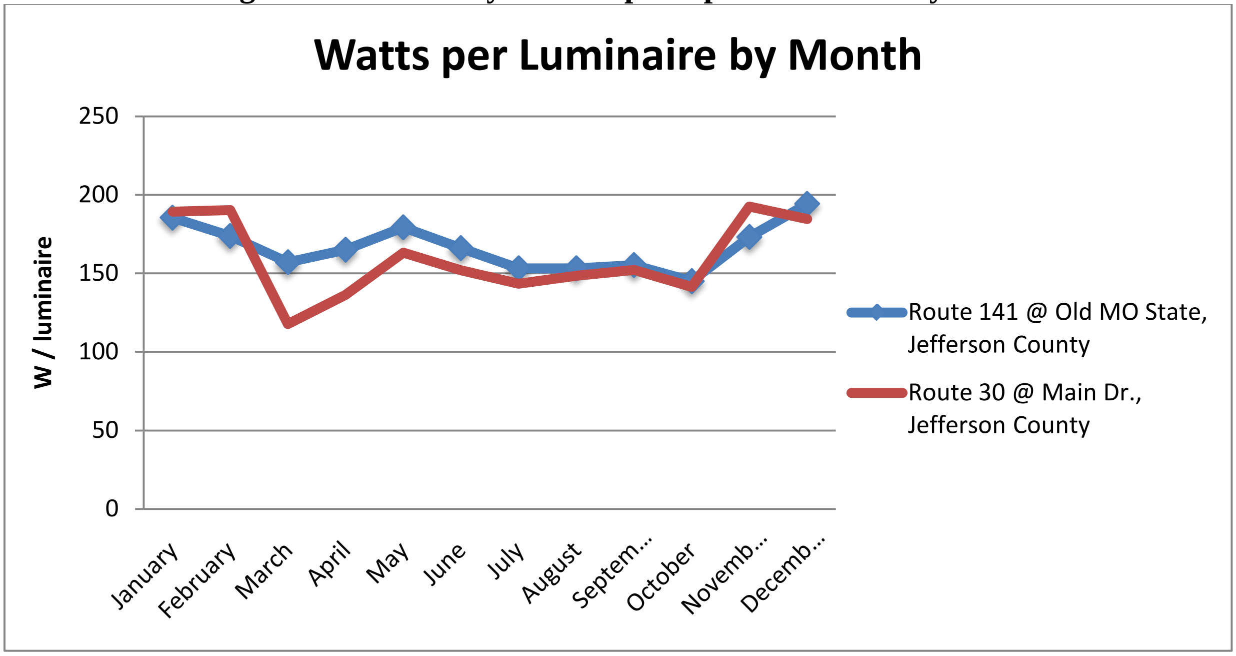
Figures 13 through 23 demonstrate the sensitivity of each luminaire's annualized cost to changes of four variables: luminaire price, expected luminaire lifetime, re-lamping/retrofit labor cost, and annual electricity consumption. Each variable varies between 75%-125% of the original value, in 12.5% increments. The sensitivity analysis determined the variables with the greatest impact on the annualized cost of LED luminaires. The two factors with the greatest impact on the annualized cost are price of the luminaire and the expected lifetime of the luminaire.

Changes in the Price of the Luminaires linearly impact the annualized cost of the respective luminaire. Changes in each luminaire's expected lifetime results in an inverse exponential change in the annualized cost of the luminaire. Thus, the greater the deviation of the actual lifetime from the expected lifetime, the exponentially greater impact the life of the luminaire has on the annualized cost of the luminaire. Therefore, it is imperative for an LED luminaire's expected lifetime to be accurate.

Task 3: Perform environmental justification including stakeholder acceptance analysis of LED roadway lighting with existing light sources

Energy Consumption and Environmental Impact Analysis
Energy consumption data was obtained on the Dialight luminaire at two separate intersections. Energy consumption data was separated by month and analyzed. Figure 24, shown below, depicts the energy consumption in Watts per luminaire per month.

Figure 24: Electricity Consumption per Luminaire by Month



The figure above shows the increase in electricity consumption between October and December, which endures through the month of February. The increase in consumption at this time period averages to 32%. This increase is independent of the duration which the lights operate. The reason is the colder outside operating temperature will increase power consumption to maintain lighting levels. LED arrays are driven at a higher electrical current rate to offset impacts from lower temperatures. This is a significant concern for public agencies and must be investigated further to ensure the economic comparisons and decisions are based on actual cost not cost at more optimum temperature conditions. The approved product list process section suggests studying this effect further on more luminaires by assessing each luminaire during both summer and winter seasons.

The sharp decrease in March in consumption at the intersection of Route 30 and Main Drive is due to a traffic crash that removed the pole for a period of time. With no replacement LED in stock, one had to be ordered.

Energy consumption was also measured to determine the energy savings of LED luminaires. Our analysis shows an actual energy savings of 11%, which is for 150 watt equivalent luminaires. Information was unable to be obtained for equivalent LED power consumption data for 250 watt or 400 watt HPS luminaires.

For a 150 Watt HPS lamp, with a system rating of 183 watts, the equivalent energy savings is 80.5 kWh per year. According to an EPA study from 2000, the average electrical generation portfolio releases 1.341 lbs. of CO_2 into the atmosphere per kWh of electricity consumed. Therefore, replacing one 150 Watt HPS lamp with the Dialight luminaire (evaluated LED luminaire) avoids the release of approximately 108 lbs. of CO_2 into the atmosphere.

Stakeholder Acceptance
In order to gather stakeholders' opinions on LED streetlights, a survey was developed and distributed to the public. The survey was based on the LED streetlight pilot in Springfield, MO. This pilot is operated by City Utilities and is located near Springfield's downtown. Despite the dense population, there were few respondents to the survey. Even with follow-on efforts to encourage public feedback and distribution of surveys to local transportation organizations, survey responses remained low. Similar results were also experienced in the Kansas City area. The survey can be found in Appendix C.

Although stakeholders showed little interest in commenting on LED luminaire installations through surveys, there is significant interest in LED luminaires nonetheless and multiple evaluation projects are underway. The following provides general information on the various activities along with an overview of public perception to date.

Mid-America Regional Council (MARC) – Kansas City Region
The Kansas City Regional Planning Organization, MARC, is leading a regional deployment of street lighting that includes two (2) different types - LED luminaires and induction luminaire replacement fixtures. The following provides a quick glance at their program:

- 3500 to 4000 replacement ~ 250 being induction type and the remaining being LED
- 25 cities in the Kansas City metro area from both Missouri and Kansas with both area major utility companies
- Five different street light manufacturers participating
- Approximately half of the replacement lights have been installed

- MARC is developing a web-based public survey
- MARC will be doing some limited field testing
- MARC will be developing a final report

MARC is very interested in developing a regional or statewide purchase order process that permits city, county, and state agencies to acquire LED lighting to help reduce cost. Early calls received from the public have mostly been favorable to the conversion of LED luminaires.

Kansas City, Missouri
The City of Kansas City and DOE are evaluating LED streetlights in residential and commercial areas. A web site has been developed along with a survey - (http://www.kcmo.org/CKCMO/Depts/PublicWorks/StreetandTrafficDivision/LEDPilot/index.htm). Kansas City is conducting extensive evaluations over a period of several years. They will be taking field readings several times; monitoring power consumption; evaluating smart technologies that can monitor, report, dim, turn-off, etc. street lighting remotely; and public perception. They are in the first year of this evaluation and have limited information to report on this project at this time. However, they are willing to share information as it becomes available.

Their web site survey has received very limited response (only a handful). The research team visited most of the sites and took field photometric readings and was one of the limited responders to the survey. Kansas City has conducted field trips with lighting industry experts and citizens. In general, the lighting industry experts were more negative in response based on their knowledge of lighting. The non-lighting industry people were more positive in their evaluation while on the bus trips. This will be a good project to follow based on the extensive multi-year evaluation.

Independence, Missouri
Independence Power and Light is also conducting an LED street light program and has a web site that describes the three test areas: http://www.ci.independence.mo.us/PL/LedStreetLight.aspx. They have received mostly positive response on the three sites. The team collected data from the various sites for inclusion into this report.

Springfield City Utilities
Springfield City Utilities conducted an internal evaluation of three different LED Luminaires and have concluded that the conversion from HPS to LED is not feasible at the current time based on cost difference between HPS and LED. Their cost analysis did not include maintenance labor cost because City Utilities normally has after hour crews conduct maintenance service as part of their routine duties – they don't have specialized crews. Public comments received were mostly positive. A major comment received from the Springfield Police Department is enhanced visibility. They could pick-up colors and noticed pedestrians and bicyclists movements better.

St. Louis City
We have learned that the City of St. Louis is conducting similar evaluations along a few major inter-city corridors.

MoDOT – St. Louis District
MoDOT St. Louis District has begun testing LED's at a few locations throughout St. Louis. The LED luminaires, as mentioned above, provides better color recognition and enhanced nighttime

images brought back to the transportation management center from traffic cameras at signalized intersections. Concerns at the district level include maintaining a quality of service for citizens while operating under current budget constraints. The appeal to reduced maintenance from a longer life lamp that resulted in less lamp failures would permit focus on other areas.

Outside of the unfamiliarity with LED luminaire technology, the district has had no complications with working with LED luminaires. However, the district has noted some differences in testing and installing luminaires.

Task 4: Determine compatibility of LED luminaires with existing infrastructure and recommend layouts/design criteria of LED roadway luminaires

Retrofitting Roadway Luminaires

Most of the deployments of LED roadway luminaires are being done as retrofits to existing poles and bracket arms. Early generation LED roadway luminaires could not meet the existing pole spacing for continuous lighting and required adding poles or changing existing pole spacing. Later generation LED roadway luminaires for most manufacturers can now meet existing spacing of previous HPS luminaire requirements.

A structural assessment for retrofitting LED roadway luminaires was conducted by reviewing existing roadway lighting standard drawings. A maximum weight of a LED roadway luminaire was determined to be approximately 45 pounds when checking information from various manufacturers. The following is a summary of the current MoDOT standard drawings:

The new LED roadway luminaires that weigh 45 pounds or less will fall under the allowable weights shown on the standard highway lighting sheets. The allowable luminaire weight is defined in each pole's standard table provided on sheets 901.00Z Page 2 of 4 and 901.01AG Page 3 of 6. Summarized below is the maximum allowable roadway luminaire weight based on pole and bracket assembly:

<u>45-foot Mounting Height</u>

Type AT Pole (6 or 15 foot bracket) → the maximum allowable luminaire weight is 60 pounds
Type B Pole (6 or 15 foot bracket) → the maximum allowable luminaire weight is 60 pounds
Type MB Pole (6 or 15 foot bracket) → the maximum allowable luminaire weight is 60 pounds

<u>30-foot Mounting Height</u>

Type AT Pole (4 -10 foot bracket) → the maximum allowable luminaire weight is 75 pounds
Type AT Pole (12 foot bracket) → the maximum allowable luminaire weight is 71 pounds
Type AT Pole (15 foot bracket) → the maximum allowable luminaire weight is 66 pounds
Type B Pole (4 foot bracket) → the maximum allowable luminaire weight is 75 pounds
Type B Pole (6 foot bracket) → the maximum allowable luminaire weight is 75 pounds
Type B Pole (8 foot bracket) → the maximum allowable luminaire weight is 54 pounds

MoDOT Standard Plan 902.40Q, sheet 3 of 3 was also reviewed based on the roadway luminaire attachment. The typical post loading diagram indicates a luminaire with 15 foot bracket atop the traffic signal post. The weight of the luminaire for design is given in the table as 30 pounds. If

MODOT specified the 45 pound LED luminaire atop a signal pole with the 15 foot bracket, it appears to fall outside the standard's typical post loading diagram. These signal support poles are designed for much higher forces from the weight of the signals, signs, lighting, etc. and the bracket shown is similar to the AT bracket on the highway lighting standard (where the 15 foot bracket's allowable is 66 pounds).

Recommendation is to review the typical post loading diagram on standard plan 902.40Q sheet 3 of 3 and assess the loading of a 45 pounds LED luminaire and revise the 902.40Q standard drawing appropriately.

Design Criteria Recommendations

The Department of Energy (DOE) Municipal Solid-State Street Lighting Consortium's Model Specification for LED Roadway Luminaires enables states, cities, utilities, and other local agencies to assemble effective bid documents for LED street lighting products. The use of this specification could be very beneficial since it is being driven nationally with input from state/local agencies, utilities, major lighting manufacturers, etc.

The templates can be found in Appendix D and Appendix E composed of two separate specification documents. The user (agency or utility) can choose one of two versions, depending on available information.

1. Model Specification with Appendix D – Application-Based

   System Specification (application efficacy), which characterizes luminaire performance based on localized site characteristics such as mounting height, pole spacing, number of driving lanes, input power, and required light levels and uniformity.

2. Model Specification with Appendix E – Material-Based

   Material Specification (luminaire efficacy), which characterizes luminaire performance without consideration of site characteristics.

The specification is a "living document" that will be updated as needed to reflect changes in technologies and associated standards, and to incorporate feedback from other national users. Model specification – application-based version above is probably a better representative of what has been and is currently being used by MoDOT. Benefits of this national specification include:

- Used and tested by other agencies,
- Manufacturers have and will have input on it,
- Creates a potential similar specification across Missouri (Kansas City, Springfield, Columbia and others are members),
- Maintained by the Consortium, an independent group lead by the DOE

The team would be willing to assist MoDOT on customizing, if MoDOT would select this recommendation.

Task 5: Develop purchasing guidelines for LED luminaires based on differences from current layouts and illumination criteria.

MoDOT has developed and maintains an approved product list (APL) that pre-qualifies various products for acquisition for construction improvements and ongoing maintenance operations. The APL process permits the evaluation of various products including highway lighting materials. The evaluation and approval process varies based on the product to ensure compliance with appropriate specifications, operations under varied conditions and functionality. The following provides a recommended APL process for LED luminaires pre-qualified acceptance.

- Product submission - MoDOT's New Product Evaluation Process – Section 106.17 Engineering Policy Guide (http://epg.modot.mo.gov/index.php?title=106.17_New_Product_Evaluation)
- Product Information Sheets Evaluation includes:
  - Compliance with current specifications
  - Lighting Facts – Luminaires Efficacy, Light Output of The Luminaire, Measured Input Power, Correlated Color Temperature and Color Rendering Index
- Product Field Evaluation will be conducted over a 12 month period and includes:
  - Luminaire measurement in footcandle (or Lux**)** in accordance with standard field measurement practices and again 11 months later (approximately 3700 hours of operation) for comparison of product's IES Distribution files (minimum 9 grid readings) – product verification and degradation
  - Power usage per luminaire based on temperature variation for summer and winter periods – power usage variation
  - General observations – lighting pattern, lighting intent, etc.
- Product Final Evaluation

Training

During conversation with various agencies, a question was asked about training needs. The training needs were centered on operation and maintenance issues. Differences in the HPS and LED roadway luminaires' performance, operations and maintenance would be good subject matter to meet identified training needs.

The Local Transportation Assistance Program (LTAP) is a good source to develop and present training. A distance learning approach could be used to deliver training that would allow the training to be done on-site during normal scheduled training meetings. This distance learning approach could be coupled with a feedback process that would follow-up on questions asked and additional information needs requested during the training session.

These training sessions could be developed for 30 to 60 minutes periods and could be offered to cities, counties, utilities, consultants, and others who work with roadway lighting. MoDOT/LTAP could also consider expanding training to including LED traffic signal indications, a similar topic.

Future Technology
Smart technologies are being developed into lighting systems that can perform various services based on the level of technology and telecommunication available. Some of these systems are internal to lighting control stations that can monitor on-site while others can transmit information back to a service provider center via a telecommunication network. Cost varies based on infrastructure and services needed.

One manufacturer uses a mesh telecommunication network where each pole becomes a repeater site. Information is transmitted across the mesh network (pole-to-pole) to a gateway collection site (information from up to 2500 poles) that transmits information gathered long distance to a service provider center. The service center processes the lighting information and provides detail reports via a protected web site. The following benefits are listed for this technology:

- Improved Safety - ensures your roadway lights are working, enhancing roadway safety and providing a proven deterrent to crime.
- Green Environmental - reduces roadway lighting energy consumption and significantly reduces carbon footprint through partial dimming during off peak nighttime periods.
- Efficient - eliminates visual patrolling and repeat maintenance trips for crews, resulting in improved efficiencies and reduced operating costs.
- Prosperous **-** enhances the lighting environment, which is proven to increase retail commerce and occupancy rates for retail spaces and multi-family dwellings.
- Proactive - enables immediate response to roadway lighting failures, virtually eliminating citizen and customer complaints.

Research is currently being done on plasma lighting and on enhanced area lighting control. These technologies should be developed and will be ready about the same time period when LED roadway luminaires installed today are ready for replacements.

Conclusions
Performance and cost are major issues when considering a change in technologies like transiting to using LED roadway luminaires.

Performance was a major issue in early development of LED roadway luminaires. Most manufacturers invested in product development to ensure that LED roadway luminaires performed at similar or higher performance levels as the HPS roadway luminaires. These initial investments were focused at 30 foot mounting height luminaires and have in the recent past moved towards mounting heights of 40 feet or higher.

Performance of the LED roadway luminaire, when compared to the current preferred HPS roadway luminaire, has seen improvements over the past few years. Impacted parties (like manufacturers, public agencies, utilities, etc.) have joined together with the intent of producing an equivalent LED roadway luminaire that can be used. Manufacturers have invested in producing new generations of LED roadway luminaires that continue to close the gap between the HPS and LED roadway luminaire. Local agencies and utilities continue to evaluate and report findings on these new generations. Their performance improvements have led some agencies like the City of Los Angeles in making major investments in the transition to LED roadway luminaires.

Based on the economic analysis performed in this report, some LED luminaires are at best break-even solutions. This trend in LED luminaires becoming a cost-effective solution should continue based on economy of scale, assuming demand increases. The following are other factors that should be considered for LED's to become a more cost-effective solution:

- **Maintenance cost -** labor and equipment costs are major components under the HPS luminaire scenario. With a 3-year lifecycle, four installations and maintenance responses could be required compared to 1 for the LED luminaire scenario. Maintenance responses are very expensive required labor and equipment cost and the worker's exposure of 3 additional roadside responses becomes a safety issue.
- **Demand -** the national interest by the Department of Energy (DOE), other local and state agencies and the lighting industry demonstrates a strong trend towards LED roadway luminaires and away from HPS roadway luminaires. This direction should help encourage manufacturers to increase production thus reducing LED roadway luminaire cost.
- **Previous technology transition -** in the 1980's a similar transition from mercury vapor roadway luminaires to HPS roadway luminaires was made. It took as long as 10 years to complete the transition and the reasons for change was power cost savings (a luminaire's cost and lifecycle were about the same) and mercury, a hazardous material, caused concerns with disposal.

Based on previous trends in LED signal indications technologies, the LED roadway luminaires should experience a reduction in cost based on the economy of increased manufacturing. The high labor and equipment cost now associated with maintaining HPS roadway luminaires should soon swing the decision to LED roadway luminaires. These facts will make LED roadway luminaires a more cost effective solution.

