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A feasibility analysis of retrofitting existing roadway lighting infrastructure with LED technology

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A FEASIBILITY ANALYSIS OF RETROFITTING EXISTING ROADWAY LIGHTING INFRASTRUCTURE WITH LED TECHNOLOGY

by

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ABSTRACT

LED technology has advanced towards use in high intensity lighting purposes. LED luminaires have a significantly longer expected lifetime than traditional high-intensity discharge lighting systems. Due to these recent improvements in LED technology, there is a growing need for a comprehensive method to analyze the applicability of LED luminaires for use on major routes and roadways.

This research investigates the acceptability of LED luminaires for use on major roadways through a feasibility analysis using data collected at various LED street light testing sites. Nine distinct LED luminaires were analyzed in field testing. The field data was then analyzed and compared to manufacturer's claims, or values produced by the manufacturer's IES file.

Sustainability was incorporated through an economic analysis, environmental impact analysis, and a stakeholder analysis. Each of the nine luminaires in the field feasibility study were also economically analyzed. An economic life cycle approach was used to analyze the economic requirements for each luminaire. The life cycle approach includes cradle to grave costs, including installation costs, operation and maintenance costs, and removal and disposal costs. A sensitivity analysis was also performed to identify the most critical variables within the life cycle analysis. The increased electrical efficiency provided by LED luminaires causes a decreased environmental impact through reductions in CO_2 production and reduced water consumption. Social sustainability was analyzed through the discussions and interviews with the penultimate end users, state and local agencies. Plans for testing products for future implementation are also discussed.

ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Suzanna Long, for her guidance, support, and never-ending supply of patience as my research has progressed throughout the past thirteen months. I especially appreciate her support of my interests outside of academic research, namely allowing me to teach on campus and remain involved with the student chapter of Engineers Without Borders. In addition, her guidance has led me to pursue a PhD in Engineering Management.

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I would also like to thank my parents for my existence, their steady support of my goals, and their interest in my work. I would also like to thank my family for their love, support, and patience for the past 6 years (and the next 3, hopefully).

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LIST OF ABBREVIATIONS

DOE	**Department of Energy**
EERE	**Energy Efficiency and Renewable Energy**
GE	**General Electric**
HPS	**High Pressure Sodium**
IES	**Illumination Engineering Society**
LED	**Light Emitting Diode**
MoDOT	**Missouri Department of Transportation**
MSSSLC	**Municipal Solid-State Street Lighting Consortium**
RP	**Recommended Practice**
W	**Watt**

1. INTRODUCTION

1.1 INTRODUCTION

LED roadway luminaires are being evaluated and considered across our nation by many local and state agencies[1,2,3]. Major evaluations are being conducted in Kansas City and St. Louis regions in conjunction with the U.S. Department of Energy (DOE). LED roadway luminaires have been installed on state highways in the Central, Southeast and St. Louis Districts for initial evaluations[4,5,].

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, the DOE’s Municipal Solid-State Street Lighting Consortium[8], is a great example of this cooperative effort.

Figure 1.1 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 document, 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.

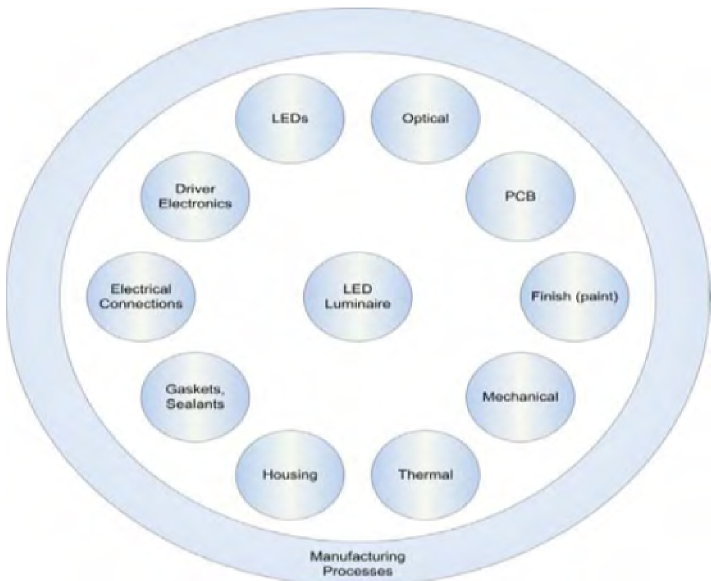


FIGURE 1.1 TOTAL SYSTEM LUMINAIRE RELIABILITY[9]

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 of LED roadway luminaires, a feasibility study and a proposed program to transition from traditional street lighting technologies to LED roadway luminaires.

1.2 LITERATURE REVIEW

LED roadway luminaires are being evaluated and installed across our country by various state and local agencies and utility companies[1-3]. 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 indicator with LEDs[8].

Previously, research has been completed on LED luminaires in the field case studies sponsored by the Department of Energy's Energy Efficiency and Renewable Energy (EERE) program[6]. In addition, it has been shown the classification of roads can have a major impact on the cost of roadway lighting. The over classification of roads will increase the cost to properly illuminate a roadway, when following Illumination Engineering Society recommended practices[7].

There is an orchestrated effort between manufacturers, governmental agencies and utilities to produce a very high quality LED roadway luminaire. One such effort is the Department of Energy's Solid-State lighting GATEWAY Demonstration programs. These programs have performed feasibility analyses on several types of LED luminaires across several uses. Thus far, the program has published reports on the use of LED lighting in parking lot[10] and minor roadway lighting[6]. However, major roadways use different lighting design criteria than minor roadways. Research has been previously been performed on combining an economic analysis with a product performance analysis to develop street lighting standards[11].

2. EVALUATION OF LED ROADWAY LUMINAIRES

2.1 LED LUMINAIRE DATA COLLECTION METHODOLOGY

Illumination readings were collected from LED luminaire testing sites 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. A total of eight unique manufacturer's luminaires were studied for this research.

Data collection points were based on a function of the pole spacing between luminaires and the width of the traffic lane at the location of the luminaire. Using intervals of one quarter of the distance between the target pole and adjacent poles minimizes interference caused by nearby streetlights. The pole spacing, roadway width, and, distance between the pole and the outer lane, and the location of the luminaire were measured, in feet, for each luminaire using a perambulator. In order to minimize the impact of nearby sources of light, luminescence readings were collected such that the readings are directed towards the target luminaire. A Konica Minolta T-10 luminescence meter was used to measure the lux for each field data location. The luminescence meter is greatly impacted by the direction in which the eyelet of the device points. Therefore, in order to minimize error, the maximum reading was recorded for each data point. 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 2.1, 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 to interpret data from .ies files, 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 software. The variation between the field data and each manufacturer's claim was analyzed and is shown in figures within the Field Data Evaluation and Assessment section.

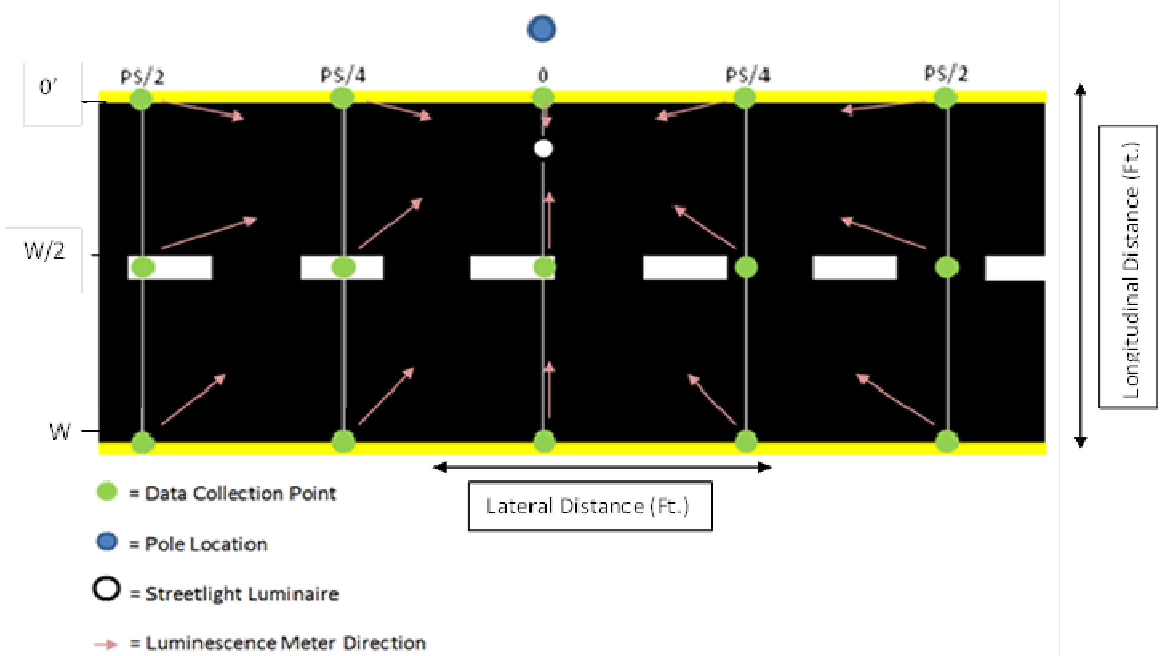


FIGURE 2.1 LED FIELD TESTING METHODOLOGY

2.2 HOLOPHANE GENERATION 1 LUMINAIRE PERFORMANCE

The first generation of Holophane products does not meet any of the Illumination Engineering Society's (IES) standards set in RP-08 (Recommended Practices – 08)[9]. Using IES standards, accompanied by data in Table 2.1, 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, which can be seen in Figure 2.2 below.

