GATEWAY DEMONSTRATIONS

Demonstration Assessment of Light-Emitting Diode (LED) Roadway Lighting

Host Site: FDR Drive,
New York, New York

Final Report prepared in support of the
U.S. DOE Solid-State Lighting
Technology Demonstration GATEWAY Program

Study Participants:
Pacific Northwest National Laboratory
U.S. Department of Energy
New York City Department of Transportation
The Climate Group

December 2011

Prepared for the U.S. Department of Energy by
Pacific Northwest National Laboratory

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Demonstration Assessment of Light-Emitting Diode Roadway Lighting on the FDR Drive in New York, New York

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Preface

This document is a report of observations and results obtained from a lighting demonstration project in collaboration with the U.S. Department of Energy (DOE) Solid-State Lighting Technology GATEWAY Demonstration Program. The program supports demonstrations of high-performance solid-state lighting (SSL) products in order to develop empirical data and experience with in-the-field applications of this advanced lighting technology. The DOE GATEWAY Demonstration Program focuses on providing a source of independent, third-party data for use in decision-making by lighting users and professionals; this data should be considered in combination with other information relevant to the particular site and application under examination. Each GATEWAY Demonstration compares one or more SSL products against the incumbent technology used in that location. Depending on available information and circumstances, the SSL product may also be compared to alternate lighting technologies. Readers of these reports are urged to conduct their own due diligence when considering these or other products in their own applications. DOE does not endorse any commercial product or in any way guarantee that users will achieve the same results through use of these products.

Executive Summary

This report documents the process and results of a solid-state lighting technology demonstration on Franklin D. Roosevelt Drive (FDR Drive) in New York City (NYC) in which light-emitting diode (LED) luminaires were compared to the incumbent high-pressure sodium (HPS) luminaires and evaluated for light output and performance. The project was supported by the U.S. Department of Energy (DOE) Solid-State Lighting Technology GATEWAY Demonstration Program in conjunction with the New York City Department of Transportation (NYCDOT) and The Climate Group.

NYCDOT selected LED luminaires[1] from four different manufacturers: LSI Industries, LED Roadway Lighting Ltd. (LED Roadway), Elumen Lighting Networks Inc. (Elumen), and BetaLED. Six luminaires of each type were mounted back-to-back on three consecutive poles.

Results from the demonstration show energy savings ranging from 26 to 57 percent from all four LED luminaires compared to the baseline HPS luminaire. However, two of the LED systems produced lower average **maintained** illuminance[2,3] and a corresponding portion of their respective energy savings must be considered in that context. The LED Roadway Lighting luminaire used the least energy (57 percent energy reduction compared to the baseline HPS) while offering equivalent **initial** illuminance to the HPS system; both BetaLED and LED Roadway Lighting saved energy and **maintained** illuminance equivalent to the HPS baseline. Measured uniformities were good across all luminaires, HPS and LED alike, with average:minimum ratios only ranging between 3.0:1.0 to 3.3:1.0.

Estimating maintained illuminance could be an ongoing challenge as other sites consider converting to LEDs. In this demonstration, three LED manufacturers stated life claims in terms of L_{70} (operating hours to 70 percent lumen maintenance, relative to initial light output), while one manufacturer used a value of essentially L_{95}. Although the recently-released TM-21 procedure details how LED package lumen maintenance should be predicted using LM-80 data, manufacturers are free to choose the Lp value. In such cases it is up to the user to do the further calculations should they want to compare luminaires from different manufacturers across similar L_p, e.g., L_{70}.[4] This burden on the user would at least be facilitated by luminaire manufacturers providing a link to the specific LM-80 data used to calculate their maintained illuminance values, whatever L_p was selected.

In this demonstration, 83 percent (5 out of 6) of the luminaires shipped from one manufacturer contained an incorrect driver and correspondingly produced less light than specified. By no means a common problem encountered with LED products, it illustrates the increased complexity of this new

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[1] See body of report for specific model numbers.