Recommended Action Items

Based on factors mentioned above and information contained in this report, we recommend that MoDOT develop and implement a strategy to facilitate the smooth transition from HPS to LED roadway luminaires based on factors of cost and performance. The results of this study suggest that LED luminaires are currently most effective for 30-foot mounting heights or less. As luminaire technology improves, testing should continue for future generations of luminaires for mounting heights greater than 30 feet. In addition to this general recommendation, we recommend two specific action items.

1. We recommend MoDOT develop formalized procedures, or specifications, for the evaluation of LED luminaire candidates under consideration for the Approved Products List. The templates developed by the DOE's MSSLC (provided in Appendices D and E) are well-suited for this purpose and are the guidelines used by the research team.

2. Luminaires should be evaluated for a period of one year to best understand performance from an economic and performance perspective. During this evaluation period,

performance based on IES specifications as well as degradation and power consumption should be collected and analyzed.

Note that although many of the luminaires studied as part of this report do not meet IES specifications, these are likely first generation luminaires. As an example, a first generation Holophane luminaire is currently in the field and was part of this study, but this model is no longer commercially available. Most current production generations of product are expected to meet IES specifications and should be evaluated for inclusion on the Approved Products List. The same is true for other manufacturers studied as part of this research.

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Appendix A

Field Data

HOLOPHANE GEN 1

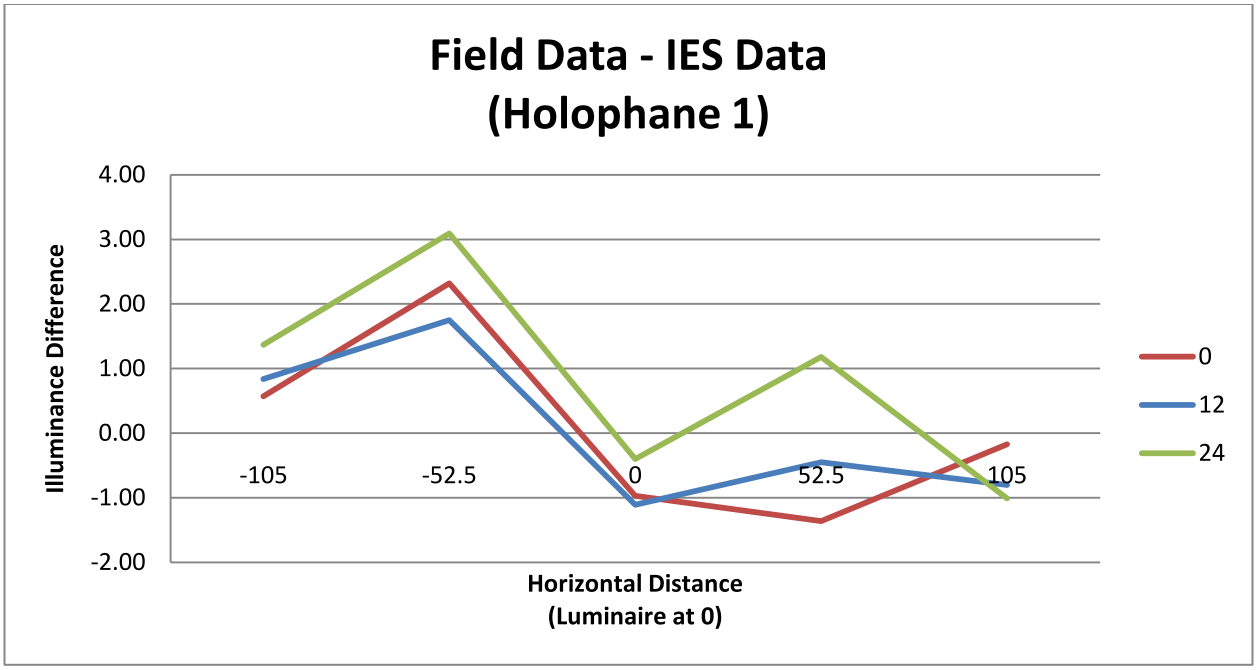
Continuous Lighting - Staggered	5/31/2011	Field Site	White Sand Ct - Indep	Roadway Width	24	Feet
Time	10:50 PM	Pole Number	#1	Spacing	210	Feet
Temperature	72	Manufacturer	Holophane	Height	30	Feet
Ambient Light Reading	0.15	Type of Luminaire	LED	Arm	8	Feet

Continuous Lighting - Staggered

Field Readings		Actual Field Measurement		Adjusted Field Measurement	
Location	Distance to Luminaire	Ground Level	18 inches Level	Ground Level	18 inches Level
0	-105	1.52	1.49	1.37	1.34
0	-52.5	7.17	7.46	7.02	7.31
0	0	4.88	4.72	4.73	4.57
0	52.5	3.49	3.31	3.34	3.16
0	105	0.78	0.49	0.63	0.34
12	-105	2.69	2.57	2.54	2.42
12	-52.5	8.90	8.90	8.75	8.75
12	0	9.34	10.19	9.19	10.04
12	52.5	6.70	6.76	6.55	6.61
12	105	0.63	0.68	0.48	0.53
24	-105	3.42	3.36	3.27	3.21
24	-52.5	9.24	9.45	9.09	9.30
24	0	9.35	11.01	9.20	10.86
24	52.5	7.33	7.11	7.18	6.96
24	105	1.04	0.91	0.89	0.76

				(Adjusted - IES)	(Difference / Field Readings)
		Field Data	IES Data	Difference	% Difference
0	-105	1.37	0.8	0.57	41.61%
0	-52.5	7.02	4.7	2.32	33.05%
0	0	4.73	5.7	-0.97	-20.51%
0	52.5	3.34	4.7	-1.36	-40.72%
0	105	0.63	0.8	-0.17	-26.98%
12	-105	2.54	1.7	0.84	33.07%
12	-52.5	8.75	7	1.75	20.00%
12	0	9.19	10.3	-1.11	-12.08%
12	52.5	6.55	7	-0.45	-6.87%
12	105	0.9	1.7	-0.80	-88.89%
24	-105	3.27	1.9	1.37	41.90%
24	-52.5	9.09	6	3.09	33.99%
24	0	9.2	9.6	-0.40	-4.35%
24	52.5	7.18	6	1.18	16.43%
24	105	0.89	1.9	-1.01	-113.48%

	Field Data	IES Data
Max	9.20	10.30
Min	0.63	0.80
Avg	4.98	4.65
Max/Min	14.60	12.88
Avg / Min	7.90	5.82


Field Data - IES Data
(Holophane 1)
Illuminance Difference
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-105
-52.5
0
52.5
105
Horizontal Distance
(Luminaire at 0)
0
12
24

HOLOPHANE GEN 2

Pole #:			
Location:	50 X 63 @ McCarthy		
Manufacturer:	Holophane		
Date	6/28/2011	Roadway Width	20'
Time	2:30 AM	Spacing	
Temperature	70 F	Height	30'
Ambient Light Reading	0.76	Arm	6'
Pole Offset	3'		

LED

Continuous?
N

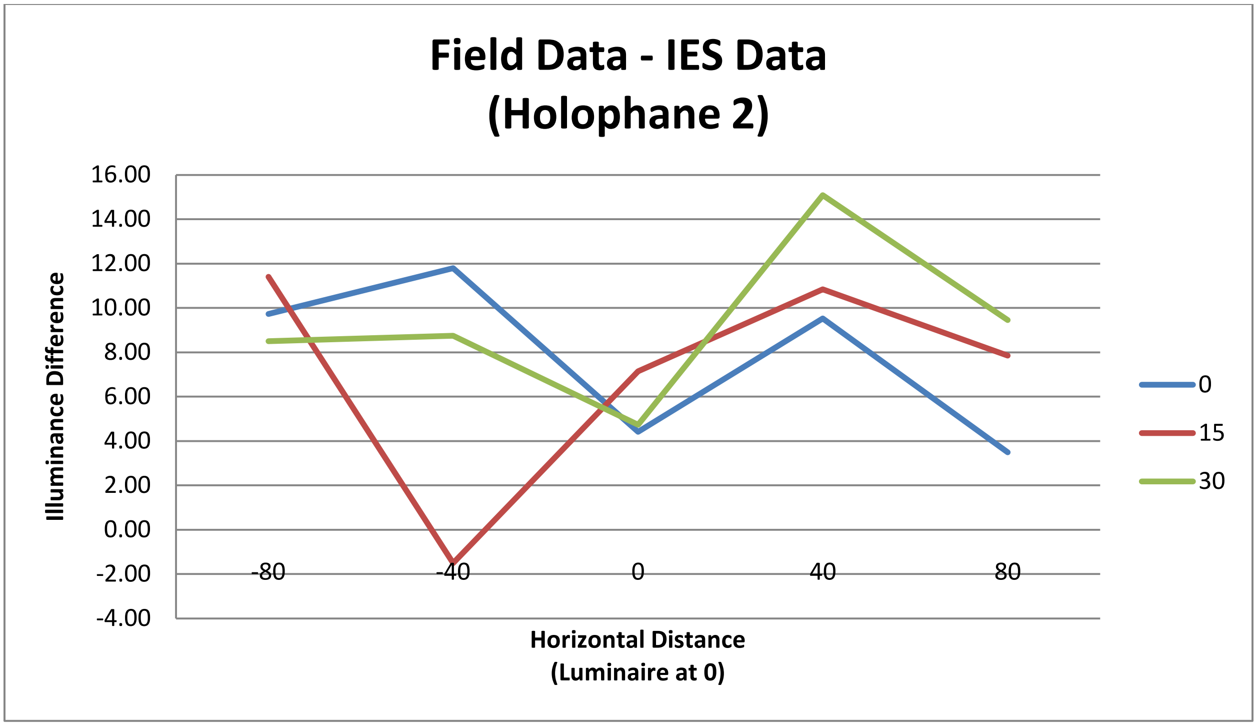
Staggered? Y

	0'		15'		30'	
Distance	0'	18"	0'	18"	0'	18"
-50	14.99	15.25	20.76	21.16	18.06	17.28
-25	21.55	23.26	21.16	38.8	25.11	24.78
0	20.28	23.18	33.2	35.3	21.39	22.25
25	19.28	20.86	33.5	34.19	24.65	23.66
50	8.75	9.42	17.21	17.24	12.62	12.55

Adjusted Readings	Close Edge of Road		Center of Road		Far Edge of Road	
Distance	0'	18"	0'	18"	0'	18"
-50	14.23	14.49	20	20.4	17.3	16.52
-25	20.79	22.5	20.4	38.04	24.35	24.02
0	19.52	22.42	32.44	34.54	20.63	21.49
25	18.52	20.1	32.74	33.43	23.89	22.9
50	7.99	8.66	16.45	16.48	11.86	11.79

				(Adjusted - IES)	(Difference / Field Readings)
X	Y	Adjusted Field Readings	IES Values	Difference	% Difference
0	-80	14.23	4.5	9.73	68.38%
0	-40	20.79	9	11.79	56.71%
0	0	19.52	15.1	4.42	22.64%
0	40	18.52	9	9.52	51.40%
0	80	7.99	4.5	3.49	43.68%
15	-80	20.00	8.6	11.40	57.00%
15	-40	20.40	21.9	-1.50	-7.35%
15	0	32.44	25.3	7.14	22.01%
15	40	32.74	21.9	10.84	33.11%
15	80	16.45	8.6	7.85	47.72%
30	-80	17.30	8.8	8.50	49.13%
30	-40	24.35	15.6	8.75	35.93%
30	0	20.63	15.9	4.73	22.93%
30	40	23.89	8.8	15.09	63.16%
30	80	11.86	2.4	9.46	79.76%

	Field Data	IES Data
Max	32.74	25.30
Min	7.99	2.40
Avg	20.07	11.99
Max/Min	4.10	10.54
Avg/Min	2.51	5.00


Field Data - IES Data
(Holophane 2)
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
Illuminance Difference
-80
-40
0
40
80
Horizontal Distance
(Luminaire at 0)
0
15
30

PHILIPS

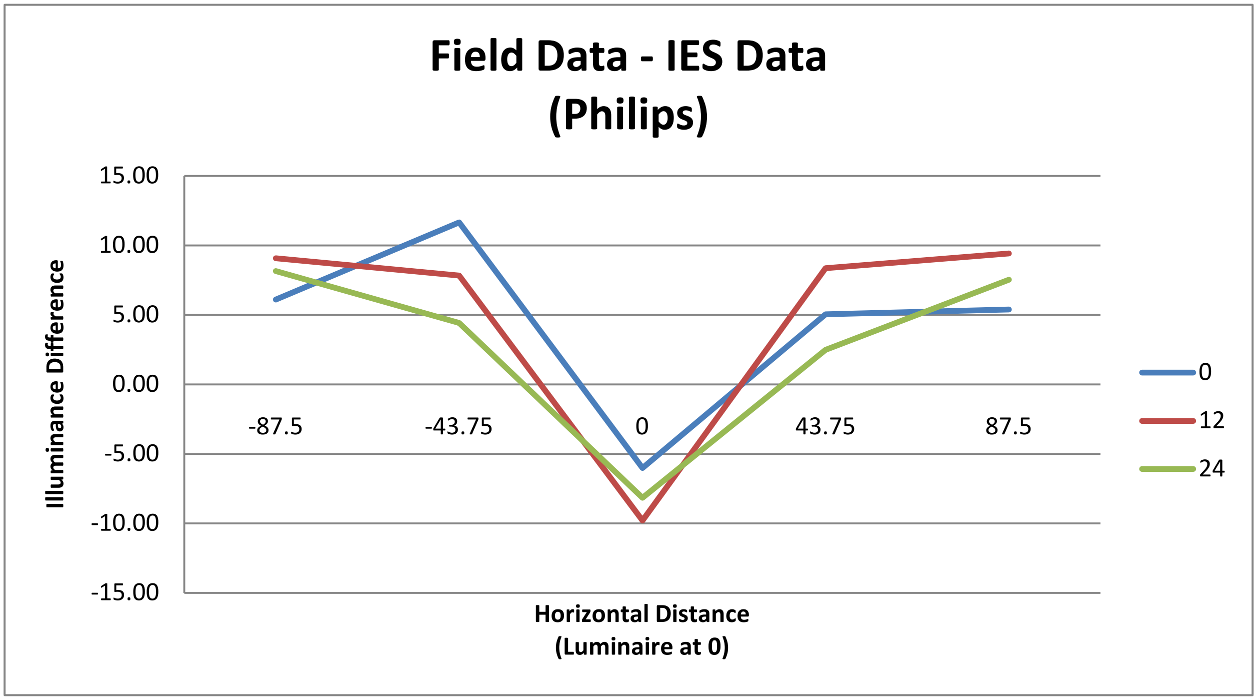
Date	6/1/2011	Field Site	KC - Reynolds	Roadway Width	32	Feet
Time	2:00 AM	Pole Number	SFA0514	Spacing	175	Feet
Temperature	68	Manufacturer	Philips	Height	30	Feet
Ambient Light Reading	0.22	Type of Luminaire	LED - 200 Watt	Arm	8	Feet

Continuous Lighting - Same Side

Field Readings		Actual Field Measurement			Adjusted Field Measurement			
Location	Distance to Luminaire		Ground Level	18 inches Level		Ground Level		18 inches Level
0	87.5 Feet Right		10.73	10.82		10.51		10.6
0	43.75 Feet Right		27.38	23.71		27.16		23.49
0	0 Feet	38.80	42.50		38.58		42.28	
0	43.75 Feet Left		20.77	22.22		20.55		22
0	87.5 Feet Left		10.01	10.25		9.79		10.03
12	87.5 Feet Right		14.59	14.71		14.37		14.49
12	43.75 Feet Right		23.65	27.70		23.43		27.48
12	0 Feet	28.83	30.30		28.61		30.08	
12	43.75 Feet Left		24.19	26.08		23.97		25.86
12	87.5 Feet Left		14.94	14.14		14.72		13.92
24	87.5 Feet Right		13.48	13.73		13.26		13.51
24	43.75 Feet Right		16.64	17.59		16.42		17.37
24	0 Feet	13.55	13.90		13.33		13.68	
24	43.75 Feet Left		14.71	15.79		14.49		15.57
24	87.5 Feet Left		12.84	12.23		12.62		12.01

				(Adjusted - IES)	(Difference / Field Readings)
		Field Data	IES Data	Difference	% Difference
0	-87.5	10.51	4.4	6.11	58.14%
0	-43.75	27.16	15.5	11.66	42.93%
0	0	38.58	44.6	-6.02	-15.60%
0	43.75	20.55	15.5	5.05	24.57%
0	87.5	9.79	4.4	5.39	55.06%
12	-87.5	14.37	5.3	9.07	63.12%
12	-43.75	23.43	15.6	7.83	33.42%
12	0	28.61	38.4	-9.79	-34.22%
12	43.75	23.97	15.6	8.37	34.92%
12	87.5	14.72	5.3	9.42	63.99%
24	-87.5	13.26	5.1	8.16	61.54%
24	-43.75	16.42	12	4.42	26.92%
24	0	13.33	21.5	-8.17	-61.29%
24	43.75	14.49	12	2.49	17.18%
24	87.5	12.62	5.1	7.52	59.59%

	Field Data	IES Data
Max	38.58	44.60
Min	9.79	4.40
Avg	18.79	14.69
Max/Min	3.94	10.14
Avg/Min	1.92	3.34


Field Data - IES Data
(Philips)
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
Illuminance Difference
-87.5
-43.75
0
43.75
87.5
Horizontal Distance
(Luminaire at 0)
0
12
24