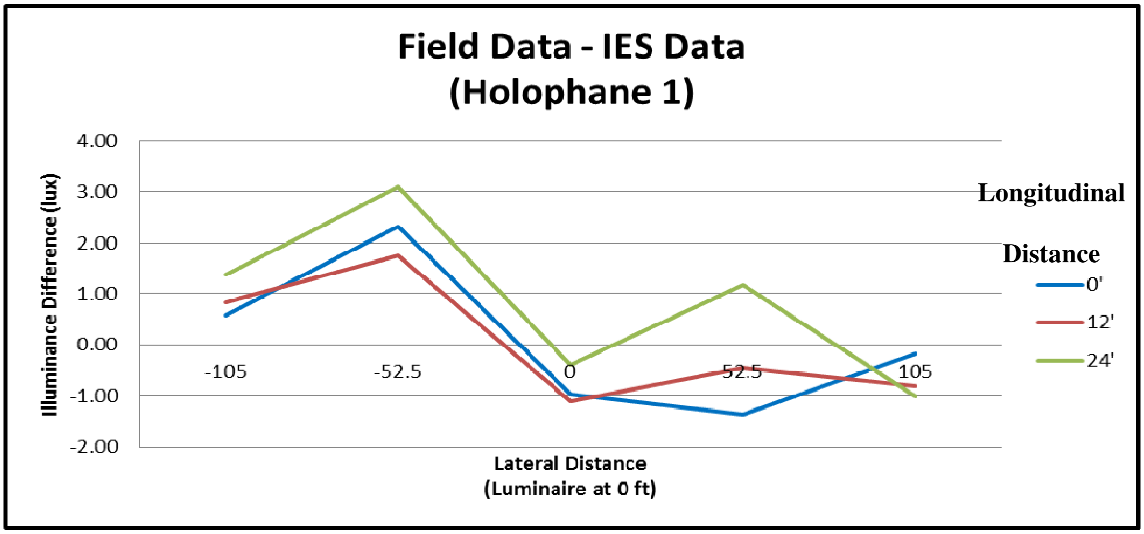


FIGURE 2.2 HOLOPHANE (GENERATION 1) ILLUMINATION DIFFERENCE

TABLE 2.1 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

2.3 HOLOPHANE (GENERATION 2) LUMINAIRE PERFORMANCE

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 recommendation by the Illumination Engineering Society of 13.0 lux. The uniformity ratios are below the IES recommendations and the average illuminance exceeds the IES recommended illuminance. This data can be seen in Figure 2.3 and Table 2.2 below.

Due to the consistently higher field data, it appears the luminaire may be being driven above the manufacturer's specifications. Monitoring electrical power usage and comparing them to manufacturer's recommendations can 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.

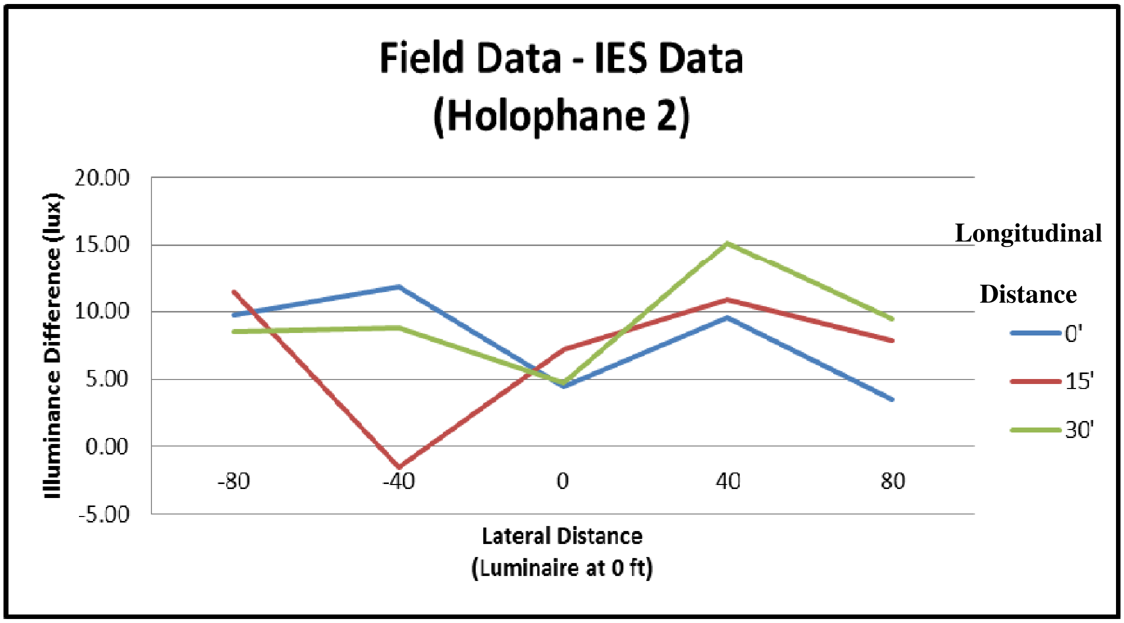


FIGURE 2.3 HOLOPHANE (GENERATION 2) ILLUMINATION DIFFERENCE

TABLE 2.2 HOLOPHANE (GENERATION 2) ILLUMINANCE 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

2.4 PHILIPS LUMINAIRE PERFORMANCE

Based on photometrics, the Philips LED luminaire appears to be a strong candidate for implementation. The field data, in Figure 2.4 and Table 2.3, 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.

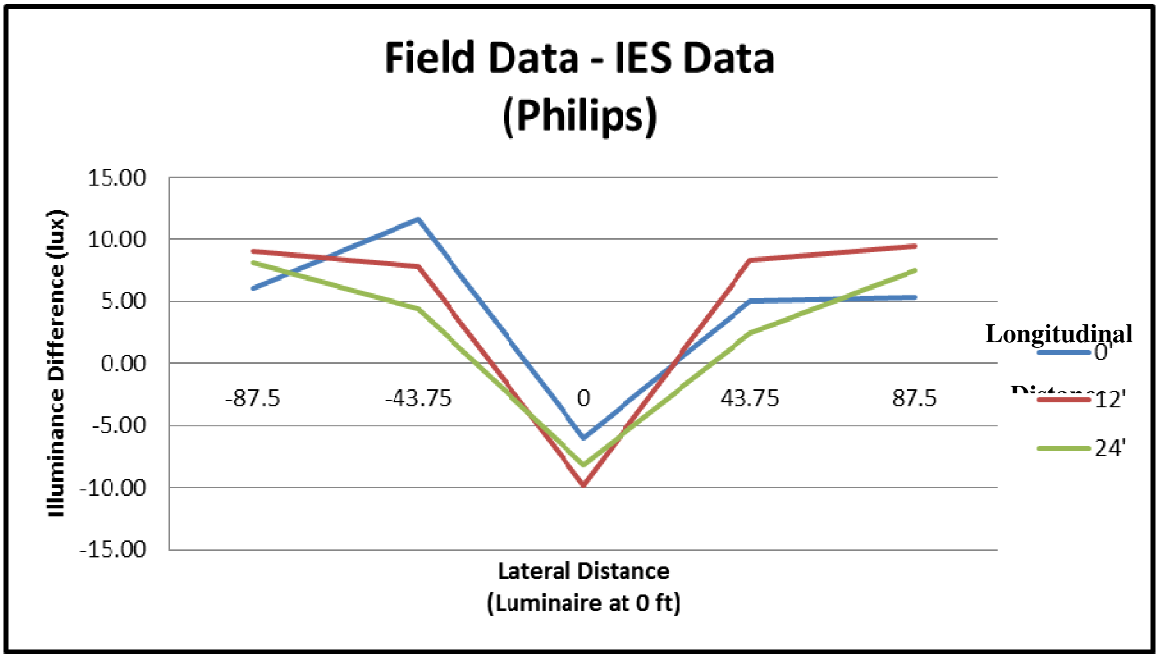


FIGURE 2.4 PHILIPS ILLUMINATION DIFFERENCE

TABLE 2.3 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

2.5 GE LUMINAIRE PERFORMANCE

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. The data collected for field readings is displayed in Figure 2.5 and Table 2.4.