[2] NYCDOT's illuminance requirements are based on footcandles and these are the units in which measurements were recorded. However, the Illuminating Engineering Society of North America has recently moved to lux–the International System of Units unit of illuminance. Illuminance values in footcandles have therefore been converted into lux using a default conversion factor of 10.

[3] Maintained illuminance values were derived by derating the initial illuminance value by the manufacturer's end-of-life definition (L_p).

[4] Part 3.3 of TM-21-11 requires a specification of rated lumen maintenance Lp where "L" denotes the operating time in hours over which the LED light source will maintain the percentage of initial light output designated by "p" (e.g., L_{70} is the time to 70 percent lumen maintenance and L_{50} is the time to 50 percent lumen maintenance). Manufacturers are allowed to define this value at their own discretion. The challenge, as in this case, is where multiple luminaires are being considered and not all of the luminaires are using the same L_p value.

lighting source and the importance of having a complete understanding of the performance expected from products using it. Such an issue might have gone unnoticed indefinitely without the scrutiny and subsequent follow up of this GATEWAY demonstration. Although impractical to pretest or confirm operation of every luminaire installed, particularly in a city the size of New York with hundreds of thousands of street lights, some means need to be undertaken on a sufficient sample to confirm that the expected performance has been delivered by the manufacturer. In the future, control systems that monitor each individual luminaire will likely offer such confirmation as one benefit of their deployment, but in the meantime users should be prepared to conduct some individual evaluation or “spot checking” as part of their commissioning process.

A second issue encountered during this demonstration was the failure of one of the luminaires following a heavy rainstorm. Forensic analysis of this unit revealed one of the screws holding the fixture together was missing, allowing water incursion into the electronics. It is unknown at what point in the process this screw disappeared, whether during its manufacture or installation. In any case, manufacturers and users alike must understand the importance of the Ingress Protection (IP) rating, and the critical need for its preservation during pole installation or when, e.g., photo-controls or other modifications are added to the luminaire. The manufacturer replaced the product and no further failures have occurred.

In terms of lighting performance and quality, the LED luminaires used in the FDR Drive demonstration direct almost no lumens upward–a favorable characteristic for reducing sky glow. All of the LED luminaires exhibited a color rendering index of 70 or above and a correlated color temperature of 5000 K or higher. The broader spectrum, relative to HPS, may result in easier color identification and color contrast by motorists, although this study did not solicit feedback on this issue.

The simple payback periods achieved by the LED luminaires based on the actual values measured onsite ranged from 8 to 16 years, based on 2009 pricing. However, these values are subject to slight interpretation/modification according to the following two issues:

1. It was difficult to precisely define the cost of electricity for lighting the FDR roadway. NYC’s own documentation (NYC 2011) includes different scenarios from which rates can be derived, with results varying from $0.120 to $0.169 per kWh. (Billing invoices combine elements of multiple sites and demand charges, etc., and so do not resolve this question.)
2. The LSI Industries product shipped with an incorrect power supply, so the measured results for that product do not present an accurate point of comparison for new units going forward, were additional LSI units to be procured.

The tables below contain values derived from different combinations of these issues to provide a general idea of their relative impacts.

In all cases, life-cycle cost savings from replacing the baseline HPS with LED luminaires are modest despite high electricity rates and lower energy usage by the LED luminaires. Table S.1 provides some illuminance and relative cost characteristics of the baseline HPS luminaire and the four LED luminaires installed for the demonstration, based on the actual measurements taken onsite.

Table S. 1. Results Based on Measured Illuminance and Power

	Initial Average Illuminance						
Product	Lux	Footcandles	Uniformity (Avg:Min)	Wattage	Energy Reduction (%)	Payback Period (years)	Life-Cycle Costs for 24.4 years ($)[5]
HPS	9.0	0.9	3.0:1	164.0	N/A	N/A	3,730
LED Roadway Lighting	12.0	1.2	3.0:1	85.0	55	7.7	2,923
LSI Industries (Delivered)	10.0	1.0	3.3:1	81.4	57	8.6	3,594
Elumen	6.0	0.6	3.0:1	107.0	43	9.7	3,194
BetaLED	13.0	1.3	3.3:1	139.3	26	19.6	3,942

HPS = High-pressure sodium.
N/A = Not applicable.
Note: IES RP-8-00 recommends 0.9 fc average, with an average-to-minimum illuminance ratio of 3.0:1.