GE

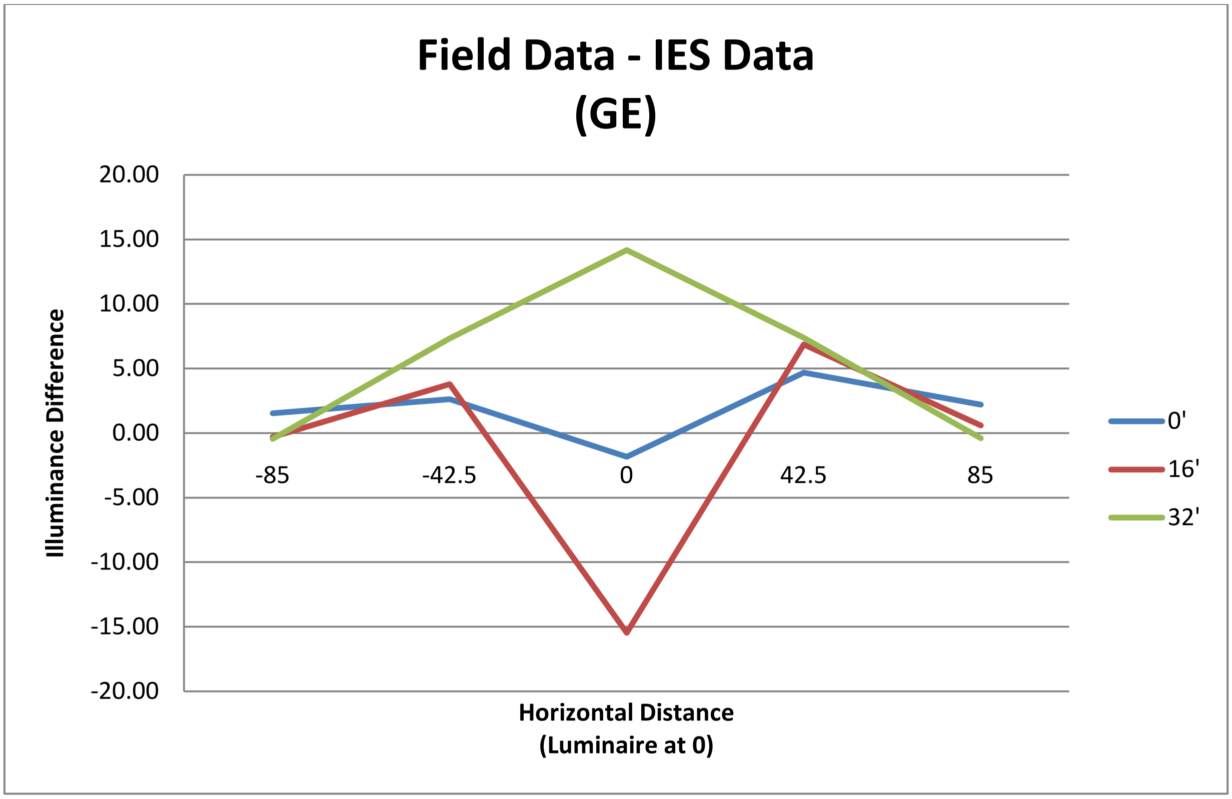
Date	6/1/2011	Field Site	KC - Deramus	Roadway Width	32	Feet
Time	1:30 AM	Pole Number	SFA1011	Spacing	170	Feet
Temperature	69	Manufacturer	GE	Height	30	Feet
Ambient Light Reading	0.67	Type of Luminaire	LED - 157 Watt	Arm	8	Feet

Continuous Lighting - Same Side

Field Readings		Actual Field Measurement		Adjusted Field Measurement	
Location	Distance to Luminaire	Ground Level	18 inches Level	Ground Level	18 inches Level
0	-85	4.71	4.96	4.04	4.29
0	-42.5	8.89	9.39	8.22	8.72
0	0	16.53	18.10	15.86	17.43
0	42.5	10.94	12.02	10.27	11.35
0	85	5.37	5.38	4.70	4.71
16	-85	5.77	5.50	5.10	4.83
16	-42.5	13.86	14.93	13.19	14.26
16	0	34.20	12.00	33.53	11.33
16	42.5	16.94	18.01	16.27	17.34
16	85	6.66	6.82	5.99	6.15
32	-85	5.61	6.00	4.94	5.33
32	-42.5	13.50	14.08	12.83	13.41
32	0	21.55	21.72	20.88	21.05
32	42.5	13.54	13.96	12.87	13.29
32	85	5.68	6.00	5.01	5.33

				(Field - IES)	(Difference / Field Data)
X	Y	IES Values	Field Readings	Difference	% Difference
0	-85	2.5	4.04	1.54	38.12%
0	-42.5	5.6	8.22	2.62	31.87%
0	0	17.7	15.86	-1.84	-11.60%
0	42.5	5.6	10.27	4.67	45.47%
0	85	2.5	4.70	2.20	46.81%
16	-85	5.4	5.10	-0.30	-5.88%
16	-42.5	9.4	13.19	3.79	28.73%
16	0	49	33.53	-15.47	-46.14%
16	42.5	9.4	16.27	6.87	42.22%
16	85	5.4	5.99	0.59	9.85%
32	-85	5.4	4.94	-0.46	-9.31%
32	-42.5	5.5	12.83	7.33	57.13%
32	0	6.7	20.88	14.18	67.91%
32	42.5	5.5	12.87	7.37	57.26%
32	85	5.4	5.01	-0.39	-7.78%

	Field Data	IES Data
Max	33.53	49
Min	4.04	2.5
Avg	11.58	9.4
Max/Min	8.30	19.60
Avg/Min	2.87	3.76


Field Data - IES Data
(GE)
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
Illuminance Difference
-85
-42.5
0
42.5
85
Horizontal Distance
(Luminaire at 0)
0'
16'
32'

BETA LEDWAY

Pole #:			
Location:	Route 141 @ Old MO State		
Manufacturer:	Beta LEDway		
Date	6/27/2011	Roadway Width	42-15-42
Time	10:45 PM	Spacing	
Temperature	70 F	Height	45'
Ambient Light Reading	0.24	Arm	3'
Pole Offset	3'		

LED

Continuous? N

Staggered? Y

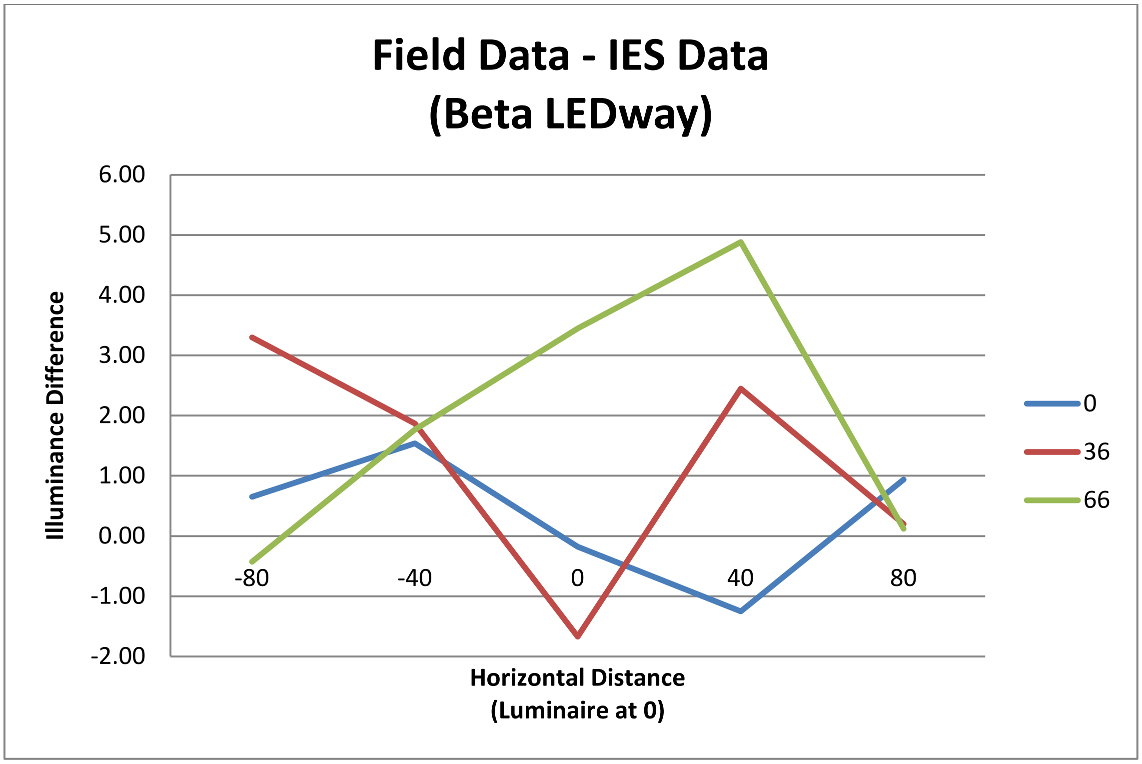
	Right Edge of Lane (0')		36'		66'	
Distance	0'	18"	0'	18"	0'	18"
-80	4.39	4.15	7.24	7.56	2.21	2.23
-40	9.18	9.73	6.91	7.9	4.61	4.16
0	5.76	5.47	7.97	8.56	6.09	6.44
40	6.39	6.59	7.49	8.98	7.72	8.73
80	4.68	4.74	4.14	4.37	2.76	3.11

Adjusted Readings	Close Edge of Road		Center of Road		Far Edge of Road	
Distance	0'	18"	0'	18"	0'	18"
-80	4.15	3.91	7	7.32	1.97	1.99
-40	8.94	9.49	6.67	7.66	4.37	3.92
0	5.52	5.23	7.73	8.32	5.85	6.2
40	6.15	6.35	7.25	8.74	7.48	8.49
80	4.44	4.5	3.9	4.13	2.52	2.87

				(Field - IES)	(Difference / Field Data)
X	Y	Field Data	IES Values	Difference	% Difference
0	-80	4.15	3.5	0.65	15.66%
0	-40	8.94	7.4	1.54	17.23%
0	0	5.52	5.7	-0.18	-3.26%
0	40	6.15	7.4	-1.25	-20.33%
0	80	4.44	3.5	0.94	21.17%
36	-80	7.00	3.7	3.30	47.14%
36	-40	6.67	4.8	1.87	28.04%
36	0	7.73	9.4	-1.67	-21.60%
36	40	7.25	4.8	2.45	33.79%
36	80	3.90	3.7	0.20	5.13%
66	-80	1.97	2.4	-0.43	-21.83%
66	-40	4.37	2.6	1.77	40.50%
66	0	5.85	2.4	3.45	58.97%
66	40	7.48	2.6	4.88	65.24%
66	80	2.52	2.4	0.12	4.76%

Adjusted Calculations	
Max	8.94
Min	1.97
Avg	5.60
Max/Min	4.54
Avg/Min	2.840609

IES File Calculations	
Max	9.4
Min	2.4
Avg	4.226667
Max/Min	3.92
Avg/Min	1.761111


Field Data - IES Data
(Beta LEDway)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
Illuminance Difference
-80
-40
0
40
80
Horizontal Distance
(Luminaire at 0)
0
36
66

AMERICAN ELECTRIC

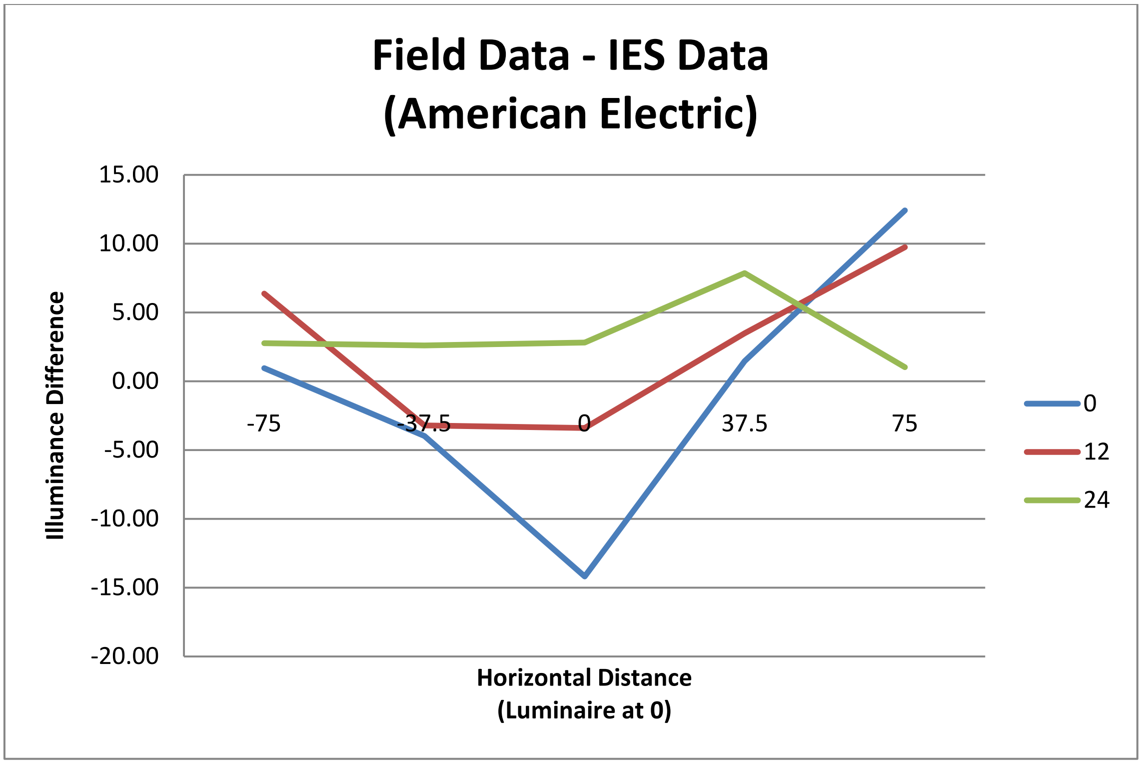
Date	6/1/2011	Field Site	KC -Municipal	Roadway Width	50	F
Time	4:00 AM	Pole Number	SEA1522	Spacing	150	F
Temperature	68	Manufacturer	American Electric	Height	30	F
Ambient light Reading	0.69	Type of Luminaire	LED - 133 Watt	Arm	8	F

Continuous Lighting - Same Side

Field Readings		Actual Field Measurement		Adjusted Field Measurement	
Location	Distance to Luminaire	Ground Level	18 inches Level	Ground Level	18 inches Level
Near Side	75 Feet Left	7.75	8.07	7.06	7.38
Near Side	37.5 Feet Left	9.30	10.44	8.61	9.75
Near Side	0 Feet	11.80	12.75	11.11	12.06
Near Side	37.5 Feet Right	15.26	16.24	14.57	15.55
Near Side	75 Feet Right	19.21	13.05	18.52	12.36
Center Line	75 Feet Left	14.35	15.30	13.66	14.61
Center Line	37.5 Feet Left	15.08	15.88	14.39	15.19
Center Line	0 Feet	27.30	33.20	26.61	32.51
Center Line	37.5 Feet Right	22.18	24.44	21.49	23.75
Center Line	75 Feet Right	18.23	19.63	17.54	18.94
Far Side	75 Feet Left	11.96	10.35	11.27	9.66
Far Side	37.5 Feet Left	19.18	18.03	18.49	17.34
Far Side	0 Feet	31.20	29.40	30.51	28.71
Far Side	37.5 Feet Right	25.64	23.65	24.95	22.96
Far Side	75 Feet Right	9.90	8.79	9.21	8.10

				(Field - IES)	(Difference / Field Readings)
		Field Data	IES Data	Difference	% Difference
0	-75	7.06	6.1	0.96	13.60%
0	-37.5	8.61	12.6	-3.99	-46.34%
0	0	11.11	25.3	-14.19	-127.72%
0	37.5	14.57	13.1	1.47	10.09%
0	75	18.52	6.1	12.42	67.06%
12	-75	13.66	7.3	6.36	46.56%
12	-37.5	14.39	17.6	-3.21	-22.31%
12	0	26.61	30	-3.39	-12.74%
12	37.5	21.49	18	3.49	16.24%
12	75	17.54	7.8	9.74	55.53%
24	-75	11.27	8.5	2.77	24.58%
24	-37.5	18.49	15.9	2.59	14.01%
24	0	30.51	27.7	2.81	9.21%
24	37.5	24.95	17.1	7.85	31.46%
24	75	9.21	8.2	1.01	10.97%

	Field Data	IES Data
Max	30.51	30.00
Min	7.06	6.10
Avg	16.53	14.75
Max/Min	4.32	4.92
Avg/Min	2.34	2.42


Field Data - IES Data
(American Electric)
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
Illuminance Difference
-75
-37.5
0
37.5
75
Horizontal Distance
(Luminaire at 0)
0
12
24

LED ROADWAY

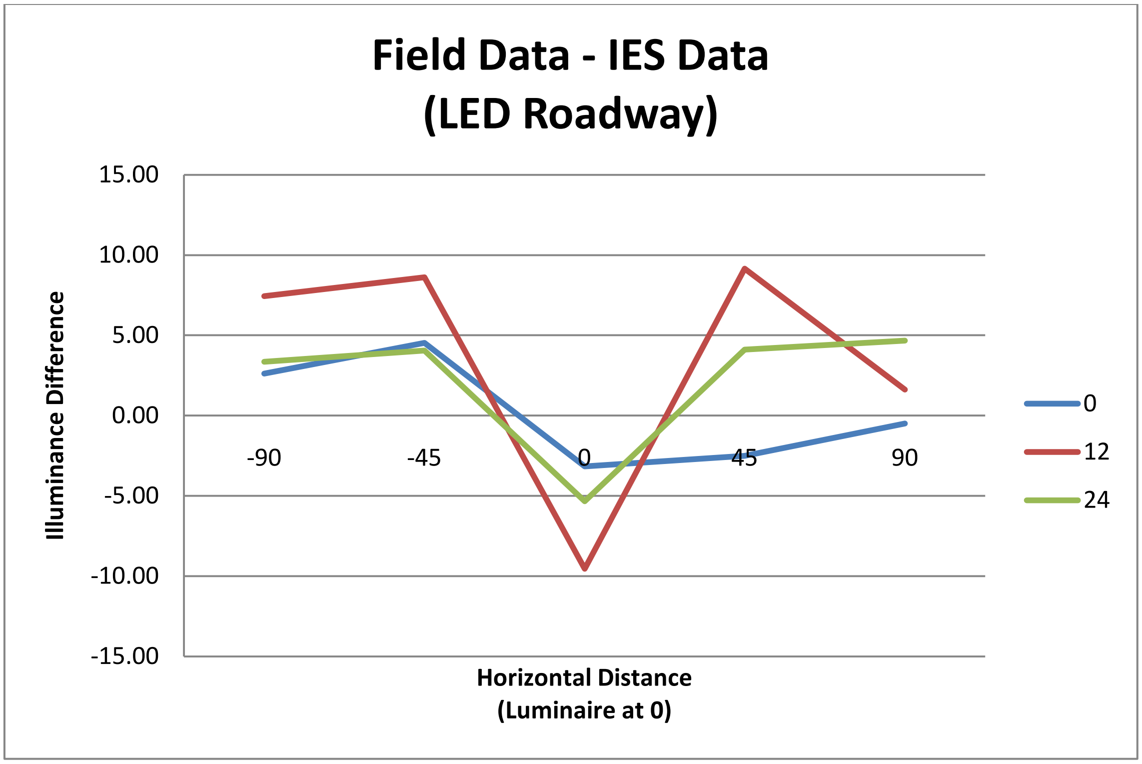
Date	6/1/2011	Field Site	KC - Equitable	Roadway Width	32	Feet
Time	2:30 AM	Pole Number	SFA1019	Spacing	180	Feet
Temperature	68	Manufacturer	LED Roadway	Height	30	Feet
Ambient Light Reading	0.44	Type of Luminaire	LED - 200 Watt	Arm	6	Feet

Continuous Lighting - Same Side

Field Readings		Actual Field Measurement		Adjusted Field Measurement	
Location	Distance to Luminaire	Ground Level	18 inches Level	Ground Level	18 inches Level
Near Side	90 Feet Left	5.56	6.70	5.12	6.26
Near Side	45 Feet Left	17.08	17.88	16.64	17.44
Near Side	0 Feet	8.17	9.22	7.73	8.78
Near Side	45 Feet Right	10.03	9.98	9.59	9.54
Near Side	90 Feet Right	2.45	2.64	2.01	2.20
Center Line	90 Feet Left	13.79	13.77	13.35	13.33
Center Line	45 Feet Left	38.85	42.90	38.41	42.46
Center Line	0 Feet	34.30	37.60	33.86	37.16
Center Line	45 Feet Right	39.40	44.30	38.96	43.86
Center Line	90 Feet Right	7.97	8.17	7.53	7.73
Far Side	90 Feet Left	11.29	11.22	10.85	10.78
Far Side	45 Feet Left	24.59	24.64	24.15	24.20
Far Side	0 Feet	25.61	26.08	25.17	25.64
Far Side	45 Feet Right	24.66	26.02	24.22	25.58
Far Side	90 Feet Right	12.61	12.76	12.17	12.32