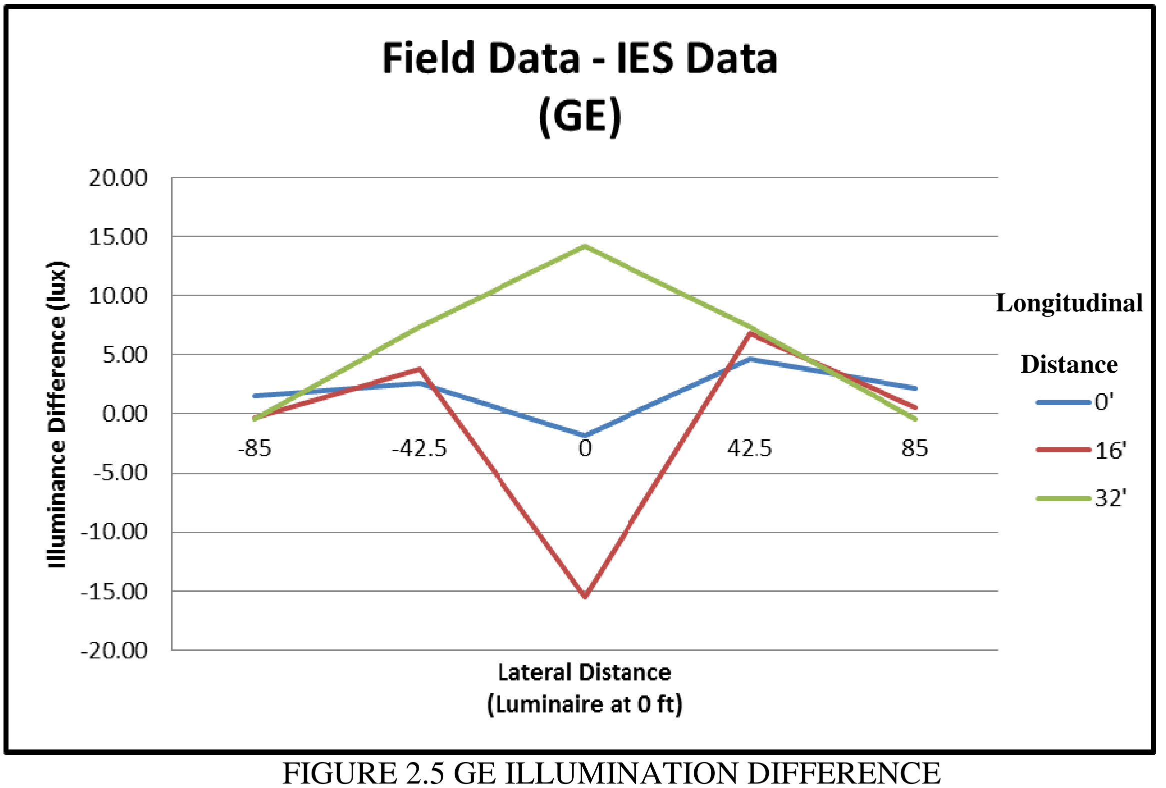


FIGURE 2.5 GE ILLUMINATION DIFFERENCE

TABLE 2.4 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

2.6 BETA LEDWAY LUMINAIRE PERFORMANCE

The field data for this particular Beta LEDway luminaire is greater than or equivalent to the related IES file. Although the field data, seen in Figure 2.6, matches the IES file, the average illuminance, seen in Table 2.5, 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.

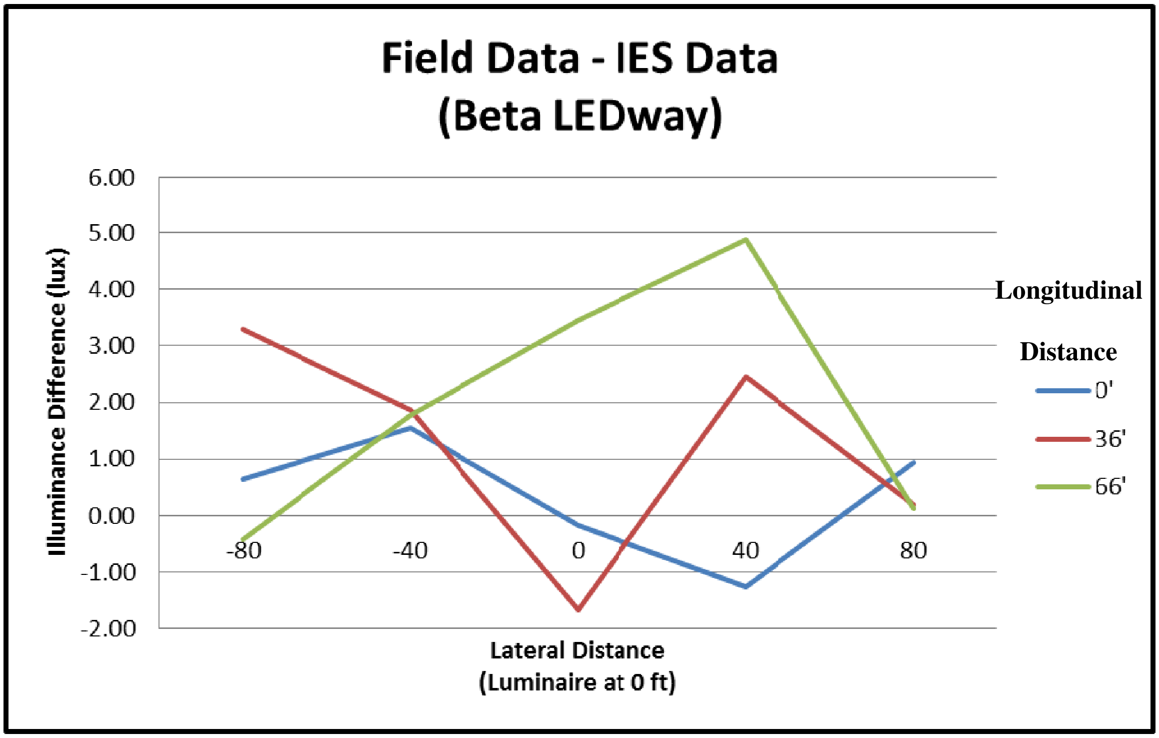


FIGURE 2.6 BETA LEDWAY ILLUMINANCE DIFFERENCE

TABLE 2.5 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

2.7 AMERICAN ELECTRIC LUMINAIRE PERFORMANCE

For the American Electric LED luminaire, whose results are displayed in Figure 2.7 and Table 2.6, 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.

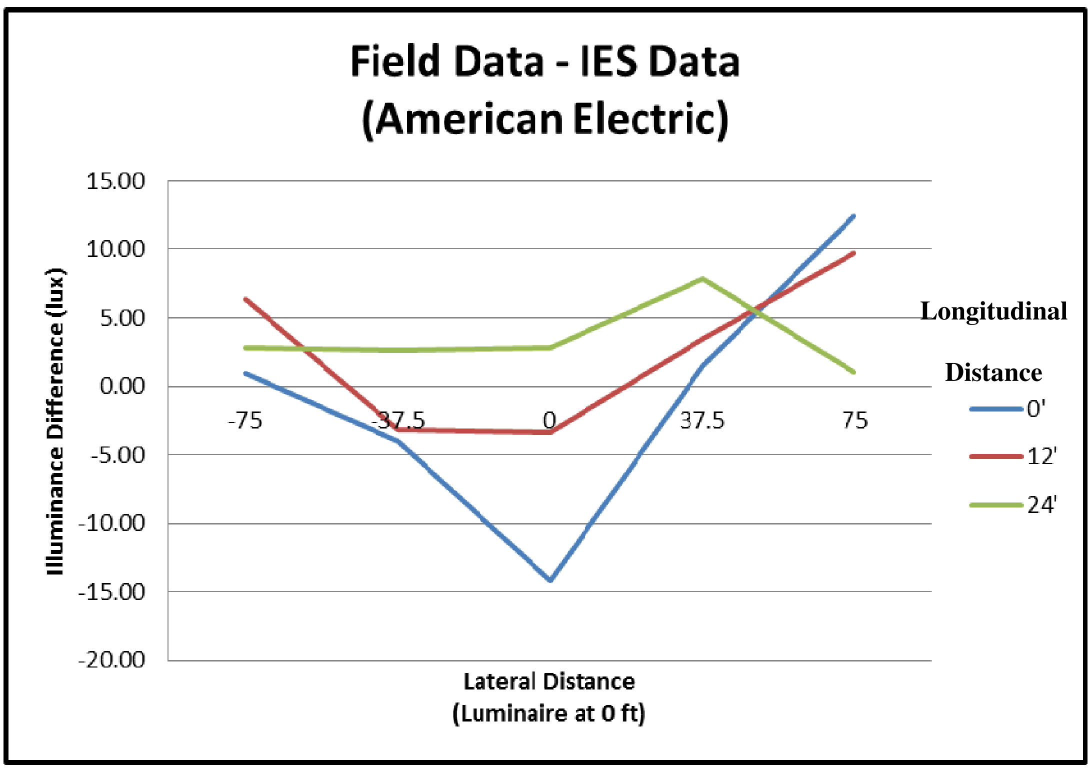


FIGURE 2.7 AMERICAN ELECTRIC ILLUMINANCE DIFFERENCE

TABLE 2.6 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

2.8 LED ROADWAY LUMINAIRE PERFORMANCE

The LED Roadway luminaire, whose results are in Figure 2.8 and Table 2.7, 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.

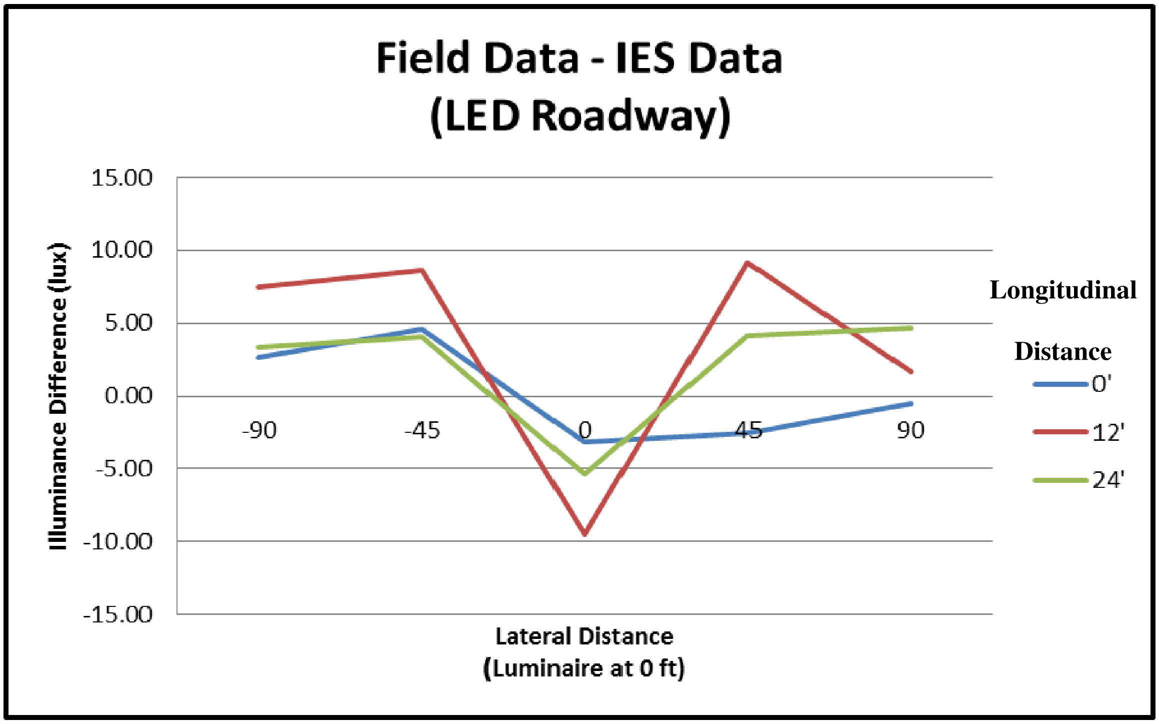


FIGURE 2.8 - LED ROADWAY ILLUMINANCE DIFFERENCE

TABLE 2.7 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

*Red text denotes not meeting IES specifications

2.9 DIALIGHT LUMINAIRE PERFORMANCE

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. Figure 2.9 and Table 2.8 display the results of the simulation and field data.