Table S.2 illustrates the impacts of varying the price paid for electricity to illuminate the FDR. In this particular situation, across all the LED products, each $0.01/kWh increment in the electricity price improves the simple payback period achieved by an average of roughly 0.5 year. Values are shown in red where they are based on manufacturer's data rather than having been measured onsite, i.e., involving the specified LED driver rather than the delivered LED driver.

Table S. 2. Simple Payback Period of LED Luminaires at Various Electricity Tariffs

	Electricity Rate ($/kWh)	SPB Period (years)	Electricity Rate ($/kWh)	SPB Period (years)	Electricity Rate ($/kWh)	SPB Period (years)	Electricity Rate ($/kWh)	SPB Period (years)
LED Roadway	0.120	9.4	0.130	9.0	0.150	8.3	0.153	8.2
LSI Industries (Delivered)	0.120	10.5	0.130	10.1	0.150	9.3	0.153	9.2
LSI Industries (Specified)	0.120	16.1	0.130	15.7	0.150	15.0	0.153	14.9
Elumen	0.120	11.4	0.130	9.2	0.150	8.5	0.153	8.4
BetaLED	0.120	21.7	0.130	21.2	0.150	20.4	0.153	19.6

PBP = Payback period. N/A = Not applicable.

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[5] A period of 24.4 years was used for the life-cycle cost analysis for all luminaires because it represents the lighting system with the longest claimed lifetime (100,000 hours in this case) divided by the annual operating hours.

Table S. 3. Life-Cycle Cost Calculations of Luminaires at Varying Electricity Price and Discount Rates

	DR (0%)	**DR (3%)**	**DR (7%)**	**DR (0%)**	**DR (3%)**	**DR (7%)**
	$0.120 / kWh			$0.169 / kWh		
HPS	$4,566	$3,163	$2,102	$5,392	$3,730	$2,476
LED Roadway	$3,468	$2,628	**$1,977**	$3,896	$2,923	**$2,171**
LSI Industries – Delivered	**$3,425**	**$2,618**	$2,008	**$3,836**	**$2,900**	$2,194
LSI Industries - Specified	$4,141	$3,111	$2,332	$4,844	$3,594	$2,650
Elumen	$3,744	$2,824	$2,115	$4,284	$3,194	$2,359
BetaLED	$4,519	$3,460	$2,635	$5,211	$3,942	$2,952

HPS = High-pressure sodium.
LCC= Life-cycle cost.
N/A = Not applicable.
DR = Discount rate.

The cost effectiveness of the FDR Drive installation depends on high electricity rates and deferred costly maintenance. Lighting system maintenance in limited-access installations like elevated roadways, tunnels, and heavily traveled urban highways can be quite expensive because it generally requires lane closures and multiple staff charging overtime labor rates, and even then the work must be carried out in close proximity to moving traffic. Safety issues increase as the speed of travel and traffic volume increase, both of which are significant at this location.

In this installation, the cost effectiveness for the lighting systems is also highly dependent on the manufacturer's claimed lifetimes of the LED light output (70 percent or greater lumen maintenance for 87,000 – 100,000 hours). If the luminaires in fact have a shorter useful life, the cost effectiveness will be reduced. At the time, the higher initial cost comprised a formidable initial obstacle to SSL roadway lighting when these luminaires were purchased, although taking a longer life-cycle perspective found the LEDs potentially competitive even then.

The costs of the luminaires in this project reflect the small quantities purchased and 2009 pricing and performance levels, and should be viewed in that context with regard to their applicability today. Nevertheless, despite a near certain achievement of energy savings and high potential for improvement in illumination quality, it remains likely at present that a longer-term life-cycle perspective is required to economically justify an investment in solid-state lighting for many roadway lighting applications. This perspective in turn relies heavily on due diligence in product selection, installation and commissioning to ensure the design intent is achieved.