				(Field - IES)	(Difference / Field Data)
		Field Data	IES Data	(Difference)	Difference %
0	-90	5.12	2.5	2.62	51.17%
0	-45	16.64	12.1	4.54	27.28%
0	0	7.73	10.9	-3.17	-41.01%
0	45	9.59	12.1	-2.51	-26.17%
0	90	2.01	2.5	-0.49	-24.38%
12	-90	13.35	5.9	7.45	55.81%
12	-45	38.41	29.8	8.61	22.42%
12	0	33.86	43.4	-9.54	-28.17%
12	45	38.96	29.8	9.16	23.51%
12	90	7.53	5.9	1.63	21.65%
24	-90	10.85	7.5	3.35	30.88%
24	-45	24.15	20.1	4.05	16.77%
24	0	25.17	30.5	-5.33	-21.18%
24	45	24.22	20.1	4.12	17.01%
24	90	12.17	7.5	4.67	38.37%

	Field Data	IES Data
Max	38.96	43.40
Min	2.01	2.50
Avg	17.98	16.04
Max/Min	19.38	17.36
Avg/Min	8.95	6.42


Field Data - IES Data
(LED Roadway)
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
Illuminance Difference
-90
-45
0
45
90
Horizontal Distance
(Luminaire at 0)
0
12
24

DIALIGHT

Pole #:			
Location:	Olive X Lindbergh		
Manufacturer:	Dialight		
Date	6/15/2011	Roadway Width	42-15-42
Time	11:45 PM	Spacing	
Temperature	70 F	Height	45'
Ambient Light Reading	0.24	Arm	3'
Pole Offset	3'		

LED

Continuous? N

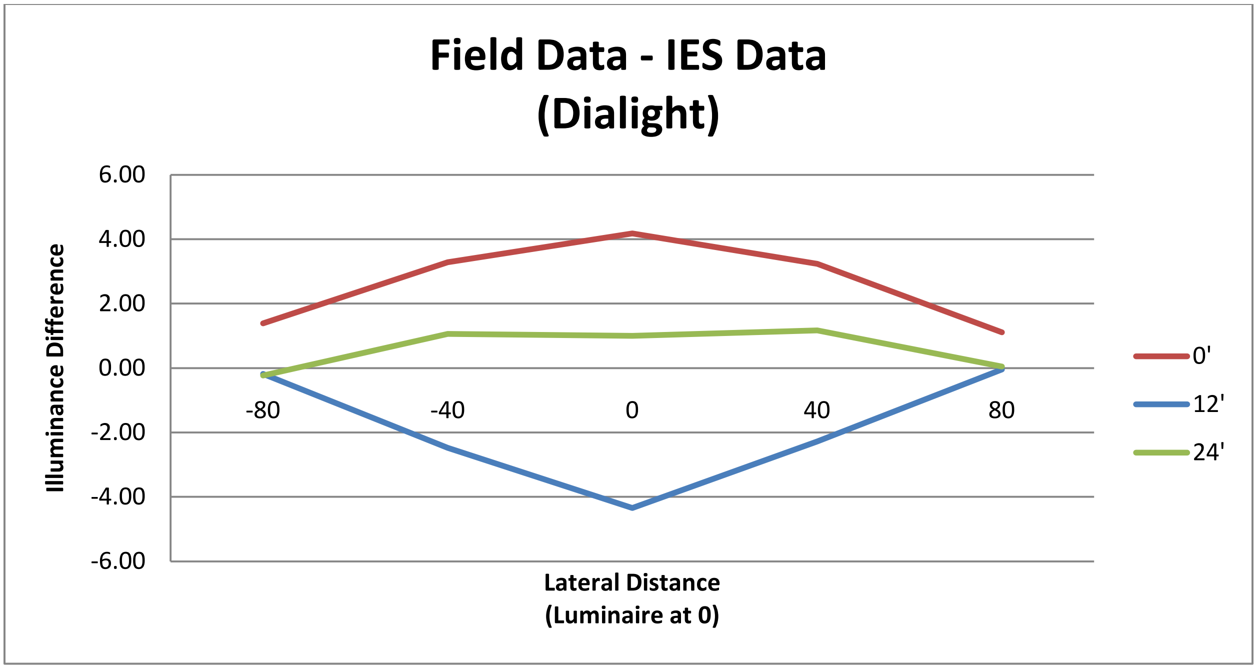
Staggered? Y

	Close Edge of Road		Center of Road		Far Edge of Road	
Distance	0'	18"	0'	18"	0'	18"
-80	4.83	4.86	4.66	4.8	4.41	4.44
-40	9.93	10.49	6.46	6.42	9.2	9.69
0	13.02	14.11	8	8.04	11.34	11.78
40	9.88	10.47	6.66	6.7	9.31	9.54
80	4.55	4.57	4.8	4.7	4.69	4.84

Adjusted Readings	Close Edge of Road		Center of Road		Far Edge of Road	
Distance	0'	18"	0'	18"	0'	18"
-80	4.59	4.62	4.42	4.56	4.17	4.2
-40	9.69	10.25	6.22	6.18	8.96	9.45
0	12.78	13.87	7.76	7.8	11.1	11.54
40	9.64	10.23	6.42	6.46	9.07	9.3
80	4.31	4.33	4.56	4.46	4.45	4.6

				(Adjusted - IES)	(Difference / Field Readings)
X	Y	Field Data	IES Data	Difference	% Difference
0'	-80	4.59	3.2	1.39	30.28%
0	-40	9.69	6.4	3.29	33.95%
0	0	12.78	8.6	4.18	32.71%
0	40	9.64	6.4	3.24	33.61%
0	80	4.31	3.2	1.11	25.75%
12'	-80	4.42	4.6	-0.18	-4.07%
12	-40	6.22	8.7	-2.48	-39.87%
12	0	7.76	12.1	-4.34	-55.93%
12	40	6.42	8.7	-2.28	-35.51%
12	80	4.56	4.6	-0.04	-0.88%
24'	-80	4.17	4.4	-0.23	-5.52%
24	-40	8.96	7.9	1.06	11.83%
24	0	11.10	10.1	1.00	9.01%
24	40	9.07	7.9	1.17	12.90%
24	80	4.45	4.4	0.05	1.12%

	Field Data	IES Data
Max	12.78	12.10
Min	4.17	3.20
Avg	7.21	7.19
Max/Min	3.06	3.78
Avg/Min	1.73	2.25



Field Data - IES Data
(Dialight)
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
Illuminance Difference
-80
-40
0
40
80
Lateral Distance
(Luminaire at 0)
0'
12'
24'

LIGHTING SCIENCE GROUP

Date	6/1/2011	Field Site	KC - Front WB	Roadway Width	29	Feet
Time	3:30 AM	Pole Number	SFB0520	Spacing	186	Feet
Temperature	68	Manufacturer	Lighting Science Group	Height	38	Feet
Ambient Light Reading	0.99	Type of Luminaire	LED - 300 Watt	Arm	10	Feet

Continuous Lighting - Both Side (both sides are being evaluated with different luminaires)

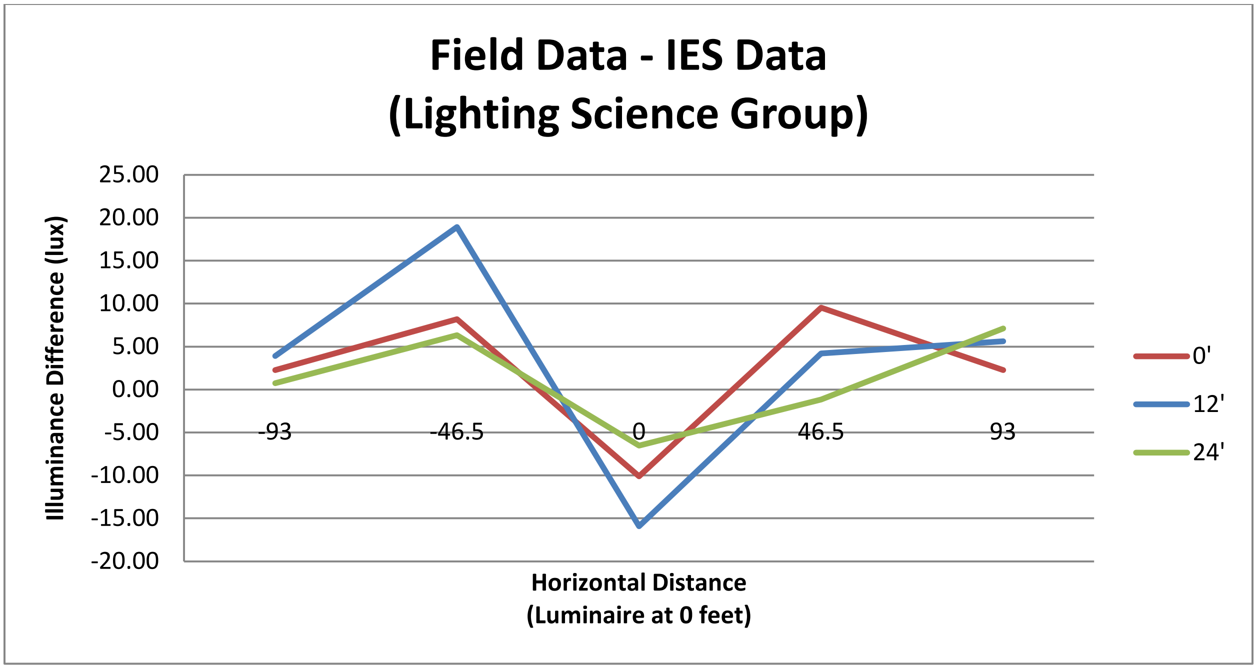
Westbound only lane width

Field Readings		Actual Field Measurement *		Adjusted Field Measurement	
Location	Distance to Luminaire	Ground Level	18 inches Level	Ground Level	18 inches Level
Near Side	93 Feet Left	5.34	4.74	4.35	3.75
Near Side	46.5 Feet Left	18.08	17.61	17.09	16.62
Near Side	0 Feet	30.30	33.50	29.31	32.51
Near Side	46.4 Feet Right	19.42	20.80	18.43	19.81
Near Side	93 Feet Right	5.36	4.69	4.37	3.70
Center Line	93 Feet Left	9.80	7.59	8.81	6.60
Center Line	46.5 Feet Left	36.10	38.40	35.11	37.41
Center Line	0 Feet	26.47	29.45	25.48	28.46
Center Line	46.4 Feet Right	21.38	22.67	20.39	21.68
Center Line	93 Feet Right	11.52	9.52	10.53	8.53
Far Side	93 Feet Left	8.42	7.64	7.43	6.65
Far Side	46.5 Feet Left	28.10	29.80	27.11	28.81
Far Side	0 Feet	22.35	24.35	21.36	23.36
Far Side	46.4 Feet Right	20.64	22.20	19.65	21.21
Far Side	93 Feet Right	14.80	13.15	13.81	12.16

* 18 inch readings may be impacted by the reflection of roadway stripe

				(Field - IES)	(Difference / Field Readings)
X	Y	Field Data	IES Data	Difference	% Difference
0'	-93	4.35	2.1	2.25	51.72%
0	-47	17.09	8.9	8.19	47.92%
0	0	29.31	39.4	-10.09	-34.43%
0	47	18.43	8.9	9.53	51.71%
0	93	4.37	2.1	2.27	51.95%
12'	-93	8.81	4.9	3.91	44.38%
12	-47	35.11	16.2	18.91	53.86%
12	0	25.48	41.4	-15.92	-62.48%
12	47	20.39	16.2	4.19	20.55%
12	93	10.53	4.9	5.63	53.47%
24'	-93	7.43	6.7	0.73	9.83%
24	-47	27.11	20.8	6.31	23.28%
24	0	21.36	27.9	-6.54	-30.62%
24	47	19.65	20.8	-1.15	-5.85%
24	93	13.81	6.7	7.11	51.48%

	Field Data	IES Data
Max	35.11	41.40
Min	4.35	2.10
Avg	17.55	17.67
Max/Min	8.07	19.71
Avg/Min	4.03	8.42


Field Data - IES Data
(Lighting Science Group)
Illuminance Difference (lux)
25.00
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
-93
-46.5
0
46.5
93
Horizontal Distance
(Luminaire at 0 feet)
0'
12'
24'

		Holophane Gen 1		Holophane Gen 2		Philips		GE		Beta LEDway		American Electric		LED Roadway		Dialight	
	MoDOT Req	Field Data	IES Data	Field Data	IES Data	Field Data	IES Data	Field Data	IES Data	Field Data	IES Data	Field Data	IES Data	Field Data	IES Data	Field Data	IES Data
Max		9.20	10.30	32.74	25.3	38.58	44.6	33.53	49	8.94	9.4	30.51	30.00	38.96	43.40	12.78	12.10
Min		0.63	0.80	7.99	2.4	9.79	4.4	4.04	2.5	1.97	2.4	7.06	6.10	2.01	2.50	4.17	3.20
Avg	> 13	4.98	4.65	20.07	11.99	18.79	14.69	11.58	9.40	5.60	4.23	16.53	14.75	17.98	16.04	7.21	7.19
Max/Min	< 6	14.60	12.88	4.10	10.54	3.94	10.14	8.30	19.60	4.54	3.92	4.32	4.92	19.38	17.36	3.06	3.78
Avg / Min	< 3	7.90	5.82	2.51	5.00	1.92	3.34	2.87	3.76	2.84	1.76	2.34	2.42	8.95	6.42	1.73	2.25

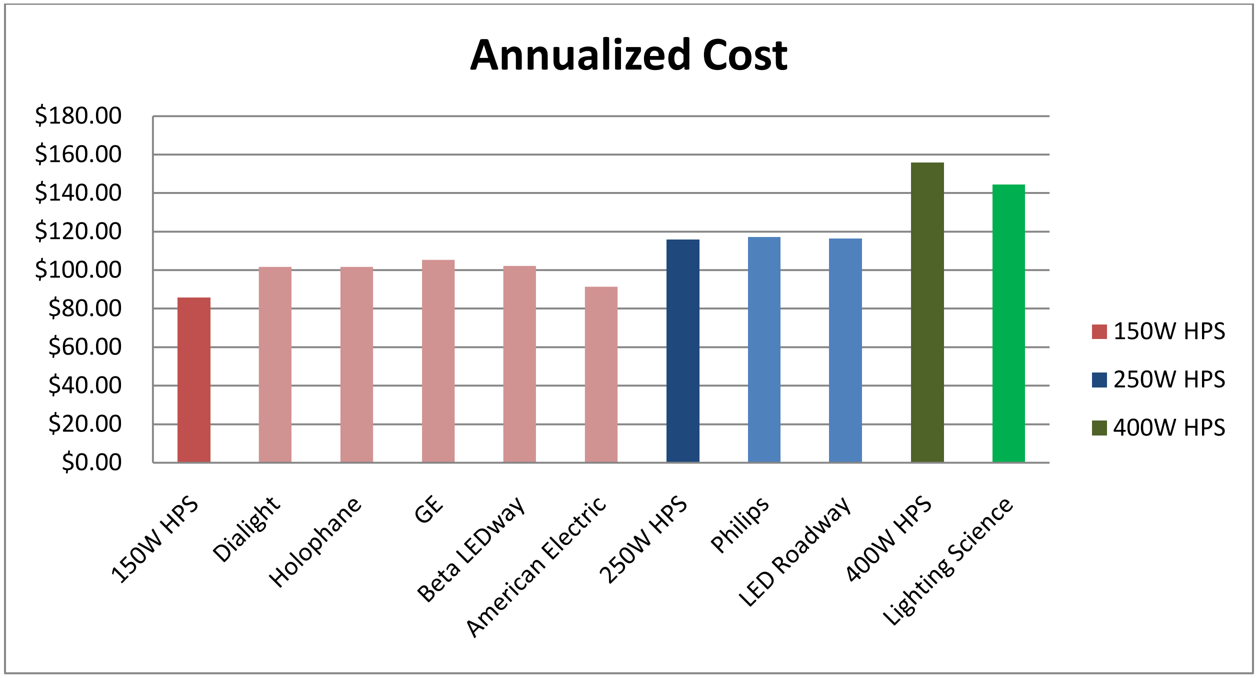
Appendix B

Economic Analysis

Life Cycle Analysis (150 W Equivalents)						
Product	150W HPS	Dialight	Holophane	GE	Beta LEDway	American Electric
Price	$100.00	$695.00	$695.00	$732.00	*$700.00*	$592.00
Expected Lifetime (years)	3	12	12	12	12	12
Expected Project Rate of Return	3%	3%	3%	3%	3%	3%
Pole Installation Costs	0	0	0	0	0	0
Relamping/Retrofit Labor Costs	$60.00	$60.00	$60.00	$60.00	$60.00	$60.00
Initial Cost per lifecycle	$160.00	$755.00	$755.00	$792.00	$760.00	$652.00
Annual Electricity Consumption	$29.28	$25.80	$25.80	$25.80	$25.80	$25.80
Annualized Cost	**$85.84**	**$101.65**	**$101.65**	**$105.37**	**$102.15**	**$91.30**

Life Cycle Analysis (250 W Equivalent)			
Product	250W HPS	Philips	LED Roadway
Price	$130.00	*$700.00*	$712.00
Expected Lifetime (years)	3	12	12
Expected Project Rate of Return	3%	3%	3%
Pole Installation Costs	0	0	0
Relamping/Retrofit Labor Costs	$60.00	$60.00	$60.00
Initial Cost per lifecycle	$190.00	$760.00	$772.00
Annual Electricity Consumption	$48.80	$41.00	$38.80
Annualized Cost	**$115.97**	**$117.35**	**$116.36**

Life Cycle Analysis (400 W Equivalent)		
Product	400W HPS	Lighting Science
Price	$160.00	*$800.00*
Expected Lifetime (years)	3	12
Expected Project Rate of Return	3%	3%
Pole Installation Costs	0	0
Relamping/Retrofit Labor Costs	$60.00	$60.00
Initial Cost per lifecycle	$220.00	$860.00
Annual Electricity Consumption	$78.08	$58.20
Annualized Cost	**$155.86**	**$144.60**



Product	150W HPS	Dialight	Holophane	GE	Beta LEDway	American Electric
Wattage	150	121	129	132	116	144
Initial Fixture Lumens	16,000	8,428	9,652	7,200	8,024	12,730
Lm/W	107	70	75	55	69.17	66
Lifetime (hours)	12,000	50,000	50,000	50,000	50,000	50,000
Lifetime (years)	3	12	12	12	12	12

Product	250 W HPS	Philips	LED Roadway
Wattage	250	211	200
Initial Fixture Lumens	26,000	17,213	11,950
Lm/W	116	96	59
Lifetime (hours)	12,000	50,000	50,000
Lifetime (years)	3	12	12

Product	400 W HPS	Lighting Science
Wattage	400	300
Initial Fixture Lumens	51,000	22,300
Lm/W	127	74
Lifetime (hours)	12,000	50,000
Lifetime (years)	3	12

In order to compare roadway lighting alternatives with varying expected lifetimes, the annual cost, or annual worth, must be calculated for each alternative. In order to calculate the annual worth, some assumptions related to costs and luminaire lifetimes had to be made. These assumptions are as follows:

- Expected return on the project: i = 3%

The expected rate of return for MoDOT projects is 3%. This rate was applied to discount costs for the calculations below.