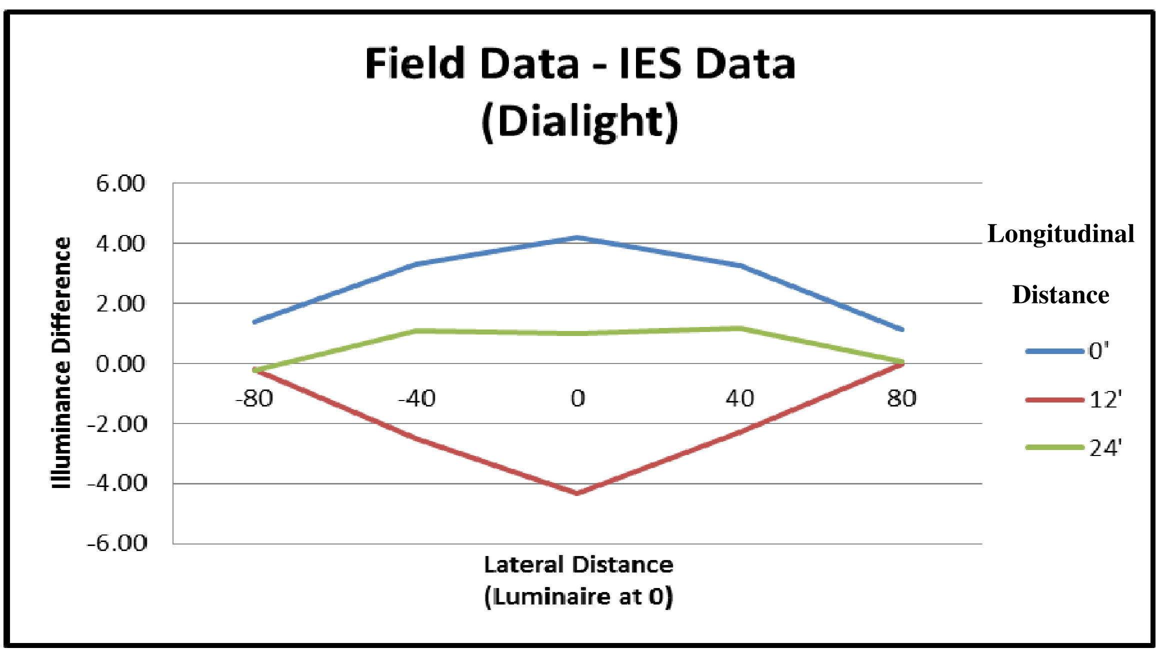


FIGURE 2.9 - DIALIGHT ILLUMINANCE DIFFERENCE

TABLE 2.8 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

2.10 LIGHTING SCIENCE GROUP LUMINAIRE PERFORMANCE

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, seen in Figure 2.10, 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, seen in Table 2.9, 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.

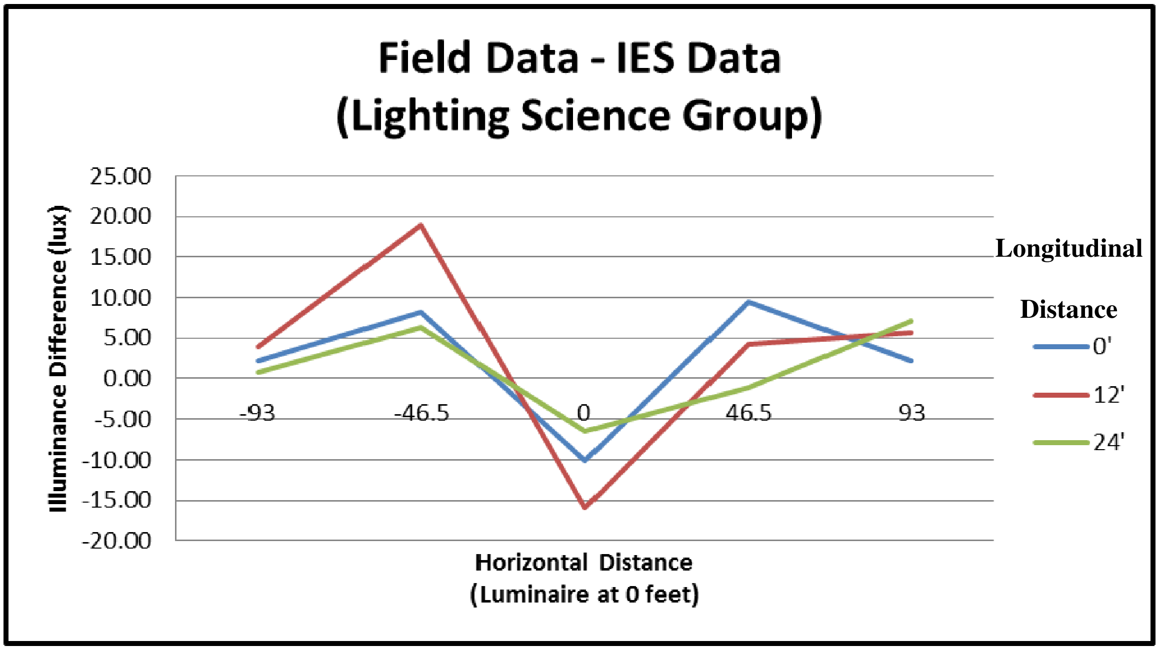


FIGURE 2.10 LIGHTING SCIENCE GROUP ILLUMINANCE DIFFERENCE

TABLE 2.9 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

2.11 250 WATT HPS LAMP

The 250 Watt High Pressure Sodium luminaire readings, seen in Figure 2.11, contained significant error compared to the expected output claimed by the manufacturer. In addition, the only uniformity ratio successfully matching the IES standard is the Average:Minimum uniformity ratio. This lamp only meets one IES standard for the field and manufacturer's claims. Comparing the field data to IES standards, as seen in Table 2.10, this lamp does not meet specifications.

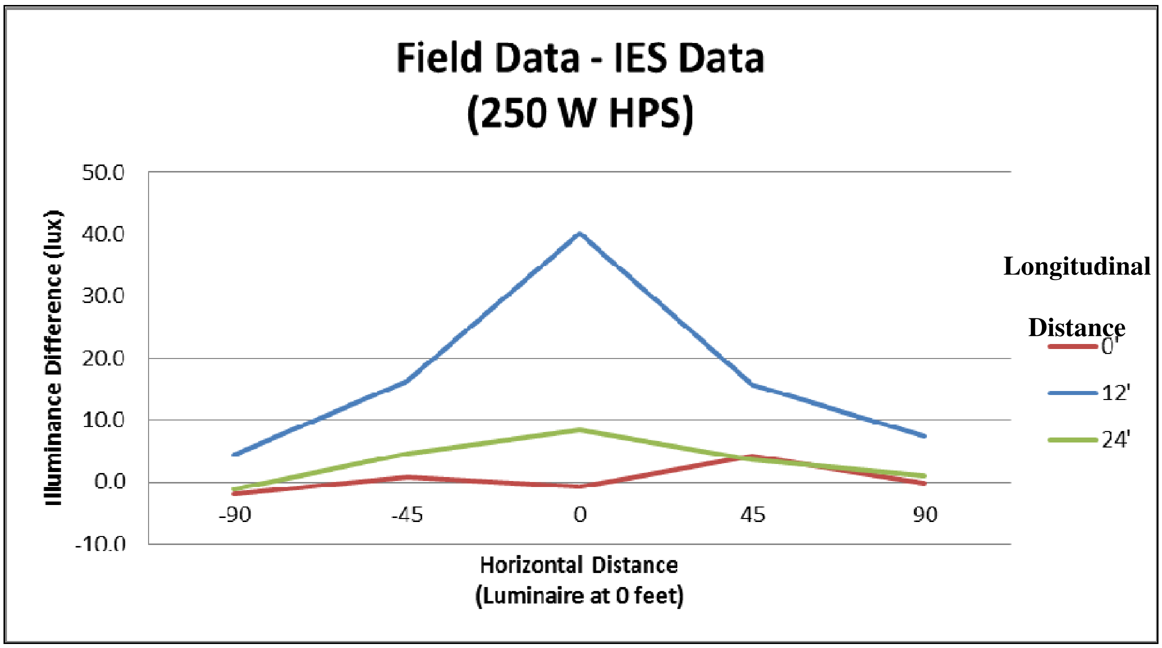


FIGURE 2.11 250 W HPS ILLUMINANCE DIFFERENCE

TABLE 2.10 250 WATT HPS ILLUMINANACE RATIOS

	Field Data (lux)	IES Data (lux)	IES Standard
Max	40.11	41.80	----
Min	2.11	4.00	----
Avg	13.27	11.55	> 13.0
Max/Min	**19.01**	**10.45**	< 6.0
Avg/Min	**6.29**	**2.89**	< 3.0

*Red text denotes not meeting IES specifications

2.12 SUMMARY OF FIELD EVALUATIONS

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.