Acronyms and Abbreviations

A	ampere(s)
BUG	back light, uplight, and glare
CCT	correlated color temperature
CRI	color rendering index
DOE	U.S. Department of Energy
Elumen	Elumen lighting networks
fc	footcandle(s)
FDR Drive	Franklin D. Roosevelt Drive
GATEWAY	U.S. Department of Energy (DOE) Solid-State Lighting Technology GATEWAY Demonstration Program
HPS	high-pressure sodium
IES	Illuminating Engineering Society of North America
IP	ingress protection
K	Kelvin
kWh	kilowatt-hour(s)
LED	light-emitting diode
lm/W	lumen(s) per watt
LSI	Lighting Science Industries Inc.
mA	milliampere(s)
MWh	megawatt-hour(s)
NYC	New York City
NYCDOT	New York City Department of Transportation
SSL	solid-state lighting
Std. Dev	Standard deviation
V	volt(s)
W	watt(s)

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1.0 Introduction

The New York City Department of Transportation (NYCDOT) maintains approximately 300,000 lights throughout the city, including lighting for streets (262,000, including bridges and underpasses), parks (12,000), and highways (26,000). In 1999, NYCDOT began replacing 60,000 of the 400-W high-pressure sodium (HPS) cobra heads with 250-W heads to conserve energy. In June 2007, NYCDOT expanded the conversion to include 160,000 250-W and 150-W HPS cobra head luminaires that were replaced with 150 and 100-W units, respectively. As of May 2009, 82,000 cobra heads had been replaced in Brooklyn and Queens.

The replacement of these fixtures provided both financial and environmental benefits. Converting 250-W heads to 150-W heads yielded a 45 percent energy savings, while switching from 150-W to 100-W heads resulted in a 35 percent energy savings (NYC 2011). NYCDOT credited converting to lower wattage cobra head streetlights for reducing upward light (sky glow). It is not readily apparent if the luminaires used more sophisticated optics or if the reduced uplight was a result of the reduced lumens from the lower power luminaires. Reduced illuminance levels on the ground resulted from the conversion, but according to calculations those levels still met the RP-8-00 criteria (see Table 2-8 later in this document).

NYC's "PlaNYC" set goals for reducing greenhouse gas emissions by more than 30 percent by 2030 through reduced energy consumption and implementation of cleaner, more reliable energy systems (NYC 2007). As part of this effort, NYCDOT is evaluating the potential energy savings from light-emitting diode (LED) street lighting. Previous roadway and street lighting demonstrations in Minneapolis, MN (DOE 2009(a)); Oakland, CA (DOE 2008); Portland, OR (DOE 2009(b)); and Palo Alto, CA (DOE 2010) have yielded between 12 and 40 percent energy savings when converting from conventional to LED luminaires. NYC hopes to replicate such savings and expressed interest in this demonstration to help them evaluate the opportunity.

Interest in using LEDs for street lighting applications has existed for some time in NYC. At one time, a bill was introduced that would have required all streetlights be converted to LED, but the bill was judged premature on the basis that more real-world experience with LED technologies was necessary (NYC 2010). NYC also sponsored a street lighting competition after the start of the new millennium and the winning design was an LED luminaire. The overall production and rollout of these luminaires was delayed, however. NYCDOT is currently engaged in a series of smaller-scale demonstrations to evaluate the luminaires before considering a larger rollout.

This report documents a demonstration of solid-state lighting (SSL) technology on Franklin D. Roosevelt Drive (FDR Drive) in NYC, in which LED luminaires were compared to the incumbent HPS luminaires and evaluated for light quantity and performance. The project was supported by the U.S. Department of Energy (DOE) GATEWAY Solid-State Lighting Technology Demonstration Program (GATEWAY) in conjunction with NYCDOT and The Climate Group.