- LED Lifetime is 12 years

LED luminaire specification sheets indicate LEDs have the potential to last up to 100,000 hours, depending on the manufacturer. Although luminaires may last up to 100,000 hours, the most pessimistic case indicates a lifetime of 50,000 hours. 50,000 hours is equivalent to at least 12 years in the field. A 12 year lifetime was used for economic calculations for all LED luminaires.

- HPS Lifetime is 3 years

High pressure sodium lamps have a significantly shorter lifetime than LED luminaires. According to a report (LED Application Series: Outdoor Area Lighting) sponsored by the Department of Energy, HPS lifetimes range from 15,000 hours to 35,000 hours[5]. Adopting a pessimistic view, the 15,000 hour operating lifetime will last for between 3-4 years. The economic analysis uses a 3 year replacement.

- Cost to relamp or replace a luminaire is $60

Labor cost to retrofit or relamp a light pole with an LED or a HPS luminaire was assumed to be $60 per luminaire. With lighting labor costs around $25-$35 per hour, the labor cost was averaged and doubled to $60 in order to account for overhead, equipment cost, setup, and travel time for conservative estimate labor cost. The annual worth of each luminaire was calculated using Equation 1: Annual Worth. In order to calculate annual worth, the present worth and capital recovery factor must be calculated, whose equations are listed in Equations 2 and 3 respectively.

Equation 1: Annual Worth

$$\mathrm{AW}(i)_j = \mathrm{PW}(i)_j(A/P, i\%, N)$$

Equation 2: Present Worth

$$\mathrm{PW}\ (i)_j = \sum_{t=1}^{N} F_{jt}\ (P/F, i\%, t)$$

Equation 3: Capital Recovery Factor

$$(A/P, i\%, N) = \frac{i(1+i)^n}{(1+i)^n - 1}$$

To ensure accuracy, calculations were completed using Excel, specifically the Excel formulas in Table F-1.

Table F-1: Engineering Economics Equations[6]

To Find	Given	Name of Factor	Algebraic	Format: Functional	Format: Excel
F	P	Compound amount factor (single payment)	$(1+i)^n$	$(F/P, i\%, N)$	FV (rate, nper, pmt, pv, type)
P	F	Present worth factor (single payment)	$(1+i)^{-n}$	$(P/F, i\%, N)$	PV(rate, nper, pmt, fv, type)
F	A	Compound amount factor (uniform series)	$\frac{(1+i)^n - 1}{i}$	$(F/A, i\%, N)$	FV(rate, nper, pmt, pv, type)
A	F	Sinking fund factor	$\frac{i}{(1+i)^n - 1}$	$(A/F, i\%, N)$	PMT(rate, nper, pv, fv, type)
A	P	Capital recovery factor	$\frac{i(1+i)^n}{(1+i)^n - 1}$	$(A/P, i\%, N)$	PMT(rate, nper, pv, fv, type)
P	A	Present worth factor (uniform series)	$\frac{(1+i)^n - 1}{i(1+i)^n}$	$(P/A, i\%, N)$	PV(ratte, nper, pmt, fv, type)
A	G	Arithmetic gradient conversion factor to uniform series	$\frac{(1+i)^n - (1+ni)}{(1+i)^n - 1}$	$(A/G, i\%, N)$	
P	G	Arithmetic gradient conversion factor to present value	$\frac{1-(1+ni)(1+i)^{-n}}{i^2}$	$(P/G, i\%, N)$	

Appendix C

Stakeholder Survey

LED Luminaire Stakeholder Survey

(Positive + Negative)

The questions below refer to the highlighted areas on this map:

Each question follows the scale at the bottom of this document.

1. **"**Compared to the lighting on nearby roads, the lighting on the indicated roadway is noticeably different?"
2. "The quality of lighting on the indicated roadway decreases my ability to see the roadway and objects that are on it."
3. "The new roadway lighting creates less glare than other roadway lights."
4. "The lighting level on the indicated roadway is too bright."
5. "The quality of the indicated roadway lighting makes it seem difficult to drive."
6. "Colors are more distinguishable with the new type of lighting."
7. "I would recommend the use of this new type of lighting elsewhere."

Demographic Questions:

"Check your age group in the box below:

16 to 20
21 to 30
31 to 40

41 t0 50
51 to 60
61 to 70
Over 70 "

"Select your gender:

Male
Female"

Scale:

1. Strongly Disagree
2. Disagree
3. Neither Agree nor Disagree
4. Agree
5. Strongly Agree

Appendix D

Model Specification for LED Roadway Luminaires
Application-Based

Municipal Solid-State Street Lighting Consortium Example

(Note: This specification contains its own appendix reference)

Instructions for the Editor (Owner, Utility, or ESCO)

This document provides System specifications, as opposed to Material specifications, to be appended to the main body of the Consortium template. Refer to the instructions provided at the beginning of the main document, which is downloaded from the Consortium website as a separate file.

1. Edit values and layout on the following pages as desired. The values indicated are **SAMPLES ONLY** and should be customized by the Editor. For example:
    a. Maximum input wattage should be carefully selected to meet energy savings criteria. An unrealistically low value could inadvertently eliminate viable options.
    b. Maximum BUG ratings should be carefully selected to balance safety, security, and obtrusive light criteria. Unrealistically low values could inadvertently eliminate viable options.
    c. Maximum effective projected area (EPA) should be based on the load capacity of the mast arm and pole, i.e., not necessarily based on the EPA of existing luminaires.
2. To add more luminaire types, copy-paste the contents of Page A-1 onto a new page, created by inserting a page break.
3. Delete/modify this page and the previous page as appropriate before appending to the main document ahead of Appendix B.

APPENDIX A
APPLICATION-BASED SYSTEM SPECIFICATION
LUMINAIRE TYPE "A"

SITE PARAMETERS		
ROADWAY DATA:	Lane width	13.5 ft
	Number of lanes, total on both sides of median	2
	Shoulder width, drivelane to edge of pavement	4 ft
	Median width	0 ft
	IES pavement class.	☐ R1 ☐ R2 ☑ R3 ☐ R4
	Posted speed limit	☐ ≤ 25 mph ☑ > 25 mph
SIDEWALK DATA:	Sidewalk width	5 ft
	Edge of sidewalk to edge of roadway pavement	6 ft
LIGHT POLE DATA:	Luminaire mounting height	27 ft
	Arm length, horizontal	6 ft
	Luminaires per pole	1
	Pole set-back from edge of pavement	2 ft
	In-line pole spacing (one pole cycle)	150 ft
	Layout	☑ One side ☐ Opposite ☐ Staggered ☐ Median
PERFORMANCE CRITERIA: APPLICATION		
ROADWAY		
PHOTOPIC ILLUMINANCE:	Maintained average horizontal at pavement	4.0 lux (0.4 fc)
	Avg:min uniformity ratio	6.0 : 1
PHOTOPIC LUMINANCE:	Maintained average luminance	n/a
	Avg:min uniformity ratio	n/a
	Max:min uniformity ratio	n/a
VEILING LUMINANCE:	Max. veiling luminance ratio	0.4
SIDEWALKS		
PHOTOPIC ILLUMINANCE:	Maintained average horizontal at pavement	2.0 lux (0.2 fc)
	Avg:min uniformity ratio (horizontal)	4.0 : 1
	Maintained min. vertical illum. at 4.9 ft, in directions of travel	1.0 lux (0.1 fc)
PERFORMANCE CRITERIA: LED LUMINAIRE		
INPUT POWER:	Max. nominal luminaire input power	103 W
NOMINAL CCT:	Rated correlated color temperature	4000 K
BUG[1] RATING:	Max. nominal backlight-uplight-glare ratings	B1-U2-G1
VOLTAGE:	Nominal luminaire input voltage	120 V
FINISH:	Luminaire housing finish color	Gray
WEIGHT:	Maximum luminaire weight	30 lb
EPA:	Maximum effective projected area	0.7 ft^2
MOUNTING:	Mtg. method	☐ Post-top ☑ Side-arm ☐ Trunnion/yoke ☐ Swivel-tenon
	Tenon nominal pipe size (NPS)	2 inches
VIBRATION:	ANSI test level	☑ Level 1 (normal) ☐ Level 2 (bridge/overpass)
DRIVER:	Control signal interface	☑ Not required ☐ Required

[1] The deprecated “cutoff” classification system cannot be accurately applied to LED luminaires.

Model Specification for LED Roadway Luminaires

Version 1.0

October 2011

Instructions for the Editor (Owner, Utility, or ESCO)

This document, as downloaded in its original unedited form from the Consortium website, is intended to be used as a model or template specification. It should be customized as needed to meet the particular needs of each Owner, Utility, or ESCO. For example, a higher degree of corrosion resistance and/or electrical immunity may be required in some regions. The unedited template is not intended to serve as a standard specification, and therefore cannot result in a single list of qualified products; since criteria will vary from municipality to municipality, a product may qualify for one while not qualifying for another.

The template is composed of two separate documents:

1. The body of the specification and appendices (beginning with Appendix B) included at the end.
2. Appendix A, to be inserted by the Editor (after printing) before Appendix B. The Editor may choose ONE of two versions of Appendix A, depending on available information.
    a. System Specification (application efficacy), which characterizes luminaire performance based on site characteristics such as mounting height, pole spacing, number of drive lanes, input power, and required light levels and uniformity.
    b. Material Specification (luminaire efficacy), which characterizes luminaire performance without consideration of site characteristics.

These three files are kept separate to allow for independent maintenance, while preventing redundancies and contradictions between documents. Again, note that only ONE of the two versions of Appendix A should be used for any given luminaire type. If both versions were used for the same luminaire type, luminaire efficacy could (inappropriately) negate application efficacy, thereby potentially excluding superior luminaires from consideration.

The submittal form in Appendix E is for use by manufacturers and should not be completed by the user.

If the material in this document is unfamiliar, please consider hiring a qualified lighting consultant.

NOTE: *Hidden text in red italicized font* provides guidance for the editor throughout these documents. The intent is for this guidance to be visible on-screen but invisible when printed as a final edited/customized specification.

While viewing the document on your monitor, you should see red italicized text between the brackets here: []

- If you don't see the text, adjust your Options in Microsoft Word as follows:
    - Under "Display" in Word 2007 or 2010, check the Hidden Text box (under Always Show These Formatting Marks On The Screen), and click OK.
    - For earlier versions of Word, adjust setting(s) in a similar manner.

And in Print Preview, you should NOT see such text between the brackets here: []

- If you DO see the text, uncheck the Print Hidden Text box in Word.

The cover page and this page may be edited or removed as desired.

PART 1 – GENERAL

1.1. REFERENCES

The publications listed below form a part of this specification to the extent referenced. Publications are referenced within the text by their basic designation only. Versions listed shall be superseded by updated versions as they become available.

A. American National Standards Institute (ANSI)
    1. C136.2-2004 (or latest), American National Standard for Roadway and Area Lighting Equipment—Luminaire Voltage Classification
    2. C136.10-2010 (or latest), American National Standard for Roadway and Area Lighting Equipment - Locking-Type Photocontrol Devices and Mating Receptacle Physical and Electrical Interchangeability and Testing
    3. C136.15-2011 (or latest), American National Standard for Roadway and Area Lighting Equipment – Luminaire Field Identification
    4. C136.22-2004 (R2009 or latest), American National Standard for Roadway and Area Lighting Equipment – Internal Labeling of Luminaires
    5. C136.25-2009 (or latest), American National Standard for Roadway and Area Lighting Equipment – Ingress Protection (Resistance to Dust, Solid Objects and Moisture) for Luminaire Enclosures
    6. C136.31-2010 (or latest), American National Standard for Roadway Lighting Equipment – Luminaire Vibration
    7. C136.37-2011 (or latest), American National Standard for Roadway and Area Lighting Equipment - Solid State Light Sources Used in Roadway and Area Lighting
B. American Society for Testing and Materials International (ASTM)
    1. B117-09 (or latest), Standard Practice for Operating Salt Spray (Fog) Apparatus
    2. D1654-08 (or latest), Standard Test Method for Evaluation of Painted or Coated Specimens Subjected to Corrosive Environments
    3. D523-08 (or latest), Standard Test Method for Specular Gloss
    4. G154-06 (or latest), Standard Practice for Operating Fluorescent Light Apparatus for UV Exposure of Nonmetallic Materials
C. Council of the European Union (EC)
    1. RoHS Directive 2002/95/EC, on the restriction of the use of certain hazardous substances in electrical and electronic equipment
D. Federal Trade Commission (FTC)
    1. Green Guides, 16 CFR Part 260, Guides for the Use of Environmental Marketing Claims
E. Illuminating Engineering Society of North America (IESNA or IES)
    1. DG-4-03 (or latest), Design Guide for Roadway Lighting Maintenance
    2. HB-10-11 (or latest), IES Lighting Handbook, 10th Edition
    3. LM-50-99 (or latest), IESNA Guide for Photometric Measurement of Roadway Lighting Installations

4. LM-61-06 (or latest), IESNA Approved Guide for Identifying Operating Factors Influencing Measured Vs. Predicted Performance for Installed Outdoor High Intensity Discharge (HID) Luminaires
5. LM-79-08 (or latest), IESNA Approved Method for the Electrical and Photometric Measurements of Solid-Sate Lighting Products
6. LM-80-08 (or latest), IESNA Approved Method for Measuring Lumen Maintenance of LED Light Sources
7. RP-8-00 (or latest), ANSI / IESNA American National Standard Practice for Roadway Lighting
8. RP-16-10 (or latest), ANSI/IES Nomenclature and Definitions for Illuminating Engineering
9. TM-3-95 (or latest), A Discussion of Appendix E - "Classification of Luminaire Lighting Distribution," from ANSI/IESNA RP-8-83
10. TM-15-11 (or latest), Luminaire Classification System for Outdoor Luminaires
11. TM-21-11 (or latest), Projecting Long Term Lumen Maintenance of LED Light Sources

F. Institute of Electrical and Electronics Engineers (IEEE)
   1. IEEE C62.41.2-2002 (or latest), IEEE Recommended Practice on Characterization of Surges in Low-Voltage (1000 V and less) AC Power Circuits
   2. ANSI/IEEE C62.45-2002 (or latest), IEEE Recommended Practice on Surge Testing for Equipment Connected to Low-Voltage (1000 V and Less) AC Power Circuits

G. National Electrical Manufacturers Association (NEMA)
   1. ANSI/NEMA/ANSLG C78.377-2008 (or latest), American National Standard for the Chromaticity of Solid State Lighting Products

H. National Fire Protection Association (NFPA)
   1. 70 – National Electrical Code (NEC)

I. Underwriters Laboratories (UL)
   1. 1449, Surge Protective Devices
   2. 1598, Luminaires
   3. 8750, Light Emitting Diode (LED) Equipment for Use in Lighting Products

1.2. RELATED DOCUMENTS

A. Contract Drawings and conditions of Contract (including General Conditions, Addendum to the General Conditions, Special Conditions, Division 01 Specifications Sections and all other Contract Documents) apply to the work of this section.
   a. See the separate Specification for Adaptive Control and Remote Monitoring of LED Roadway Luminaires for additional driver performance and interface requirements.

1.3. DEFINITIONS

A. Lighting terminology used herein is defined in IES RP-16. See referenced documents for additional definitions.
   1. Exception: The term “driver” is used herein to broadly cover both drivers and power supplies, where applicable.

2. Clarification: The term “LED light source(s)” is used herein per IES LM-80 to broadly cover LED package(s), module(s), and array(s).

1.4. QUALITY ASSURANCE

A. Before approval and purchase, Owner may request luminaire sample(s) identical to product configuration(s) submitted for inspection. Owner may request IES LM-79 testing of luminaire sample(s) to verify performance is within manufacturer-reported tolerances.
B. After installation, Owner may perform IES LM-50 field measurements to verify performance requirements outlined in Appendix A, giving consideration to measurement uncertainties outlined in IES LM-61.

1.5. LIGHTING SYSTEM PERFORMANCE

A. Energy Conservation
    1. Connected Load
        a. Luminaires shall have maximum nominal luminaire input wattage as specified for each luminaire type in Appendix A.
    2. Lighting Controls
        a. See separate controls specification identified in section 1.2 above, if applicable.
        b. See section 2.1-B below for driver control interface and performance requirements.
        c. See section 2.1-K below for photocontrol receptacle requirements.
B. Photometric Requirements
    1. Luminaires shall meet the general criteria provided in the body of this specification and the particular criteria for each luminaire type defined in Appendix A.

1.6. REQUIRED SUBMITTALS FOR EACH LUMINAIRE TYPE DEFINED IN APPENDIX A

A. General submittal content shall include
    1. Completed Appendix E submittal form
    2. Luminaire cutsheets
    3. Cutsheets for LED light sources
    4. Cutsheets for LED driver(s)
        a. If dimmable LED driver is specified, provide diagrams illustrating light output and input power as a function of control signal.
    5. Cutsheets for surge protection device, if applicable
    6. Instructions for installation and maintenance
    7. Summary of luminaire recycled content and recyclability per the FTC Green Guides, expressed by percentage of luminaire weight
B. LM-79 luminaire photometric report(s) shall be produced by the test laboratory and include
    1. Name of test laboratory

a. The test laboratory must hold National Voluntary Laboratory Accreditation Program (NVLAP) accreditation for the IES LM-79 test procedure or must be qualified, verified, and recognized through the U.S. Department of Energy's CALiPER program. For more information, see http://ts.nist.gov/standards/scopes/eelit.htm or www.ssl.energy.gov/test_labs.html.

2. Report number
3. Date
4. Complete luminaire catalog number
    a. Provide explanation if catalog number in test report(s) does not match catalog number of luminaire submitted
        i. Clarify whether discrepancy does not affect performance, e.g., in the case of differing luminaire housing color.
        ii. If nominal performance of submitted and tested products differ, submit additional LM-79 report(s) and derivation as indicated in Appendix C.
5. Description of luminaire, LED light source(s), and LED driver(s)
6. Goniophotometry
7. Colorimetry
    a. If a scotopic/photopic (S/P) ratio is not reported, a spectral power distribution table adequate for accurate calculation of the ratio shall be included.