3. ECONOMIC FEASIBILITY ANALYSIS

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. Many 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 12 years is a conservative lifetime overall for LED luminaires. Therefore, 12 years was used for the LED luminaire lifetime for the economic analysis.

Perspective on labor costs will dramatically affect the outcome of the economic analysis. Organizations which do not consider maintenance savings as a large factor to their organization will not likely find LED luminaires beneficial. For example, City Utilities in Springfield, MO replaces traditional street lighting technology on the "downtime" of their line workers. City Utility policy states there must be line workers on the 24 hours per day, 7 days per week in order to respond to outages and emergencies. Therefore, when City Utilities economically analyzed LED luminaires, the results did not favor LED luminaires because the avoided maintenance costs were not included in economic analysis. It is essential for each agency to consider their perspective on replacing or repairing luminaires when performing an economic analysis.

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 to estimate a 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.

3.1 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 3.1 – 3.6, 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.

3.2 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 the need to change between the high pressure sodium and LED luminaires.

TABLE 3.1 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 3.2 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 3.3 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 3.4 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

TABLE 3.5 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 3.6 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

3.3 SENSITIVITY ANALYSIS

Figures 3.1 through 3.11 demonstrate the sensitivity of each luminaire's annualized cost to changes of four variables: luminaire price, expected luminaire lifetime, relamping/retrofit labor cost, and annual electricity consumption. Each variable varies between 75%-125% of the original value, in 12.5% intervals. The sensitivity analysis determined the variables with the greatest impact on the annualized cost of LED luminaires. In addition, an incremental economic analysis was performed. The results of the incremental analysis are displayed in Table 3.7. This analysis used the same values as the sensitivity analysis but calculated the change in annual worth per 1% change in each variable. Due to the non-linearity of the expected lifetime variable, the incremental analysis results were averaged, using intervals of 12.5% between the range of 75%-125%.