Although energy savings are a primary focus of GATEWAY studies, meeting the lighting requirements and cost-effectiveness are also key components of the evaluation criteria. FDR Drive was chosen for the roadway lighting demonstration because of its isolated location near the river and because maintenance of its luminaires requires closing down part of the roadway, which is an inconvenience to the public, and is costly because it involves many personnel with multiple vehicles later at night. After-hours maintenance reduces traffic volume, in turn increasing the safety of the staff and limiting the delays on the roadway, but simultaneously increases the hourly rate of the staff involved. The longer-lived LED products are hoped to have significant impact on some of these high costs.

2.0 Methodology

2.1 Site Description

FDR Drive is a 9-1/2-mile-long highway that follows the irregular contour of Manhattan along the East River. The highway is predominantly three lanes in each direction, with the exception of a small section near the Brooklyn Bridge. The roadway includes partially covered tunnels, portions below grade, at grade, and elevated sections. The roadway is somewhat isolated in that the East River bounds it on one side and parks and buildings on the other, all of which help prevent significant stray light from entering the roadway. A three-lane section of the FDR Drive between 16th Street and 25th Street was chosen for the demonstration as shown in Figure 2.1. The diagonal road in Figure 2.1 is 20th Street.

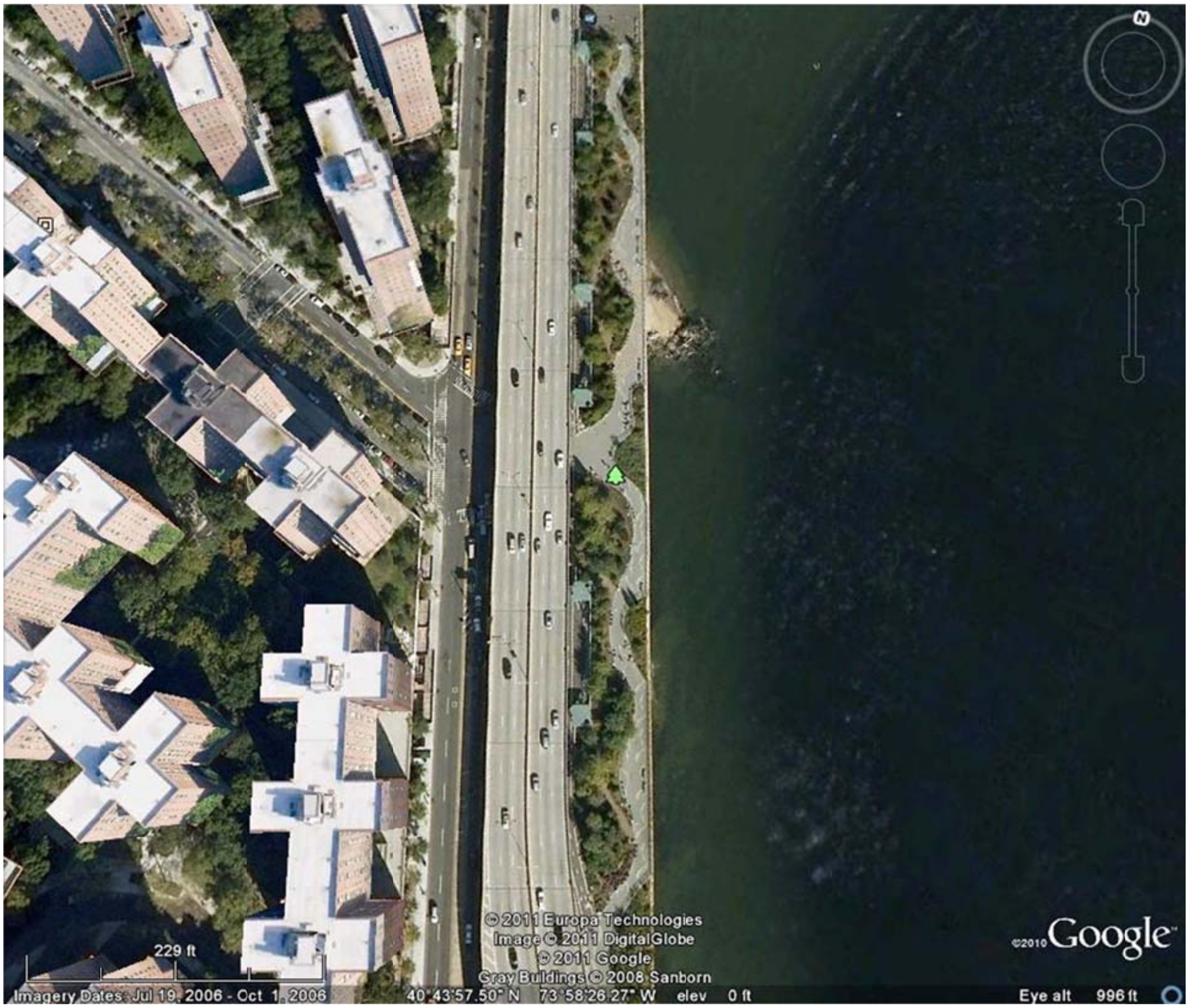

Figure 2.1. Google Earth Image of Franklin D. Roosevelt Drive (Courtesy: Google Earth)

2.2 Existing Luminaires

The existing luminaire is a 150-W HPS luminaire manufactured by Streetworks – a Cooper Lighting brand (Model No. OVD-15-S-2-2) and is shown in Figure 2.2. According to an analysis using Photometric Toolbox[6], the luminaire has a Type II distribution and back light, uplight, and glare (BUG) rating of B3-U3-G3. The lamp used in the luminaire is a 150-W Philips Ceramalux HPS lamp with a correlated color temperature (CCT) of 2100 K and color rendering index (CRI) of 21. According to the manufacturer's catalog information the rated life of the lamp is 24,000 hours.