C. Calculations and supporting test data per Appendix B indicating a lumen maintenance life of not less than 36,000 operating hours

D. Computer-generated point-by-point photometric analysis of maintained photopic light levels as per Appendix A
1. Calculations shall be for maintained values, i.e. Light Loss Factor (LLF) < 1.0, where LLF = LLD x LDD x LATF, and
    a. Lamp Lumen Depreciation (LLD)
        i. Shall be 0.70 (L_{70}) for all luminaires as per IES HB-10.
        ii. Shall be the percentage of initial output calculated in section 1.6-C.
    b. Luminaire Dirt Depreciation (LDD) = 0.90, as per IES DG-4 for an enclosed and gasketed roadway luminaire installed in an environment with less than 150 $\mu g/m^3$ airborne particulate matter and cleaned every four years.
    c. Luminaire Ambient Temperature Factor (LATF) = 1.00
2. Use of IES HB-10 mesopic multipliers
    a. Shall be disallowed herein, by assuming an S/P ratio of 1.00 for all luminaires.
    b. Shall only be permitted for luminaire types indicated in Appendix A for use in 25 mph speed zones, using nominal S/P ratio and bilinear interpolation. Mesopic multiplier(s) used shall be clearly indicated in the calculations.
3. Calculation/measurement points shall be per IES RP-8.

E. Summary of Joint Electron Devices Engineering Council (JEDEC) or Japan Electronics and Information Technology Industries (JEITA) reliability testing performed for LED packages
F. Summary of reliability testing performed for LED driver(s)
G. Written product warranty as per section 1.7 below
H. Safety certification and file number
    1. Applicable testing bodies are determined by the US Occupational Safety Health Administration (OSHA) as Nationally Recognized Testing Laboratories (NRTL) and include: CSA (Canadian Standards Association), ETL (Edison Testing Laboratory), and UL (Underwriters Laboratory).
I. Buy American documentation
    1. Manufacturers listed on the current NEMA Listing of Companies Offering Outdoor Luminaires Manufactured in U.S.A. for Recovery Act Projects need only provide a copy of the document (http://www.nema.org/gov/economic-stimulus).
    2. Other manufacturers shall submit documentation as per the DOE Guidance on Documenting Compliance with the Recovery Act Buy American Provisions (http://www1.eere.energy.gov/recovery/buy_american_provision.html).

1.7. WARRANTY

A. Provide a minimum five-year warranty covering maintained integrity and functionality of
    1. Luminaire housing, wiring, and connections
    2. LED light source(s)
        a. Negligible light output from more than 10 percent of the LED packages constitutes luminaire failure.
    3. LED driver(s)
B. Warranty period shall begin 90 days after date of invoice, or as negotiated by owner such as in the case of an auditable asset management system.

PART 2 – PRODUCTS

2.1. LUMINAIRE REQUIREMENTS

A. General Requirements
    1. Luminaires shall be as specified for each type in Appendix A.
    2. Luminaire shall have an external label per ANSI C136.15
    3. Luminaire shall have an internal label per ANSI C136.22.
    4. Nominal luminaire input wattage shall account for nominal applied voltage and any reduction in driver efficiency due to sub-optimal driver loading.
    5. Luminaires shall start and operate in -20°C to +40°C ambient.
    6. Electrically test fully assembled luminaires before shipment from factory.
    7. Effective Projected Area (EPA) and weight of the luminaire shall not exceed the values indicated in Appendix A.
    8. Luminaires shall be designed for ease of component replacement and end-of-life disassembly.

9. Luminaires shall be rated for the ANSI C136.31 Vibration Level indicated in Appendix A.
10. LED light source(s) and driver(s) shall be RoHS compliant.
11. Transmissive optical components shall be applied in accordance with OEM design guidelines to ensure suitability for the thermal/mechanical/chemical environment.

B. Driver
   1. Rated case temperature shall be suitable for operation in the luminaire operating in the ambient temperatures indicated in section 2.1-A above.
   2. Shall accept the voltage or voltage range indicated in Appendix A at 50/60 Hz, and shall operate normally for input voltage fluctuations of plus or minus 10 percent.
   3. Shall have a minimum Power Factor (PF) of 0.90 at full input power and across specified voltage range.
   4. Control signal interface
      a. Luminaire types indicated “Required” in Appendix A shall accept a control signal as specified via separate controls specification referenced in section 1.2 above, e.g., for dimming.
      b. Luminaire types indicated “Not Required” in Appendix A need not accept a control signal.

C. Electrical immunity
   1. Luminaire shall meet the “Basic” requirements in Appendix D. Manufacturer shall indicate on submittal form (Appendix E) whether failure of the electrical immunity system can possibly result in disconnect of power to luminaire.
   2. Luminaire shall meet the “Elevated” requirements in Appendix D. Manufacturer shall indicate on submittal form (Appendix E) whether failure of the electrical immunity system can possibly result in disconnect of power to luminaire.

D. Electromagnetic interference
   1. Shall have a maximum Total Harmonic Distortion (THD) of 20% at full input power and across specified voltage range.
   2. Shall comply with FCC 47 CFR part 15 non-consumer RFI/EMI standards.

E. Electrical safety testing
   1. Luminaire shall be listed for wet locations by an OSHA NRTL.
   2. Luminaires shall have locality-appropriate governing mark and certification.

F. Painted or finished luminaire components exposed to the environment
   1. Shall exceed a rating of six per ASTM D1654 after 1000hrs of testing per ASTM B117.
   2. The coating shall exhibit no greater than 30% reduction of gloss per ASTM D523, after 500 hours of QUV testing at ASTM G154 Cycle 6.

G. Thermal management
   1. Mechanical design of protruding external surfaces (heat sink fins) for shall facilitate hose-down cleaning and discourage debris accumulation.
   2. Liquids or other moving parts shall be clearly indicated in submittals, shall be consistent with product testing, and shall be subject to review by Owner.

H. IES TM-15 limits for Backlight, Uplight, and Glare (BUG Ratings) shall be as specified for each luminaire type in Appendix A.

1. Calculation of BUG Ratings shall be for initial (worst-case) values, i.e., Light Loss Factor (LLF) = 1.0.
2. If luminaires are tilted upward for calculations in section 1.6-D, BUG Ratings shall be calculated for the same angle(s) of tilt.

I. Minimum Color Rendering Index (CRI): 60.

J. Correlated Color Temperature (CCT)
1. If nominal CCT specified in Appendix A is listed in Table 1 below, measured CCT and Duv shall be as listed in Table 1.

Table 1. Allowable CCT and Duv (adapted from NEMA C78.377)

Manufacturer-Rated Nominal CCT (K)	Allowable LM-79 Chromaticity Values	
	Measured CCT (K)	Measured Duv
2700	2580 to 2870	-0.006 to 0.006
3000	2870 to 3220	-0.006 to 0.006
3500	3220 to 3710	-0.006 to 0.006
4000	3710 to 4260	-0.005 to 0.007
4500	4260 to 4746	-0.005 to 0.007
5000	4745 to 5311	-0.004 to 0.008
5700	5310 to 6020	-0.004 to 0.008
6500	6020 to 7040	-0.003 to 0.009

2. If nominal CCT specified in Appendix A is not listed in Table 1, measured CCT and Duv shall be as per the criteria for Flexible CCT defined in NEMA C78.377.

K. The following shall be in accordance with corresponding sections of ANSI C136.37
1. Wiring and grounding
   a. All internal components shall be assembled and pre-wired using modular electrical connections.
2. Mounting provisions
   a. Specific configurations are indicated in Appendix A
3. Terminal blocks for incoming AC lines
4. Photocontrol receptacle
5. Latching and hinging
6. Ingress protection

2.2. PRODUCT MANUFACTURERS

A. Any manufacturer offering products that comply with the required product performance and operation criteria may be considered.

2.3. MANUFACTURER SERVICES

A. Manufacturer or local sales representative shall provide installation and troubleshooting support via telephone and/or email.

END OF SECTION

Appendix B
Estimating LED Lumen Maintenance

IES TM-21 allows for extrapolation of expected lumen maintenance from available test data. The extent of such extrapolation is limited by the duration of testing completed and the number of samples used in the testing. The TM-21 methodology shall be used by the manufacturer to determine lamp lumen depreciation (LLD) at end of lumen maintenance life per section 1.6-C.

The applicant may estimate lumen maintenance in one of two ways:

<u>Option 1: Component Performance</u>

Under this compliance path, the applicant must submit calculations per TM-21 predicting lumen maintenance at the luminaire level using In Situ Temperature Measurement Testing (ISTMT) and LM-80 data. To be eligible for the Component Performance option, ALL of the conditions below must be met. If ANY of the conditions is not met, the component performance option may not be used and the applicant must use Option 2 for compliance.

1. The LED light source(s) have been tested according to LM-80.
2. The LED drive current specified by the luminaire manufacturer is less than or equal to the drive current specified in the LM-80 test report.
3. The LED light source(s) manufacturer prescribes/indicates a temperature measurement point (T_S) on the light source(s).
4. The T_S is accessible to allow temporary attachment of a thermocouple for measurement of in situ temperature. Access via a temporary hole in the housing, tightly resealed during testing with putty or other flexible sealant is allowable.
5. For the hottest LED light source in the luminaire, the temperature measured at the T_S during ISTMT is less than or equal to the temperature specified in the LM-80 test report for the corresponding drive current or higher, within the manufacturer's specified operating current range.
    a. The ISTMT laboratory must be approved by OSHA as a Nationally Recognized Testing Lab (NRTL), must be qualified, verified, and recognized through DOE's CALiPER program, or must be recognized through UL's Data Acceptance Program.
    b. The ISTMT must be conducted with the luminaire installed in the appropriate application as defined by ANSI/UL 1598 (hardwired luminaires), with bird-fouling appropriately simulated (and documented by photograph) as determined by the manufacturer.

<u>Option 2: Luminaire Performance</u>

Under this compliance path, the applicant must submit TM-21 calculations based on LM-79 photometric test data for no less than three samples of the entire luminaire. Duration of operation and interval between photometric tests shall conform to the TM-21 criteria for LED light sources. For example, testing solely at 0 and 6000 hours of operation would not be adequate for the purposes of extrapolation.

Between LM-79 tests, the luminaire test samples must be operated long-term in the appropriate application as defined by ANSI/UL 1598 (hardwired luminaires). The test laboratory must hold

NVLAP accreditation for the LM-79 test procedure or must be qualified, verified, and recognized through the U.S. Department of Energy (DOE)'s CALiPER program. The extent of allowable extrapolation (either 5.5 or 6 times the test duration) depends on the total number of LED light sources (no less than 10 and preferably more than 19) installed in the luminaire samples, as per TM-21.

This compliance path poses a greater testing burden to luminaire manufacturers but incorporates long-term testing of other components in the system, such as drivers.

Under either compliance path, values used for extrapolation shall be summarized per TM-21 Tables 1 and 2. Submitted values for lumen maintenance lifetime and the associated percentage lumen maintenance shall be "reported" rather than "projected" as defined by TM-21. Supporting diagrams are requested to facilitate interpretation by Owner.

APPENDIX C
PRODUCT FAMILY TESTING - LM-79 AND ISTMT

It is recognized that due to the time and cost required for product testing, it would not be realistic to expect manufacturers offering a multitude of unique luminaire configurations to test every possible configuration. Therefore, the "product families" method may be utilized for LM-79 and ISTMT, whereby manufacturers identify a set of representative products for which test data can be used to demonstrate the accuracy of interpolated or extrapolated performance of product configurations lacking test data. Precedent for this approach can be found in LM-80.

If the particular luminaire configuration submitted has not been tested, the performance may be conservatively represented by test data for another luminaire configuration having:

- The same intensity distribution (typically only applies to LM-79)
- The same or lower nominal CCT
- The same or higher nominal drive current
- The same or greater number of LED light source(s)
- The same or lower percentage driver loading and efficiency
- The same or smaller size luminaire housing.

A more accurate estimate of performance can be obtained by linear interpolation between two or more tests differing in terms of the six parameters listed above. For example, consider a hypothetical luminaire offered in a single size housing, and having the following parameters:

- Three intensity distributions: IES Type II, III, or IV
- Three CCTs: 4000, 5000, and 6000K
- Three drive currents: 350, 525, and 700 mA
- Four LED quantities: 20, 40, 60, or 80 LEDs.

Table C.1 illustrates a set of tests which could allow for accurate interpolation between tested configurations, given a single luminaire housing size and essentially constant driver efficiency; these 10 tests may provide representative data for the 108 possible product configurations. Note that normalized intensity distribution must not be affected by the other three parameters.

Table C.1. Representative testing of a single luminaire housing size

Tests	Intensity distribution (IES Type)	CCT (K)	Drive current (mA)	# of LEDs
1, 2, 3	II, III, IV	4000	700	80
4, 5	IV	5000, 6000	700	80
6, 7	IV	4000	325, 525	80
8, 9, 10	IV	4000	700	20, 40, 60

For example, the manufacturer could detail interpolation as shown in Table C.2, applying the following multipliers to the base test #2 to model a configuration with Type III intensity distribution, 5000K CCT, 525 mA drive current, and 40 LEDs:

- Ratio of test #4 lumens to test #3 lumens
- Ratio of test #7 lumens to test #3 lumens
- Ratio of test #9 lumens to test #3 lumens.

Table C.2. Multipliers for Test #2 to yield: Type III , 5000K, 525mA, 40 LEDs

Test #	Intensity distribution (IES Type)	CCT (K)	Drive current (mA)	# of LEDs	Multiplier (lumens ratio)
2	III	4000	700	80	n/a
3	IV	4000	700	80	n/a
4	IV	5000	700	80	#4 / #3
7	IV	4000	525	80	#7 / #3
9	IV	4000	700	40	#9 / #3

Interpolation between minimal LM-79 and ISTMT data is more difficult if housing size increases with increasing wattage; it may not be clear whether the lowest-wattage configuration would be expected to "run cooler" than the highest-wattage configuration. In these circumstances, the adequacy of submitted data is subject to Owner approval.

At this time, the "successor" method cannot be used; luminaires tested must utilize the LED light source(s) characterized by the submitted LM-80 report.

APPENDIX D
ELECTRICAL IMMUNITY

Test Procedure

- Electrical Immunity Tests 1, 2 and 3, as defined by their Test Specifications, shall be performed on an entire powered and connected luminaire, including any control modules housed within the luminaire, but excluding any control modules mounted externally, such as a NEMA socket connected photo-control. A shorting cap should be placed across any such exterior connector.
- The luminaire shall be connected to an AC power source with a configuration appropriate for nominal operation. The AC power source shall have a minimum available short-circuit current of 200A. The luminaire shall be tested at the nominal input voltage specified in Appendix A, or at the highest input voltage in the input voltage range specified in Appendix A.
- Electrical Immunity test waveforms shall be superimposed on the input AC power line at a point within 6 inches (15cm) of entry into the luminaire using appropriate high-voltage probes and a series coupler/decoupler network (CDN) appropriate for each coupling mode, as defined by ANSI/IEEE C62.45-2002. The test area for all tests shall be set up according to ANSI/IEEE C62.45-2002, as appropriate.
- Prior to electrical immunity testing a set of diagnostic measurements shall be performed, and the results recorded to note the pre-test function of the luminaire after it has reached thermal equilibrium. These measurements should include at a minimum:
  a) For all luminaires, Real Power, Input RMS Current, Power Factor and THD at full power/light output
  b) For luminaires specified as dimmable, Real Power, Input RMS Current, Power Factor and THD at a minimum of 4 additional dimmed levels, including the rated minimum dimmed level
- Tests shall be applied in sequential order (Test 1, followed by Test 2, followed by Test 3). If a failure occurs during Test 3, then Test 3 shall be re-applied to a secondary luminaire of identical construction.
- Following the completion of Tests 1, 2, and 3, the same set of diagnostic measurements performed pre-test should be repeated for all tested luminaires, and the results recorded to note the post-test function of the luminaire(s).
- A luminaire must function normally and show no evidence of failure following the completion of Test 1 + Test 2 + Test 3 (for a single tested luminaire), or the completion of Test 1 + Test 2 on a primary luminaire and Test 3 on a secondary luminaire. Abnormal behavior during testing is acceptable.
- A luminaire failure will be deemed to have occurred if any of the following conditions exists following the completion of testing:
  a) A hard power reset is required to return to normal operation
  b) A noticeable reduction in full light output (e.g. one or more LEDs fail to produce light, or become unstable) is observed

c) Any of the post-test diagnostic measurements exceeds by ±5% the corresponding pre-test diagnostic measurement.
d) The luminaire, or any component in the luminaire (including but not limited to an electrical connector, a driver, a protection component or module) has ignited or shows evidence of melting or other heat-induced damage. Evidence of cracking, splitting, rupturing, or smoke damage on any component is acceptable.

Test Specifications

NOTE: L1 is typically "HOT", L2 is typically "NEUTRAL" and PE = Protective Earth.

Test 1) Ring Wave: The luminaire shall be subjected to repetitive strikes of a "C Low Ring Wave" as defined in IEEE C62.41.2-2002, Scenario 1, Location Category C. The test strikes shall be applied as specified by Table D.1. Prior to testing, the ring wave generator shall be calibrated to simultaneously meet BOTH the specified short circuit current peak and open circuit voltage peak MINIMUM requirements. Note that this may require that the generator charging voltage be raised above the specified level to obtain the specified current peak. Calibrated current probes/transformers designed for measuring high-frequency currents shall be used to measure test waveform currents.

Test waveform current shapes and peaks for all strikes shall be compared to ensure uniformity throughout each set (coupling mode + polarity/phase angle) of test strikes, and the average peak current shall be calculated and recorded. If any individual peak current in a set exceeds by ±10% the average, the test setup shall be checked, and the test strikes repeated.

Table D.1: 0.5 µS – 100Hz Ring Wave Specification

Parameter	Test Level/Configuration
Short Circuit Current Peak	0.5 kA
Open Circuit Voltage Peak	6 kV
Source Impedance	12 Ω
Coupling Modes	L1 to PE, L2 to PE, L1 to L2
Polarity and Phase Angle	Positive at 90° and Negative at 270°
Test Strikes	5 for each Coupling Mode and Polarity/Phase Angle combination
Time between Strikes	1 minute
Total Number of Strikes	= 5 strikes x 4 coupling modes x 2 polarity/phase angles = 40 total strikes

Test 2) Combination Wave: The luminaire shall be subjected to repetitive strikes of a "C High Combination Wave" or "C Low Combination Wave", as defined in IEEE C62.41.2-2002, Scenario 1, Location Category C. The test strikes shall be applied as specified by Table D.2. The "Low" test level shall be used for luminaires with **Basic** Electrical Immunity requirements, while the "High" test level shall be used for luminaires with **Elevated** Electrical Immunity requirements. Prior to testing, the combination wave generator shall be calibrated to simultaneously meet BOTH the specified short circuit current peak and open circuit voltage peak MINIMUM requirements. Note that this may require that the generator charging voltage be raised above the specified level to obtain the specified current peak. Calibrated current

probes/transformers designed for measuring high-frequency currents shall be used to measure test waveform currents.

Test waveform current shapes and peaks for all strikes shall be compared to ensure uniformity throughout each set (coupling mode + polarity/phase angle) of test strikes, and the average peak current shall be calculated and recorded. If any individual peak current in a set exceeds by ±10% the average, the test setup shall be checked, and the test strikes repeated.