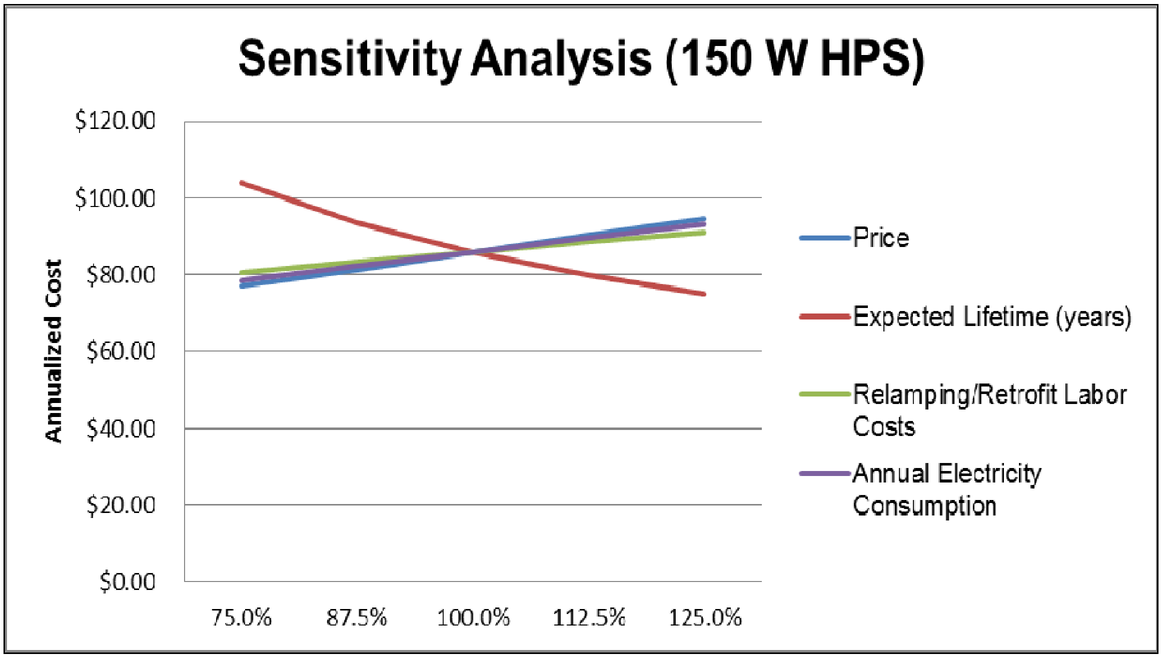


FIGURE 3.1 150 W HPS SENSITIVITY ANALYSIS

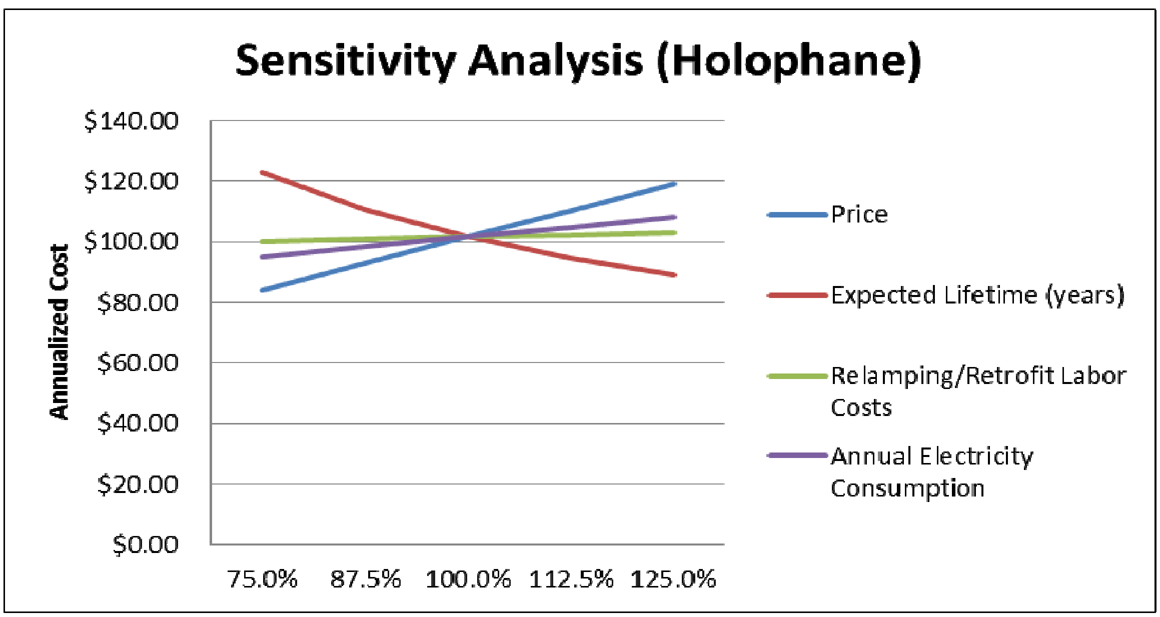


FIGURE 3.2 HOLOPHANE SENSITIVITY ANALYSIS

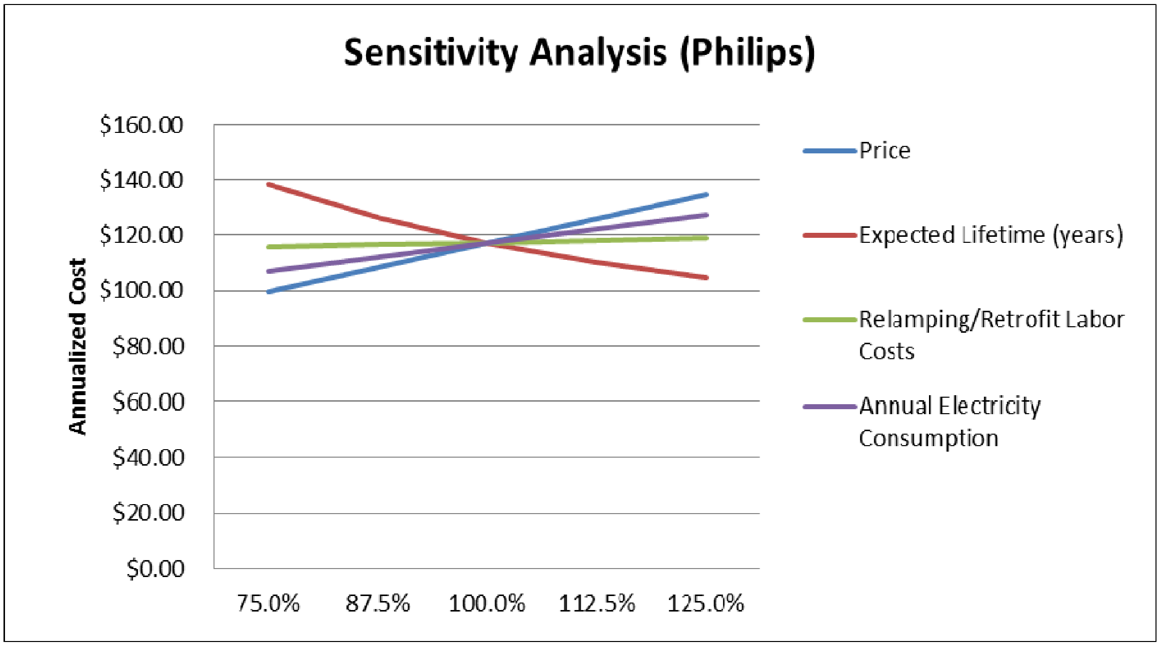


FIGURE 3.3 PHILIPS SENSITIVITY ANALYSIS

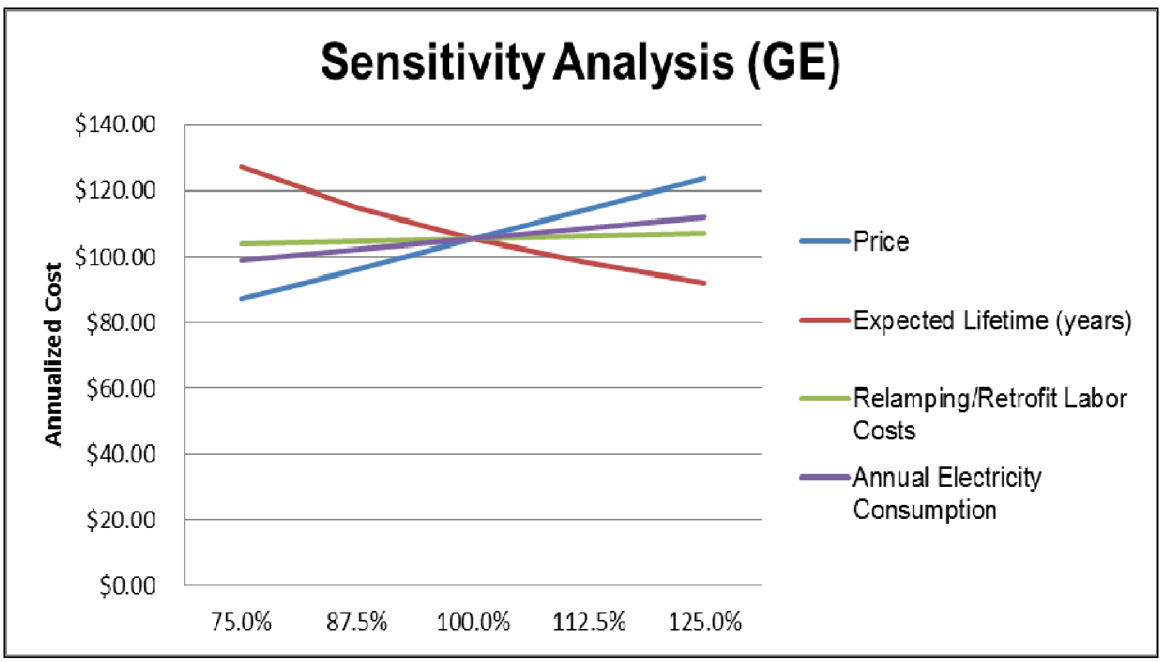


FIGURE 3.4 GE SENSITIVITY ANALYSIS

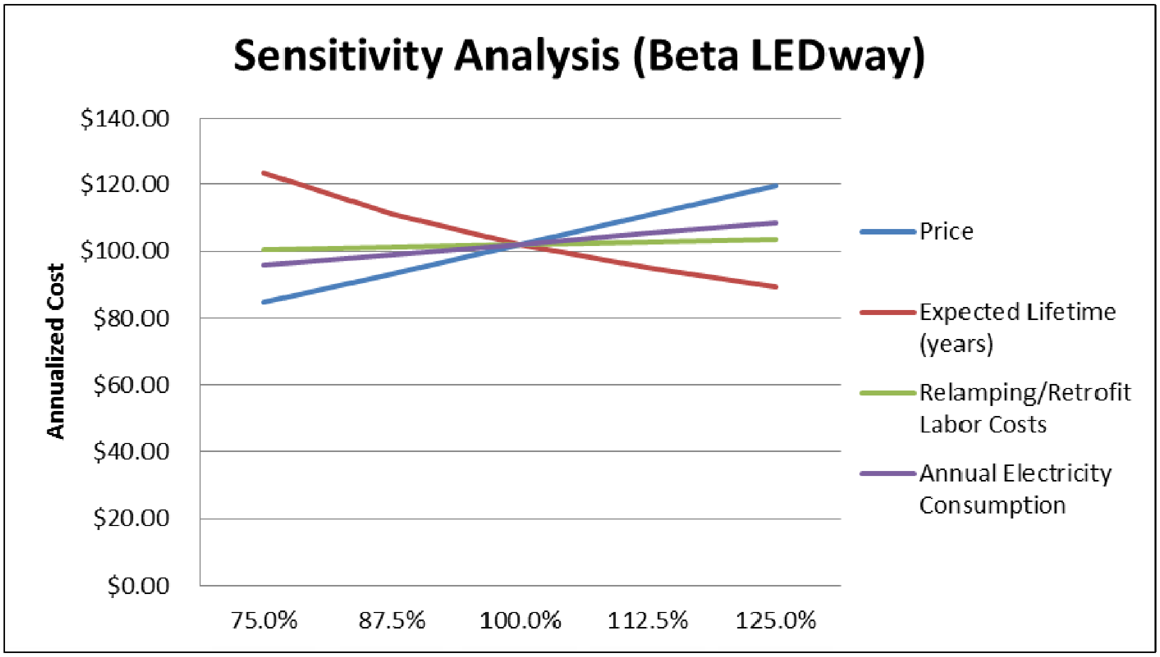


FIGURE 3.5 BETA LEDWAY SENSITIVITY ANALYSIS

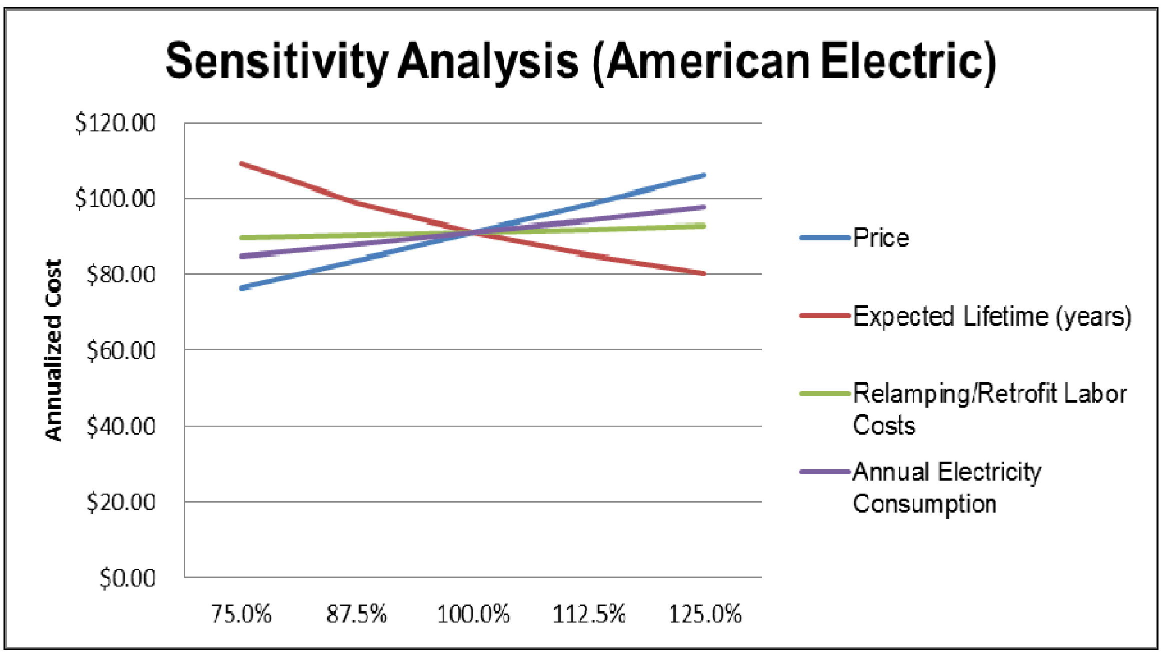


FIGURE 3.6 AMERICAN ELECTRIC SENSITIVITY ANALYSIS

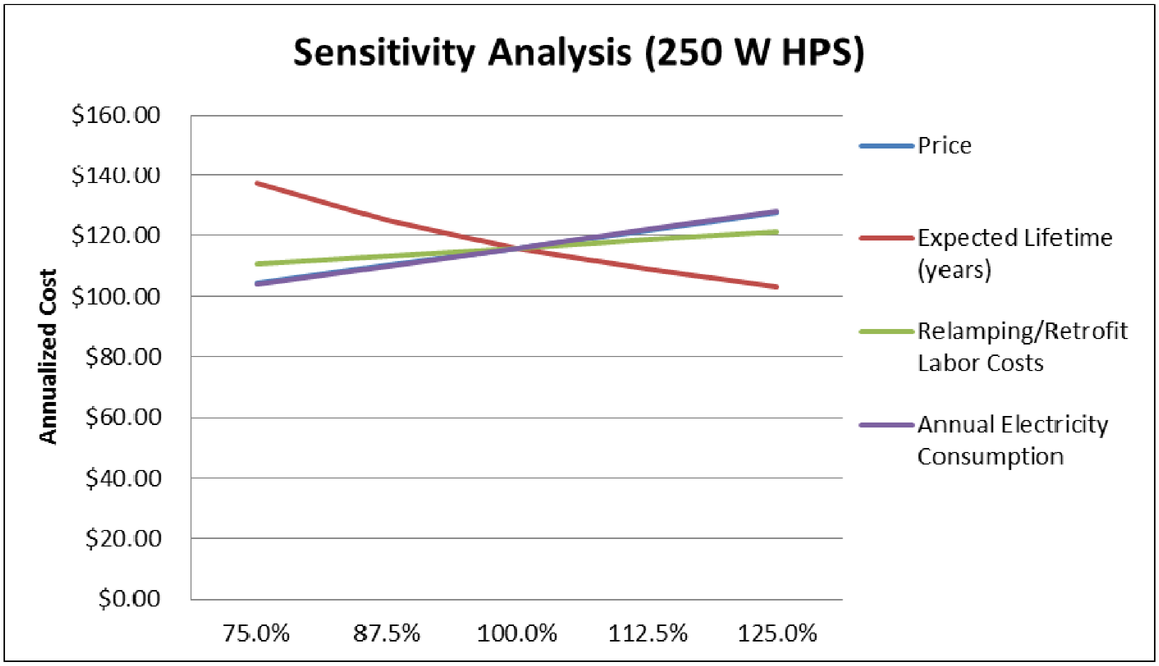


FIGURE 3.7 250 W HPS SENSITIVITY ANALYSIS

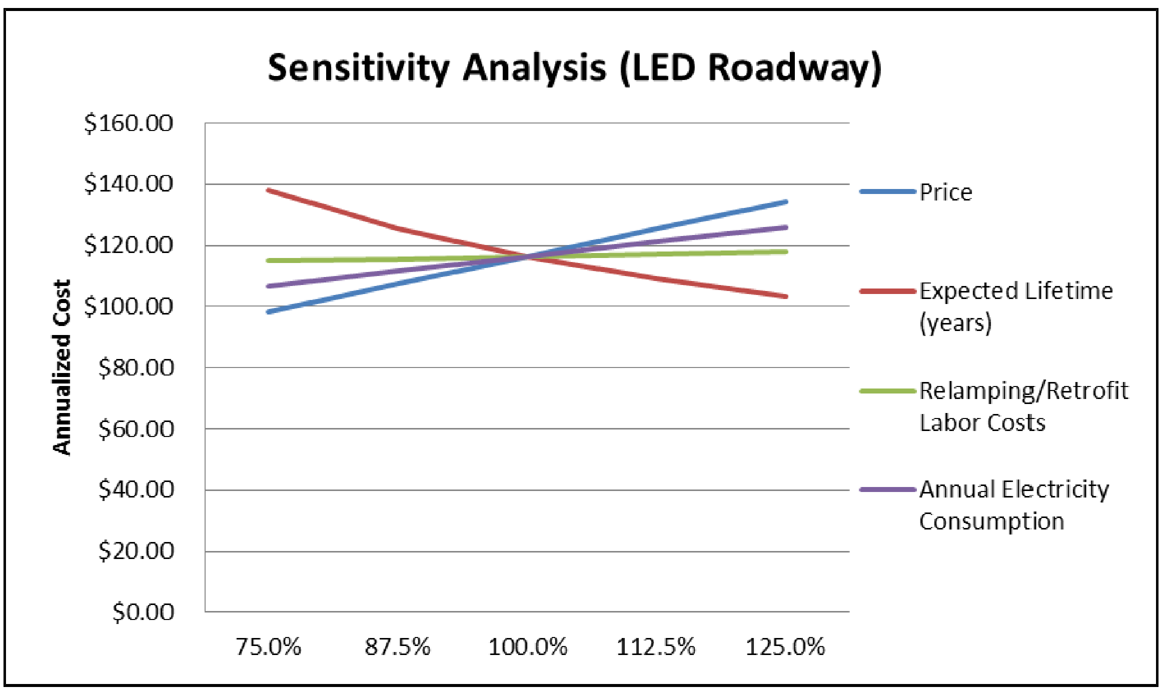


FIGURE 3.8 LED ROADWAY SENSITIVITY ANALYSIS

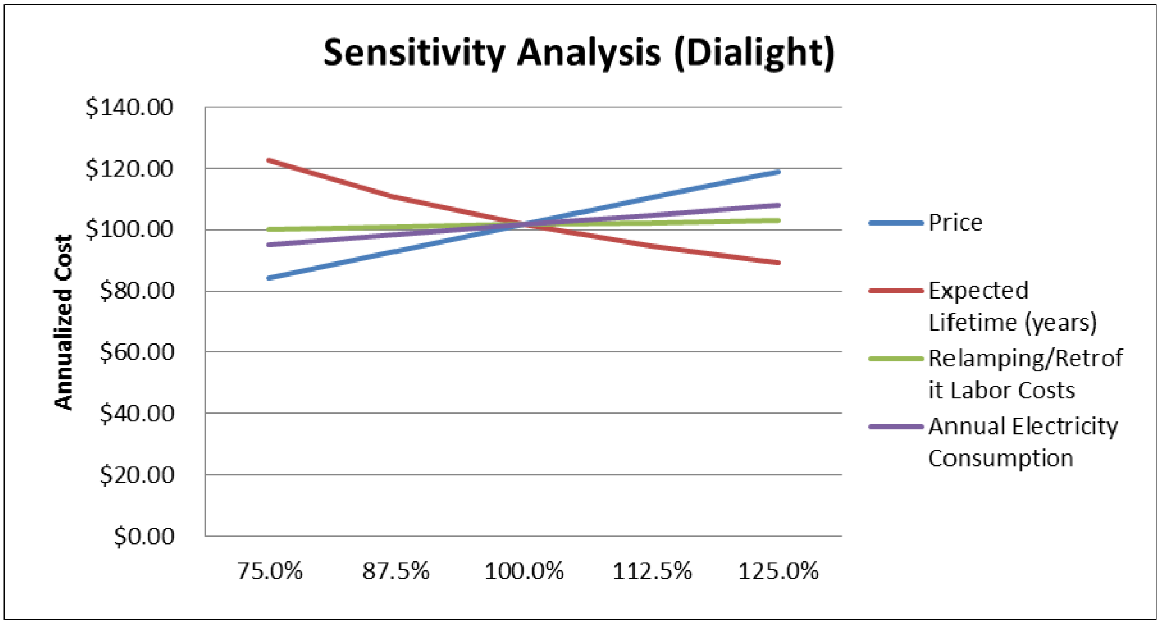


FIGURE 3.9 DIALIGHT SENSITIVITY ANALYSIS