[7] Photometric Toolbox analysis of the provided .IES file indicates that the luminaire has an efficacy of 87 lumens per watt (lm/W), producing 13,002 initial lamp lumens with a fixture efficiency of 81 percent. Figure 2.3 shows both the vertical and horizontal distribution of the luminaire.

Figure 2.2. Baseline High-Pressure Sodium Streetworks Luminaire

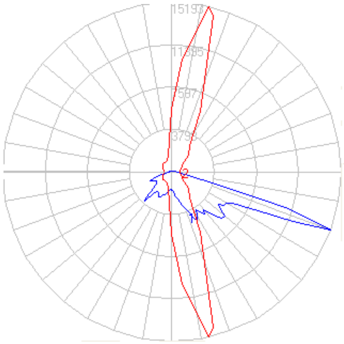

Figure 2.3. Photometric Distribution of High-Pressure Sodium Luminaire

2.3 New Luminaires

LED luminaires from four different manufacturers were selected for the demonstration, as follows (listed according to order of installation north to south on FDR Drive): LED Roadway Lighting Ltd. (LED Roadway); LSI, Industries; Elumen Lighting Networks Inc. (Elumen); and BetaLED.

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[6] Photometric Toolbox is lighting software by Lighting Analysts – Illumination engineering software. (http://www.agi32.com/catalog/product_info.php?products_id=39)

[7] http://www.ecat.lighting.philips.com

2.3.1 LED Roadway Lighting Luminaires

The first LED luminaire used in this demonstration was manufactured by LED Roadway Lighting (Catalog No. SAT- 96M) (Figure 2.4).[8] According to analysis of the manufacturer's .IES file using Photometric Toolbox, the luminaire has a Type II distribution, a BUG rating of B1-U2-G1, produces 6,296 lumens (initial), draws 89.4 W, and has a luminaire efficacy of 70 lm/W. According to the manufacturer's data sheet, the LED luminaire contains 96 multi-chip white LEDs, with a CCT of 5000 K and CRI of 70. The manufacturer claims a rated life of the luminaire of 90,000 hours with an operating ambient temperature of the luminaires between -40 °C and 60 °C. The manufacturer's data sheet also states that the luminaire has an ingress protection (IP) rating of 66[9]. Figure 2.5 shows both the vertical and horizontal distribution of the luminaire.