Table D.2: 1.2/50µS – 8/20 µS Combination Wave Specification

Parameter	Test Level/ Configuration	
1.2/50 µS Open Circuit Voltage Peak	Low: 6 kV	High: 10kV
8/20 µS Short Circuit Current Peak	Low: 3 kA	High: 10kA
Source Impedance	2Ω	
Coupling Modes	L1 to PE, L2 to PE, L1 to L2	
Polarity and Phase Angle	Positive at 90° and Negative at 270°	
Test Strikes	5 for each Coupling Mode and Polarity/Phase Angle combination	
Time Between Strikes	1 minute	
Total Number of Strikes	= 5 strikes x 4 coupling modes x 2 polarity/phase angles = 40 total strikes	

Test 3) Electrical Fast Transient (EFT): The luminaire shall be subjected to “Electrical Fast Transient Bursts”, as defined in IEEE C62.41.2 -2002. The test area shall be set up according to IEEE C62.45-2002. The bursts shall be applied as specified by Table D.3. Direct coupling is required; the use of a coupling clamp is not allowed.

Table D.3: Electrical Fast Transient (EFT) Specification

Parameter	Test Level/ Configuration
Open Circuit Voltage Peak	3 kV
Burst Repetition Rate	2.5 kHz
Burst Duration	15 mS
Burst Period	300 mS
Coupling Modes	L1 to PE, L2 to PE, L1 to L2
Polarity	Positive and Negative
Test Duration	1 minute for each Coupling Mode and Polarity combination
Total Test Duration	= 1 minute x 7 coupling modes x 2 polarities = 14 minutes

APPENDIX E
PRODUCT SUBMITTAL FORM

Luminaire Type[1]		
Manufacturer		
Model number		
Housing finish color		
Tenon nominal pipe size (inches)		
Nominal luminaire weight (lb)		
Nominal luminaire EPA (ft^2)		
Nominal input voltage (V)		
ANSI vibration test level	☑ Level 1 (Normal)	☐ Level 2 (bridge/overpass)
Nominal BUG Ratings		
Make/model of LED light source(s)		
Make/model of LED driver(s)		
Dimmability	☐ Dimmable	☑ Not dimmable
Control signal interface		
Upon electrical immunity system failure	☐ Possible disconnect	☐ No possible disconnect
Thermal management	☐ Moving parts	☑ No moving parts
Lumen maintenance testing duration (hr)		
Reported lumen maintenance life (hr) [2]		
Warranty period (yr)		
Parameter	Nominal value	Tolerance (%)
Initial photopic output (lm)		
Maintained photopic output (lm)		
Lamp lumen depreciation		
Initial input power (W)		
Maintained input power (W)		
Initial LED drive current (mA)		
Maintained LED drive current (mA)		
Drive current used		
In-situ LED T_c (°C)		
CCT (K)		
S/P ratio		
Additional product description		

[1] See Appendix A, and attach supporting documentation as required.
[2] Value shall be no less than as specified in section 1.6-C, and shall not exceed six times the testing duration indicated in the row above. Value shall be consistent with values submitted in the rows below for maintained light output, maintained input power, and maintained drive current.

Appendix E

Model Specification for LED Roadway Luminaires
Material-Based

Municipal Solid-State Street Lighting Consortium Example

(Note: This specification contains its own appendix reference)

Instructions for the Editor (Owner, Utility, or ESCO)

This document provides Material specifications, as opposed to System specifications, to be appended to the main body of the Consortium template. Refer to the instructions provided at the beginning of the main document, which is downloaded from the Consortium website as a separate file.

NOTE: For any given luminaire type, the user should select either the System specification or this Material specification, but not both. The System specification is preferred, where practical, to provide greater assurance that quality and quantity of illumination will meet expectations.

1. Edit values and layout on the following pages as desired. The values indicated are **SAMPLES ONLY** and should be customized by the Editor. For example:
    a. Maximum input wattage should be carefully selected to meet energy savings criteria. An unrealistically low value could inadvertently eliminate viable options.
    b. Maximum BUG ratings should be carefully selected to balance safety, security, and obtrusive light criteria. Unrealistically low values could inadvertently eliminate viable options.
    c. Maximum effective projected area (EPA) should be based on the load capacity of the mast arm and pole, i.e., not necessarily based on the EPA of existing luminaires.
2. To add more luminaire types, copy-paste the contents of Page A-1 onto a new page, created by inserting a page break.
3. Delete/modify this page and the previous page as appropriate before appending to the main document, ahead of Appendix B.

APPENDIX A
MATERIAL SPECIFICATION
LUMINAIRE TYPE "A"

EXISTING LUMINAIRE TO BE REPLACED (FOR REFERENCE ONLY)		
BENCHMARK LUMINAIRE:	Lamp wattage and type	70 W HPS
	Initial downward luminaire output (lumens below horizontal)	4284 lm
	Light loss factor	0.76
LENS:	☐ Flat ("cutoff" style) ☑ Sag/drop	
IES[1] FORWARD TYPE:	☐ I ☐ II ☑ III ☐ IV ☐ V ☐ VS	
IES[1] LATERAL TYPE:	☐ Very short ☐ Short ☑ Medium ☐ Long ☐ Very long	
PERFORMANCE CRITERIA: LED LUMINAIRE		
INPUT POWER:	Max. nominal luminaire input power	103 W
NOMINAL CCT:	Rated correlated color temperature	4000 K
PHOTOPIC[2] DOWNWARD LUMINAIRE OUTPUT:	Minimum *maintained* luminaire output below horizontal	3256 lm
BUG[3] RATING:	Max. nominal backlight-uplight-glare ratings	B1-U2-G1
VOLTAGE:	Nominal luminaire input voltage	120 V
FINISH:	Luminaire housing finish color	Gray
WEIGHT:	Maximum luminaire weight	30 lb
EPA:	Maximum effective projected area	0.7 ft^2
MOUNTING:	Mtg. method	☐ Post-top ☑ Side-arm ☐ Trunnion/yoke ☐ Swivel-tenon
	Tenon nominal pipe size (NPS)	2 inches
VIBRATION:	ANSI test level	☑ Level 1 (normal) ☐ Level 2 (bridge/overpass)
DRIVER:	Control signal interface	☑ Not required ☐ Required

[1] See IES TM-3 and TM-15 for an explanation of this classification system. "Very" indicates out of defined range.
[2] Mesopic multipliers are not applicable if speed limit and/or adaptation luminance are unknown.
[3] The deprecated "cutoff" classification system cannot be accurately applied to LED luminaires.

Model Specification for LED Roadway Luminaires

Version 1.0

October 2011

Instructions for the Editor (Owner, Utility, or ESCO)

This document, as downloaded in its original unedited form from the Consortium website, is intended to be used as a model or template specification. It should be customized as needed to meet the particular needs of each Owner, Utility, or ESCO. For example, a higher degree of corrosion resistance and/or electrical immunity may be required in some regions. The unedited template is not intended to serve as a standard specification, and therefore cannot result in a single list of qualified products; since criteria will vary from municipality to municipality, a product may qualify for one while not qualifying for another.

The template is composed of two separate documents:

3. The body of the specification and appendices (beginning with Appendix B) included at the end.
4. Appendix A, to be inserted by the Editor (after printing) before Appendix B. The Editor may choose ONE of two versions of Appendix A, depending on available information.
    a. System Specification (application efficacy), which characterizes luminaire performance based on site characteristics such as mounting height, pole spacing, number of drive lanes, input power, and required light levels and uniformity.
    b. Material Specification (luminaire efficacy), which characterizes luminaire performance without consideration of site characteristics.

These three files are kept separate to allow for independent maintenance, while preventing redundancies and contradictions between documents. Again, note that only ONE of the two versions of Appendix A should be used for any given luminaire type. If both versions were used for the same luminaire type, luminaire efficacy could (inappropriately) negate application efficacy, thereby potentially excluding superior luminaires from consideration.

The submittal form in Appendix E is for use by manufacturers and should not be completed by the user.

If the material in this document is unfamiliar, please consider hiring a qualified lighting consultant.

NOTE: *Hidden text in red italicized font* provides guidance for the editor throughout these documents. The intent is for this guidance to be visible on-screen but invisible when printed as a final edited/customized specification.

While viewing the document on your monitor, you should see red italicized text between the brackets here: []

- If you don't see the text, adjust your Options in Microsoft Word as follows:
    - Under "Display" in Word 2007 or 2010, check the Hidden Text box (under Always Show These Formatting Marks On The Screen), and click OK.
    - For earlier versions of Word, adjust setting(s) in a similar manner.

And in Print Preview, you should NOT see such text between the brackets here: []

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PART 1 – GENERAL

1.8. REFERENCES

The publications listed below form a part of this specification to the extent referenced. Publications are referenced within the text by their basic designation only. Versions listed shall be superseded by updated versions as they become available.

J. American National Standards Institute (ANSI)
   1. C136.2-2004 (or latest), American National Standard for Roadway and Area Lighting Equipment—Luminaire Voltage Classification
   2. C136.10-2010 (or latest), American National Standard for Roadway and Area Lighting Equipment - Locking-Type Photocontrol Devices and Mating Receptacle Physical and Electrical Interchangeability and Testing
   3. C136.15-2011 (or latest), American National Standard for Roadway and Area Lighting Equipment – Luminaire Field Identification
   4. C136.22-2004 (R2009 or latest), American National Standard for Roadway and Area Lighting Equipment – Internal Labeling of Luminaires
   5. C136.25-2009 (or latest), American National Standard for Roadway and Area Lighting Equipment – Ingress Protection (Resistance to Dust, Solid Objects and Moisture) for Luminaire Enclosures
   6. C136.31-2010 (or latest), American National Standard for Roadway Lighting Equipment – Luminaire Vibration
   7. C136.37-2011 (or latest), American National Standard for Roadway and Area Lighting Equipment - Solid State Light Sources Used in Roadway and Area Lighting
K. American Society for Testing and Materials International (ASTM)
   1. B117-09 (or latest), Standard Practice for Operating Salt Spray (Fog) Apparatus
   2. D1654-08 (or latest), Standard Test Method for Evaluation of Painted or Coated Specimens Subjected to Corrosive Environments
   3. D523-08 (or latest), Standard Test Method for Specular Gloss
   4. G154-06 (or latest), Standard Practice for Operating Fluorescent Light Apparatus for UV Exposure of Nonmetallic Materials
L. Council of the European Union (EC)
   1. RoHS Directive 2002/95/EC, on the restriction of the use of certain hazardous substances in electrical and electronic equipment
M. Federal Trade Commission (FTC)
   1. Green Guides, 16 CFR Part 260, Guides for the Use of Environmental Marketing Claims
N. Illuminating Engineering Society of North America (IESNA or IES)
   1. DG-4-03 (or latest), Design Guide for Roadway Lighting Maintenance
   2. HB-10-11 (or latest), IES Lighting Handbook, 10th Edition
   3. LM-50-99 (or latest), IESNA Guide for Photometric Measurement of Roadway Lighting Installations

4. LM-61-06 (or latest), IESNA Approved Guide for Identifying Operating Factors Influencing Measured Vs. Predicted Performance for Installed Outdoor High Intensity Discharge (HID) Luminaires
5. LM-79-08 (or latest), IESNA Approved Method for the Electrical and Photometric Measurements of Solid-Sate Lighting Products
6. LM-80-08 (or latest), IESNA Approved Method for Measuring Lumen Maintenance of LED Light Sources
7. RP-8-00 (or latest), ANSI / IESNA American National Standard Practice for Roadway Lighting
8. RP-16-10 (or latest), ANSI/IES Nomenclature and Definitions for Illuminating Engineering
9. TM-3-95 (or latest), A Discussion of Appendix E - "Classification of Luminaire Lighting Distribution," from ANSI/IESNA RP-8-83
10. TM-15-11 (or latest), Luminaire Classification System for Outdoor Luminaires
11. TM-21-11 (or latest), Projecting Long Term Lumen Maintenance of LED Light Sources

O. Institute of Electrical and Electronics Engineers (IEEE)
   1. IEEE C62.41.2-2002 (or latest), IEEE Recommended Practice on Characterization of Surges in Low-Voltage (1000 V and less) AC Power Circuits
   2. ANSI/IEEE C62.45-2002 (or latest), IEEE Recommended Practice on Surge Testing for Equipment Connected to Low-Voltage (1000 V and Less) AC Power Circuits

P. National Electrical Manufacturers Association (NEMA)
   1. ANSI/NEMA/ANSLG C78.377-2008 (or latest), American National Standard for the Chromaticity of Solid State Lighting Products

Q. National Fire Protection Association (NFPA)
   1. 70 – National Electrical Code (NEC)

R. Underwriters Laboratories (UL)
   1. 1449, Surge Protective Devices
   2. 1598, Luminaires
   3. 8750, Light Emitting Diode (LED) Equipment for Use in Lighting Products

1.9. RELATED DOCUMENTS

B. Contract Drawings and conditions of Contract (including General Conditions, Addendum to the General Conditions, Special Conditions, Division 01 Specifications Sections and all other Contract Documents) apply to the work of this section.
   a. See the separate Specification for Adaptive Control and Remote Monitoring of LED Roadway Luminaires for additional driver performance and interface requirements.

1.10. DEFINITIONS

A. Lighting terminology used herein is defined in IES RP-16. See referenced documents for additional definitions.
   3. Exception: The term “driver” is used herein to broadly cover both drivers and power supplies, where applicable.

4. Clarification: The term "LED light source(s)" is used herein per IES LM-80 to broadly cover LED package(s), module(s), and array(s).

1.11. QUALITY ASSURANCE

C. Before approval and purchase, Owner may request luminaire sample(s) identical to product configuration(s) submitted for inspection. Owner may request IES LM-79 testing of luminaire sample(s) to verify performance is within manufacturer-reported tolerances.

D. After installation, Owner may perform IES LM-50 field measurements to verify performance requirements outlined in Appendix A, giving consideration to measurement uncertainties outlined in IES LM-61.

1.12. LIGHTING SYSTEM PERFORMANCE

C. Energy Conservation
   1. Connected Load
      a. Luminaires shall have maximum nominal luminaire input wattage as specified for each luminaire type in Appendix A.
   2. Lighting Controls
      a. See separate controls specification identified in section 1.2 above, if applicable.
      b. See section 2.1-B below for driver control interface and performance requirements.
      c. See section 2.1-K below for photocontrol receptacle requirements.

D. Photometric Requirements
   1. Luminaires shall meet the general criteria provided in the body of this specification and the particular criteria for each luminaire type defined in Appendix A.

1.13. REQUIRED SUBMITTALS FOR EACH LUMINAIRE TYPE DEFINED IN APPENDIX A

J. General submittal content shall include
   1. Completed Appendix E submittal form
   2. Luminaire cutsheets
   3. Cutsheets for LED light sources
   4. Cutsheets for LED driver(s)
      a. If dimmable LED driver is specified, provide diagrams illustrating light output and input power as a function of control signal.
   5. Cutsheets for surge protection device, if applicable
   6. Instructions for installation and maintenance
   7. Summary of luminaire recycled content and recyclability per the FTC Green Guides, expressed by percentage of luminaire weight

K. LM-79 luminaire photometric report(s) shall be produced by the test laboratory and include
   1. Name of test laboratory

a. The test laboratory must hold National Voluntary Laboratory Accreditation Program (NVLAP) accreditation for the IES LM-79 test procedure or must be qualified, verified, and recognized through the U.S. Department of Energy's CALiPER program. For more information, see http://ts.nist.gov/standards/scopes/eelit.htm or www.ssl.energy.gov/test_labs.html.

2. Report number
3. Date
4. Complete luminaire catalog number
   a. Provide explanation if catalog number in test report(s) does not match catalog number of luminaire submitted
      i. Clarify whether discrepancy does not affect performance, e.g., in the case of differing luminaire housing color.
      ii. If nominal performance of submitted and tested products differ, submit additional LM-79 report(s) and derivation as indicated in Appendix C.
5. Description of luminaire, LED light source(s), and LED driver(s)
6. Goniophotometry
7. Colorimetry
   a. If a scotopic/photopic (S/P) ratio is not reported, a spectral power distribution table adequate for accurate calculation of the ratio shall be included.

L. Calculations and supporting test data per Appendix B indicating a lumen maintenance life of not less than 36,000 operating hours

M. Computer-generated point-by-point photometric analysis of maintained photopic light levels as per Appendix A

1. Calculations shall be for maintained values, i.e. Light Loss Factor (LLF) < 1.0, where LLF = LLD x LDD x LATF, and
   d. Lamp Lumen Depreciation (LLD)
      iii. Shall be 0.70 (L_{70}) for all luminaires as per IES HB-10.
      iv. Shall be the percentage of initial output calculated in section 1.6-C.
   e. Luminaire Dirt Depreciation (LDD) = 0.90, as per IES DG-4 for an enclosed and gasketed roadway luminaire installed in an environment with less than 150 $\mu g/m^3$ airborne particulate matter and cleaned every four years.
   f. Luminaire Ambient Temperature Factor (LATF) = 1.00
2. Use of IES HB-10 mesopic multipliers
   a. Shall be disallowed herein, by assuming an S/P ratio of 1.00 for all luminaires.
   b. Shall only be permitted for luminaire types indicated in Appendix A for use in 25 mph speed zones, using nominal S/P ratio and bilinear interpolation. Mesopic multiplier(s) used shall be clearly indicated in the calculations.
3. Calculation/measurement points shall be per IES RP-8.

N. Summary of Joint Electron Devices Engineering Council (JEDEC) or Japan Electronics and Information Technology Industries (JEITA) reliability testing performed for LED packages
O. Summary of reliability testing performed for LED driver(s)
P. Written product warranty as per section 1.7 below
Q. Safety certification and file number
    1. Applicable testing bodies are determined by the US Occupational Safety Health Administration (OSHA) as Nationally Recognized Testing Laboratories (NRTL) and include: CSA (Canadian Standards Association), ETL (Edison Testing Laboratory), and UL (Underwriters Laboratory).
R. Buy American documentation
    1. Manufacturers listed on the current NEMA Listing of Companies Offering Outdoor Luminaires Manufactured in U.S.A. for Recovery Act Projects need only provide a copy of the document (http://www.nema.org/gov/economic-stimulus).
    2. Other manufacturers shall submit documentation as per the DOE Guidance on Documenting Compliance with the Recovery Act Buy American Provisions (http://www1.eere.energy.gov/recovery/buy_american_provision.html).

1.14. WARRANTY

C. Provide a minimum five-year warranty covering maintained integrity and functionality of
    1. Luminaire housing, wiring, and connections
    2. LED light source(s)
        a. Negligible light output from more than 10 percent of the LED packages constitutes luminaire failure.
    3. LED driver(s)
D. Warranty period shall begin 90 days after date of invoice, or as negotiated by owner such as in the case of an auditable asset management system.

PART 2 – PRODUCTS

2.4. LUMINAIRE REQUIREMENTS

L. General Requirements
    12. Luminaires shall be as specified for each type in Appendix A.
    13. Luminaire shall have an external label per ANSI C136.15
    14. Luminaire shall have an internal label per ANSI C136.22.
    15. Nominal luminaire input wattage shall account for nominal applied voltage and any reduction in driver efficiency due to sub-optimal driver loading.
    16. Luminaires shall start and operate in -20°C to +40°C ambient.
    17. Electrically test fully assembled luminaires before shipment from factory.
    18. Effective Projected Area (EPA) and weight of the luminaire shall not exceed the values indicated in Appendix A.
    19. Luminaires shall be designed for ease of component replacement and end-of-life disassembly.