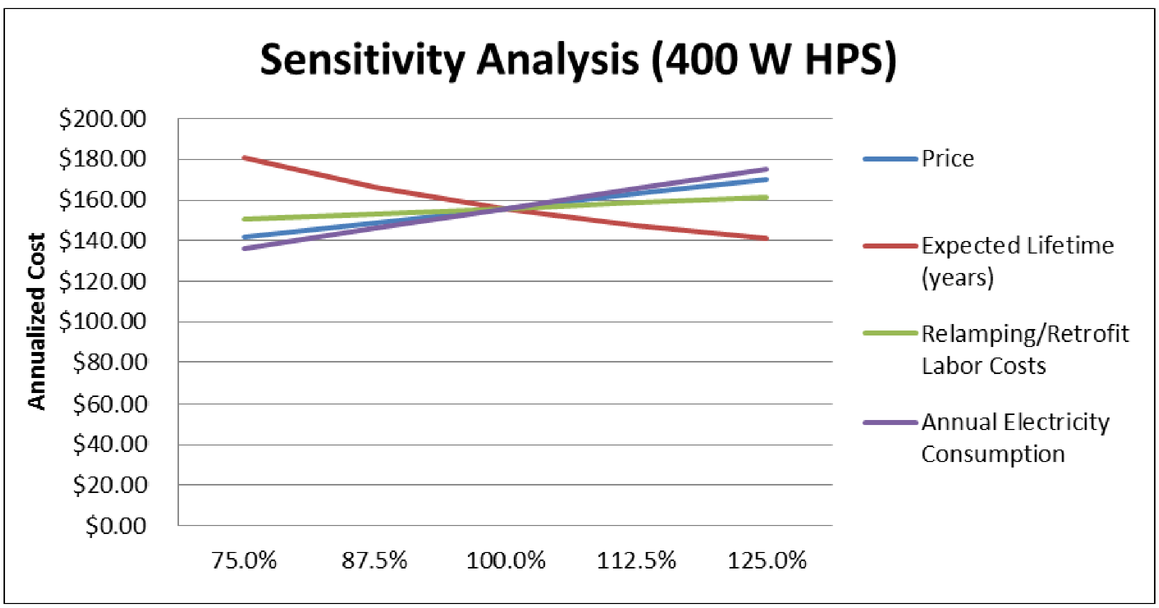


FIGURE 3.10 400 W HPS SENSITIVITY ANALYSIS

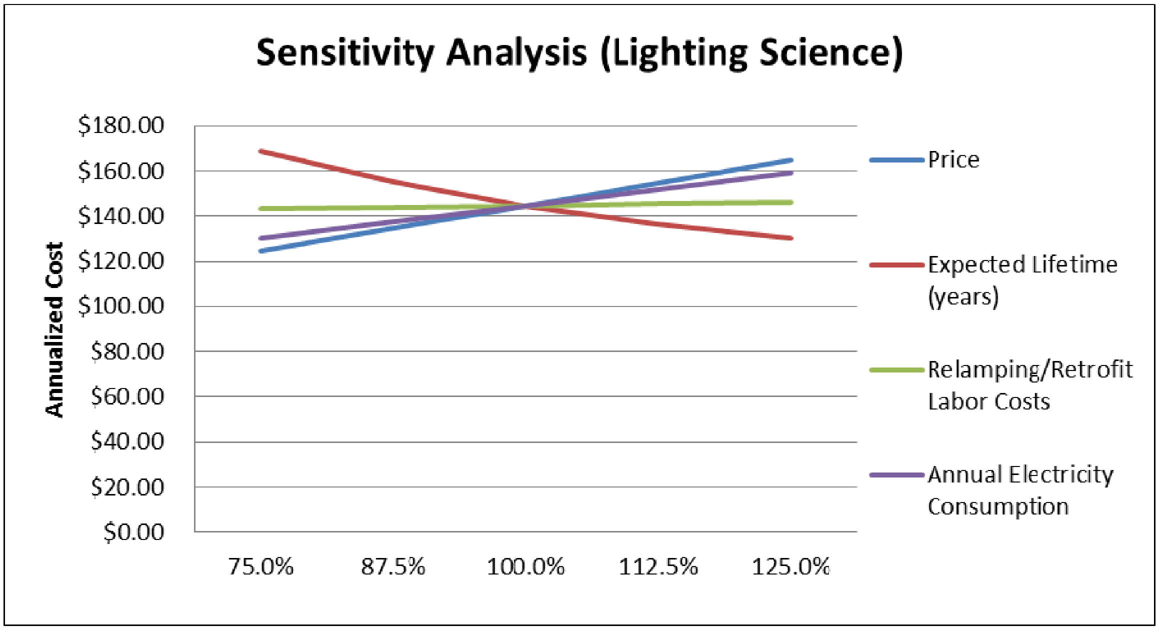


FIGURE 3.11 LIGHTING SCIENCE GROUP SENSITIVITY ANALYSIS

TABLE 3.7 INCREMENTAL SENSITIVITY ANALYSIS

Incremental Economic Sensitivity Analysis ($/% Change)				
Luminaire	Price	Expected Lifetime (Averaged)	Relamping/Retrofit Labor Costs	Annual Electricity Consumption
150W HPS	$0.35	$0.56	$0.21	$0.29
Dialight	$0.70	$0.66	$0.06	$0.26
Holophane	$0.70	$0.66	$0.06	$0.26
GE	$0.74	$0.69	$0.06	$0.26
Beta LEDway	$0.70	$0.66	$0.06	$0.26
American Electric	$0.59	$0.57	$0.06	$0.26
250W HPS	$0.46	$0.67	$0.21	$0.49
Philips	$0.70	$0.66	$0.06	$0.41
LED Roadway	$0.72	$0.67	$0.06	$0.39
400W HPS	$0.57	$0.77	$0.21	$0.78
Lighting Science	$0.80	$0.75	$0.06	$0.58