20. Luminaires shall be rated for the ANSI C136.31 Vibration Level indicated in Appendix A.
21. LED light source(s) and driver(s) shall be RoHS compliant.
22. Transmissive optical components shall be applied in accordance with OEM design guidelines to ensure suitability for the thermal/mechanical/chemical environment.

M. Driver
1. Rated case temperature shall be suitable for operation in the luminaire operating in the ambient temperatures indicated in section 2.1-A above.
2. Shall accept the voltage or voltage range indicated in Appendix A at 50/60 Hz, and shall operate normally for input voltage fluctuations of plus or minus 10 percent.
3. Shall have a minimum Power Factor (PF) of 0.90 at full input power and across specified voltage range.
4. Control signal interface
    a. Luminaire types indicated “Required” in Appendix A shall accept a control signal as specified via separate controls specification referenced in section 1.2 above, e.g., for dimming.
    b. Luminaire types indicated “Not Required” in Appendix A need not accept a control signal.

N. Electrical immunity
1. Luminaire shall meet the “Basic” requirements in Appendix D. Manufacturer shall indicate on submittal form (Appendix E) whether failure of the electrical immunity system can possibly result in disconnect of power to luminaire.
2. Luminaire shall meet the “Elevated” requirements in Appendix D. Manufacturer shall indicate on submittal form (Appendix E) whether failure of the electrical immunity system can possibly result in disconnect of power to luminaire.

O. Electromagnetic interference
1. Shall have a maximum Total Harmonic Distortion (THD) of 20% at full input power and across specified voltage range.
2. Shall comply with FCC 47 CFR part 15 non-consumer RFI/EMI standards.

P. Electrical safety testing
1. Luminaire shall be listed for wet locations by an OSHA NRTL.
2. Luminaires shall have locality-appropriate governing mark and certification.

Q. Painted or finished luminaire components exposed to the environment
1. Shall exceed a rating of six per ASTM D1654 after 1000hrs of testing per ASTM B117.
2. The coating shall exhibit no greater than 30% reduction of gloss per ASTM D523, after 500 hours of QUV testing at ASTM G154 Cycle 6.

R. Thermal management
1. Mechanical design of protruding external surfaces (heat sink fins) for shall facilitate hose-down cleaning and discourage debris accumulation.
2. Liquids or other moving parts shall be clearly indicated in submittals, shall be consistent with product testing, and shall be subject to review by Owner.

S. IES TM-15 limits for Backlight, Uplight, and Glare (BUG Ratings) shall be as specified for each luminaire type in Appendix A.

1. Calculation of BUG Ratings shall be for initial (worst-case) values, i.e., Light Loss Factor (LLF) = 1.0.
2. If luminaires are tilted upward for calculations in section 1.6-D, BUG Ratings shall be calculated for the same angle(s) of tilt.

T. Minimum Color Rendering Index (CRI): 60.

U. Correlated Color Temperature (CCT)

1. If nominal CCT specified in Appendix A is listed in Table 1 below, measured CCT and Duv shall be as listed in Table 1.

Table 1. Allowable CCT and Duv (adapted from NEMA C78.377)

Manufacturer-Rated Nominal CCT (K)	Allowable LM-79 Chromaticity Values	
	Measured CCT (K)	Measured Duv
2700	2580 to 2870	-0.006 to 0.006
3000	2870 to 3220	-0.006 to 0.006
3500	3220 to 3710	-0.006 to 0.006
4000	3710 to 4260	-0.005 to 0.007
4500	4260 to 4746	-0.005 to 0.007
5000	4745 to 5311	-0.004 to 0.008
5700	5310 to 6020	-0.004 to 0.008
6500	6020 to 7040	-0.003 to 0.009

2. If nominal CCT specified in Appendix A is not listed in Table 1, measured CCT and Duv shall be as per the criteria for Flexible CCT defined in NEMA C78.377.

V. The following shall be in accordance with corresponding sections of ANSI C136.37

1. Wiring and grounding
   a. All internal components shall be assembled and pre-wired using modular electrical connections.
2. Mounting provisions
   a. Specific configurations are indicated in Appendix A
3. Terminal blocks for incoming AC lines
4. Photocontrol receptacle
5. Latching and hinging
6. Ingress protection

2.5. PRODUCT MANUFACTURERS

B. Any manufacturer offering products that comply with the required product performance and operation criteria may be considered.

2.6. MANUFACTURER SERVICES

B. Manufacturer or local sales representative shall provide installation and troubleshooting support via telephone and/or email.

END OF SECTION

Appendix B
Estimating LED Lumen Maintenance

IES TM-21 allows for extrapolation of expected lumen maintenance from available test data. The extent of such extrapolation is limited by the duration of testing completed and the number of samples used in the testing. The TM-21 methodology shall be used by the manufacturer to determine lamp lumen depreciation (LLD) at end of lumen maintenance life per section 1.6-C.

The applicant may estimate lumen maintenance in one of two ways:

Option 1: Component Performance

Under this compliance path, the applicant must submit calculations per TM-21 predicting lumen maintenance at the luminaire level using In Situ Temperature Measurement Testing (ISTMT) and LM-80 data. To be eligible for the Component Performance option, ALL of the conditions below must be met. If ANY of the conditions is not met, the component performance option may not be used and the applicant must use Option 2 for compliance.

6. The LED light source(s) have been tested according to LM-80.
7. The LED drive current specified by the luminaire manufacturer is less than or equal to the drive current specified in the LM-80 test report.
8. The LED light source(s) manufacturer prescribes/indicates a temperature measurement point (T_S) on the light source(s).
9. The T_S is accessible to allow temporary attachment of a thermocouple for measurement of in situ temperature. Access via a temporary hole in the housing, tightly resealed during testing with putty or other flexible sealant is allowable.
10. For the hottest LED light source in the luminaire, the temperature measured at the T_S during ISTMT is less than or equal to the temperature specified in the LM-80 test report for the corresponding drive current or higher, within the manufacturer's specified operating current range.
    a. The ISTMT laboratory must be approved by OSHA as a Nationally Recognized Testing Lab (NRTL), must be qualified, verified, and recognized through DOE's CALiPER program, or must be recognized through UL's Data Acceptance Program.
    b. The ISTMT must be conducted with the luminaire installed in the appropriate application as defined by ANSI/UL 1598 (hardwired luminaires), with bird-fouling appropriately simulated (and documented by photograph) as determined by the manufacturer.

Option 2: Luminaire Performance

Under this compliance path, the applicant must submit TM-21 calculations based on LM-79 photometric test data for no less than three samples of the entire luminaire. Duration of operation and interval between photometric tests shall conform to the TM-21 criteria for LED light sources. For example, testing solely at 0 and 6000 hours of operation would not be adequate for the purposes of extrapolation.

Between LM-79 tests, the luminaire test samples must be operated long-term in the appropriate application as defined by ANSI/UL 1598 (hardwired luminaires). The test laboratory must hold

NVLAP accreditation for the LM-79 test procedure or must be qualified, verified, and recognized through the U.S. Department of Energy (DOE)'s CALiPER program. The extent of allowable extrapolation (either 5.5 or 6 times the test duration) depends on the total number of LED light sources (no less than 10 and preferably more than 19) installed in the luminaire samples, as per TM-21.

This compliance path poses a greater testing burden to luminaire manufacturers but incorporates long-term testing of other components in the system, such as drivers.

Under either compliance path, values used for extrapolation shall be summarized per TM-21 Tables 1 and 2. Submitted values for lumen maintenance lifetime and the associated percentage lumen maintenance shall be "reported" rather than "projected" as defined by TM-21. Supporting diagrams are requested to facilitate interpretation by Owner.

APPENDIX C
PRODUCT FAMILY TESTING
LM-79 AND ISTMT

It is recognized that due to the time and cost required for product testing, it would not be realistic to expect manufacturers offering a multitude of unique luminaire configurations to test every possible configuration. Therefore, the “product families” method may be utilized for LM-79 and ISTMT, whereby manufacturers identify a set of representative products for which test data can be used to demonstrate the accuracy of interpolated or extrapolated performance of product configurations lacking test data. Precedent for this approach can be found in LM-80.

If the particular luminaire configuration submitted has not been tested, the performance may be conservatively represented by test data for another luminaire configuration having:

- The same intensity distribution (typically only applies to LM-79)
- The same or lower nominal CCT
- The same or higher nominal drive current
- The same or greater number of LED light source(s)
- The same or lower percentage driver loading and efficiency
- The same or smaller size luminaire housing.

A more accurate estimate of performance can be obtained by linear interpolation between two or more tests differing in terms of the six parameters listed above. For example, consider a hypothetical luminaire offered in a single size housing, and having the following parameters:

- Three intensity distributions: IES Type II, III, or IV
- Three CCTs: 4000, 5000, and 6000K
- Three drive currents: 350, 525, and 700 mA
- Four LED quantities: 20, 40, 60, or 80 LEDs.

Table C.1 illustrates a set of tests which could allow for accurate interpolation between tested configurations, given a single luminaire housing size and essentially constant driver efficiency; these 10 tests may provide representative data for the 108 possible product configurations. Note that normalized intensity distribution must not be affected by the other three parameters.

Table C.1. Representative testing of a single luminaire housing size

Tests	Intensity distribution (IES Type)	CCT (K)	Drive current (mA)	# of LEDs
1, 2, 3	II, III, IV	4000	700	80
4, 5	IV	5000, 6000	700	80
6, 7	IV	4000	325, 525	80
8, 9, 10	IV	4000	700	20, 40, 60

For example, the manufacturer could detail interpolation as shown in Table C.2, applying the following multipliers to the base test #2 to model a configuration with Type III intensity distribution, 5000K CCT, 525 mA drive current, and 40 LEDs:

- Ratio of test #4 lumens to test #3 lumens
- Ratio of test #7 lumens to test #3 lumens
- Ratio of test #9 lumens to test #3 lumens.

Table C.2. Multipliers for Test #2 to yield: Type III , 5000K, 525mA, 40 LEDs

Test #	Intensity distribution (IES Type)	CCT (K)	Drive current (mA)	# of LEDs	Multiplier (lumens ratio)
2	III	4000	700	80	n/a
3	IV	4000	700	80	n/a
4	IV	5000	700	80	#4 / #3
7	IV	4000	525	80	#7 / #3
9	IV	4000	700	40	#9 / #3

Interpolation between minimal LM-79 and ISTMT data is more difficult if housing size increases with increasing wattage; it may not be clear whether the lowest-wattage configuration would be expected to "run cooler" than the highest-wattage configuration. In these circumstances, the adequacy of submitted data is subject to Owner approval.

At this time, the "successor" method cannot be used; luminaires tested must utilize the LED light source(s) characterized by the submitted LM-80 report.

APPENDIX D
ELECTRICAL IMMUNITY

Test Procedure

- Electrical Immunity Tests 1, 2 and 3, as defined by their Test Specifications, shall be performed on an entire powered and connected luminaire, including any control modules housed within the luminaire, but excluding any control modules mounted externally, such as a NEMA socket connected photo-control. A shorting cap should be placed across any such exterior connector.
- The luminaire shall be connected to an AC power source with a configuration appropriate for nominal operation. The AC power source shall have a minimum available short-circuit current of 200A. The luminaire shall be tested at the nominal input voltage specified in Appendix A, or at the highest input voltage in the input voltage range specified in Appendix A.
- Electrical Immunity test waveforms shall be superimposed on the input AC power line at a point within 6 inches (15cm) of entry into the luminaire using appropriate high-voltage probes and a series coupler/decoupler network (CDN) appropriate for each coupling mode, as defined by ANSI/IEEE C62.45-2002. The test area for all tests shall be set up according to ANSI/IEEE C62.45-2002, as appropriate.
- Prior to electrical immunity testing a set of diagnostic measurements shall be performed, and the results recorded to note the pre-test function of the luminaire after it has reached thermal equilibrium. These measurements should include at a minimum:
  a) For all luminaires, Real Power, Input RMS Current, Power Factor and THD at full power/light output
  b) For luminaires specified as dimmable, Real Power, Input RMS Current, Power Factor and THD at a minimum of 4 additional dimmed levels, including the rated minimum dimmed level
- Tests shall be applied in sequential order (Test 1, followed by Test 2, followed by Test 3). If a failure occurs during Test 3, then Test 3 shall be re-applied to a secondary luminaire of identical construction.
- Following the completion of Tests 1, 2, and 3, the same set of diagnostic measurements performed pre-test should be repeated for all tested luminaires, and the results recorded to note the post-test function of the luminaire(s).
- A luminaire must function normally and show no evidence of failure following the completion of Test 1 + Test 2 + Test 3 (for a single tested luminaire), or the completion of Test 1 + Test 2 on a primary luminaire and Test 3 on a secondary luminaire. Abnormal behavior during testing is acceptable.
- A luminaire failure will be deemed to have occurred if any of the following conditions exists following the completion of testing:
  e) A hard power reset is required to return to normal operation
  f) A noticeable reduction in full light output (e.g. one or more LEDs fail to produce light, or become unstable) is observed

g) Any of the post-test diagnostic measurements exceeds by ±5% the corresponding pre-test diagnostic measurement.
h) The luminaire, or any component in the luminaire (including but not limited to an electrical connector, a driver, a protection component or module) has ignited or shows evidence of melting or other heat-induced damage. Evidence of cracking, splitting, rupturing, or smoke damage on any component is acceptable.

Test Specifications

NOTE: L1 is typically "HOT", L2 is typically "NEUTRAL" and PE = Protective Earth.

Test 1) Ring Wave: The luminaire shall be subjected to repetitive strikes of a "C Low Ring Wave" as defined in IEEE C62.41.2-2002, Scenario 1, Location Category C. The test strikes shall be applied as specified by Table D.1. Prior to testing, the ring wave generator shall be calibrated to simultaneously meet BOTH the specified short circuit current peak and open circuit voltage peak MINIMUM requirements. Note that this may require that the generator charging voltage be raised above the specified level to obtain the specified current peak. Calibrated current probes/transformers designed for measuring high-frequency currents shall be used to measure test waveform currents.

Test waveform current shapes and peaks for all strikes shall be compared to ensure uniformity throughout each set (coupling mode + polarity/phase angle) of test strikes, and the average peak current shall be calculated and recorded. If any individual peak current in a set exceeds by ±10% the average, the test setup shall be checked, and the test strikes repeated.

Table D.1: 0.5 µS – 100Hz Ring Wave Specification

Parameter	Test Level/Configuration
Short Circuit Current Peak	0.5 kA
Open Circuit Voltage Peak	6 kV
Source Impedance	12 Ω
Coupling Modes	L1 to PE, L2 to PE, L1 to L2
Polarity and Phase Angle	Positive at 90° and Negative at 270°
Test Strikes	5 for each Coupling Mode and Polarity/Phase Angle combination
Time between Strikes	1 minute
Total Number of Strikes	= 5 strikes x 4 coupling modes x 2 polarity/phase angles = 40 total strikes

Test 2) Combination Wave: The luminaire shall be subjected to repetitive strikes of a "C High Combination Wave" or "C Low Combination Wave", as defined in IEEE C62.41.2-2002, Scenario 1, Location Category C. The test strikes shall be applied as specified by Table D.2. The "Low" test level shall be used for luminaires with **Basic** Electrical Immunity requirements, while the "High" test level shall be used for luminaires with **Elevated** Electrical Immunity requirements. Prior to testing, the combination wave generator shall be calibrated to simultaneously meet BOTH the specified short circuit current peak and open circuit voltage peak

MINIMUM requirements. Note that this may require that the generator charging voltage be raised above the specified level to obtain the specified current peak. Calibrated current probes/transformers designed for measuring high-frequency currents shall be used to measure test waveform currents.

Test waveform current shapes and peaks for all strikes shall be compared to ensure uniformity throughout each set (coupling mode + polarity/phase angle) of test strikes, and the average peak current shall be calculated and recorded. If any individual peak current in a set exceeds by ±10% the average, the test setup shall be checked, and the test strikes repeated.

Table D.2: 1.2/50µS – 8/20 µS Combination Wave Specification

Parameter	Test Level/ Configuration	
1.2/50 µS Open Circuit Voltage Peak	Low: 6 kV	High: 10kV
8/20 µS Short Circuit Current Peak	Low: 3 kA	High: 10kA
Source Impedance	2Ω	
Coupling Modes	L1 to PE, L2 to PE, L1 to L2	
Polarity and Phase Angle	Positive at 90° and Negative at 270°	
Test Strikes	5 for each Coupling Mode and Polarity/Phase Angle combination	
Time Between Strikes	1 minute	
Total Number of Strikes	= 5 strikes x 4 coupling modes x 2 polarity/phase angles = 40 total strikes	

Test 3) Electrical Fast Transient (EFT): The luminaire shall be subjected to "Electrical Fast Transient Bursts", as defined in IEEE C62.41.2 -2002. The test area shall be set up according to IEEE C62.45-2002. The bursts shall be applied as specified by Table D.3. Direct coupling is required; the use of a coupling clamp is not allowed.

Table D.3: Electrical Fast Transient (EFT) Specification

Parameter	Test Level/ Configuration
Open Circuit Voltage Peak	3 kV
Burst Repetition Rate	2.5 kHz
Burst Duration	15 mS
Burst Period	300 mS
Coupling Modes	L1 to PE, L2 to PE, L1 to L2
Polarity	Positive and Negative
Test Duration	1 minute for each Coupling Mode and Polarity combination
Total Test Duration	= 1 minute x 7 coupling modes x 2 polarities = 14 minutes

APPENDIX E
PRODUCT SUBMITTAL FORM

Luminaire Type[3]		
Manufacturer		
Model number		
Housing finish color		
Tenon nominal pipe size (inches)		
Nominal luminaire weight (lb)		
Nominal luminaire EPA (ft^2)		
Nominal input voltage (V)		
ANSI vibration test level	☑ Level 1 (Normal)	☐ Level 2 (bridge/overpass)
Nominal BUG Ratings		
Make/model of LED light source(s)		
Make/model of LED driver(s)		
Dimmability	☐ Dimmable	☑ Not dimmable
Control signal interface		
Upon electrical immunity system failure	☐ Possible disconnect	☐ No possible disconnect
Thermal management	☐ Moving parts	☑ No moving parts
Lumen maintenance testing duration (hr)		
Reported lumen maintenance life (hr) [4]		
Warranty period (yr)		
Parameter	Nominal value	Tolerance (%)
Initial photopic output (lm)		
Maintained photopic output (lm)		
Lamp lumen depreciation		
Initial input power (W)		
Maintained input power (W)		
Initial LED drive current (mA)		
Maintained LED drive current (mA)		
Drive current used		
In-situ LED T_c (°C)		
CCT (K)		
S/P ratio		
Additional product description		

[3] See Appendix A, and attach supporting documentation as required.
[4] Value shall be no less than as specified in section 1.6-C, and shall not exceed six times the testing duration indicated in the row above. Value shall be consistent with values submitted in the rows below for maintained light output, maintained input power, and maintained drive current.