3.4 SENSITIVITY ANALYSIS CONCLUSIONS

The results of the sensitivity analysis show the contrast between HPS and LED luminaires as costs change. LED luminaires are significantly less sensitive to changes in retrofitting costs, which consist mostly of labor costs. However, LED luminaires are significantly more sensitive to changes in 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.

4. ENVIRONMENTAL IMPACT ANALYSIS

4.1 ENERGY CONSUMPTION AND ENVIRONMENTAL IMPACT ANALYSIS

Energy consumption data was obtained on the studied Dialight luminaire at two separate intersections. Both intersections were located in St. Louis, MO. Energy consumption data was normalized to account for days in each month, hours of operation in each month, and number of luminaires operated at each intersection. Energy consumption data was separated by month and analyzed. Figure 4.1, shown below, depicts the energy consumption in Watts per luminaire per month.

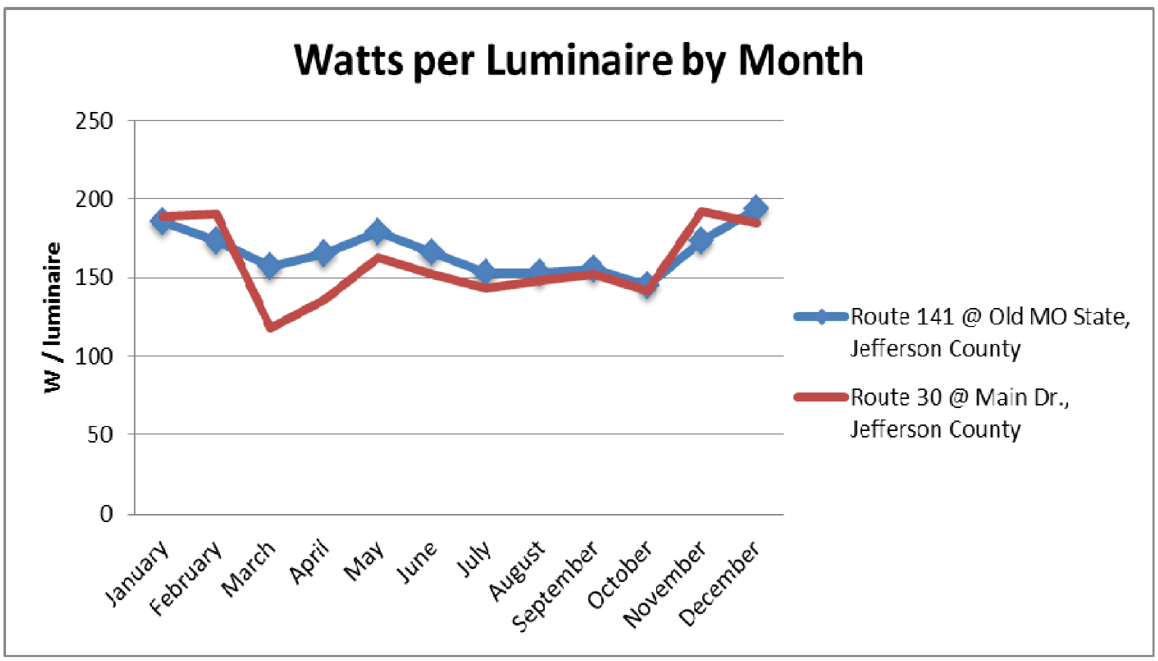


FIGURE 4.1 ELECTRICITY CONSUMPTION PER LUMINAIRE BY MONTH

Figure 4.1, 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.

5. 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 A.

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.

5.1 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 summary 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.

5.2 KANSAS CITY, MISSOURI

The City of Kansas City and DOE are evaluating LED streetlights in residential and commercial areas. 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.

5.3 INDEPENDENCE, MISSOURI

Independence Power and Light is also conducting an LED street light program and has a web site that describes three testing locations[14]. They have received mostly positive response on the three sites. The team collected data from the various sites for inclusion into this report.

5.4 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.

5.5 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.

6. INFRASTRUCTURE COMPATIBILITY VERIFICATION

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. Recent 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.

6.1 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.

Two templates are available from the Municipal Solid-State Street Lighting Consortium that detail two sets of specifications for the use by state and local agencies that own or operate street lights.

Model Specification– 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.

Model Specification – 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

7. PURCHASING GUIDELINES

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

7.1 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.

7.2 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.

8. 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.

8.1 RECOMMENDED ACTION ITEMS

Based on factors mentioned above and information contained in this report, it is recommended transportation agencies 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, two specific action items are recommended.

It is recommended for transportation agencies to develop policies, 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.

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.

APPENDIX A

FIELD DATA AND MANUFACTURER CLAIMS

TABLE A.1 LED FIELD DATA AND MANUFACTURER CLAIMS

		Holophane Gen 1		Holophane Gen 2		Philips		GE		Beta LEDway		American Electric		LED Roadway		Dialight	
	IES RP	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	10.3	32.7	25.3	38.5	44.6	33.5	49	8.94	9.4	30.5	30.0	38.9	43.4	12.7	12.1
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	20.0	11.9	18.7	14.6	11.5	9.40	5.60	4.23	16.5	14.7	17.9	16.0	7.21	7.19
Max/Min	< 6	14.6	12.8	4.10	10.5	3.94	10.1	8.30	19.6	4.54	3.92	4.32	4.92	19.3	17.3	3.06	3.78
Avg / Min	< 3	7.90	5.82	2.51	5.00	1.92	3.3	2.87	3.76	2.84	1.76	2.34	2.42	8.95	6.42	1.73	2.25

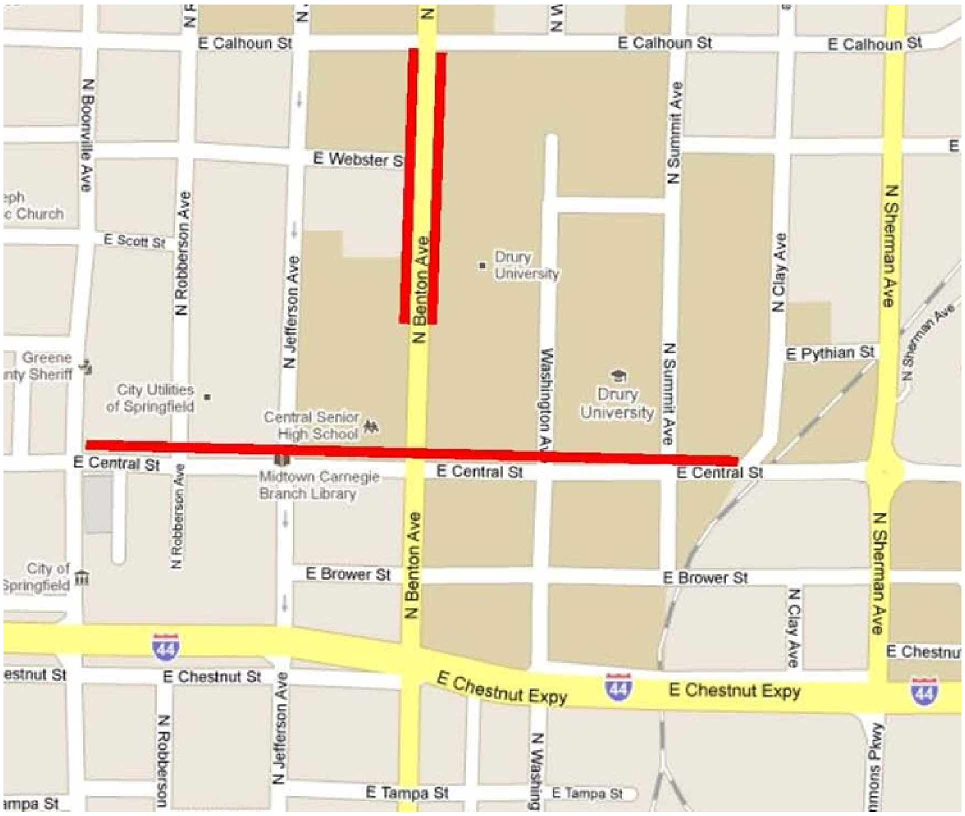
APPENDIX B

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 fewer glares 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 4
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. Strong

APPENDIX C

LED LUMINAIRE DATA

1. INTRODUCTION

Included with this Thesis is a CD-ROM, which contains the data values collected for the ten luminaires analyzed within this report. The data values have been stored within an Excel spreadsheet. Each studied luminaire contains its own tab within the spreadsheet.

2. CONTENTS

LED Luminaire Data.xlsx

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VITA

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