Figure 2.4. LED Roadway Luminaire

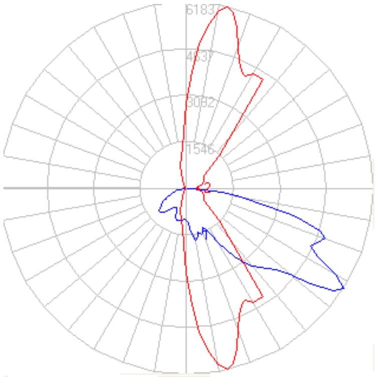

Figure 2.5. Photometric Distribution of LED Roadway Luminaire

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[8] http://www.ledroadwaylighting.com/

[9] The first digit of the IP rating indicates the protection against entry of foreign objects and currently ranges from 0 (not protected) to 6 (dust tight). The second digit indicates the protection against moisture and currently ranges from 0 (not protected) to 8 (completely submersible).

2.3.2 LSI Industries Luminaires

The LSI Industries LED luminaire used in this demonstration has catalog number XRM-2-LED-119-CW-UE and is shown in Figure 2.6.[10] According to Photometric Toolbox analysis of the provided .IES file, the luminaire has a Type II distribution, BUG rating of B2-U1-G2, produces 9,912 lumens (initial), draws 139.5 W, and has a luminaire efficacy of 71 lm/W. According to the manufacturer's data sheet, the LED luminaire has 119 1.15-W LEDs, a CCT of 5900 K, and CRI of 70. The manufacturer claims the life of the luminaire is 100,000 hours at a junction temperature of 85 °C (see Section 2.3.7 for more information about life). The manufacturer's data sheet also lists an IP rating of 67. Figure 2.7 shows both the vertical and horizontal distribution of the luminaire.

Figure 2.6. LSI Industries Luminaire

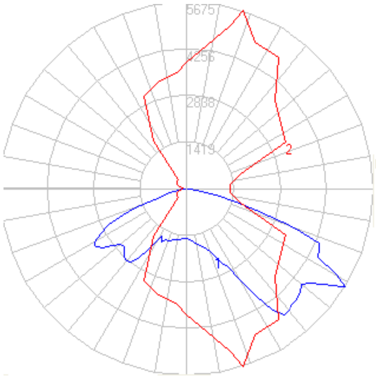

Figure 2.7. Photometric Distribution of LSI Industries Luminaire

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[10] http://www.lsi-industries.com/

2.3.3 Elumen Luminaires

The third LED luminaire used in this demonstration was manufactured by Elumen[11] (Model No. SE-100X-C3-TM-5) and is shown in Figure 2.8. Photometric Toolbox analysis of the manufacturer’s .IES file reveals a Type II distribution, BUG rating of B1-U2-G1, initial output of 6,462 lumens, power draw of 107.7 W, and a luminaire efficacy of 60 lm/W. According to the manufacturer’s data sheet, the LED luminaire contains 2,160 5-mm low-power LEDs, a nominal CCT of 5000 K, and a CRI higher than 80. The manufacturer claims the rated life of the luminaire is 88,000 hours. The manufacturer’s data sheet also states that the luminaire has an IP rating of 66. Figure 2.9 shows both the vertical and horizontal distribution of the luminaire.

Figure 2.8. Elumen Luminaire

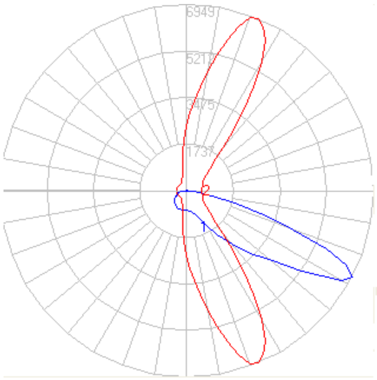

Figure 2.9. Photometric Distribution of Elumen Luminaire

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[11] http://www.Elumenlighting.com/

2.3.4 BetaLED Luminaires

The final LED luminaire used in this demonstration was manufactured by BetaLED (Model No. BLD-STR-HT-068-LED-B) and is shown in Figure 2.10.[12] According to Photometric Toolbox analysis of the manufacturer's .IES file, the luminaire has a Type II distribution, BUG rating of B2-U1-G2, emits 8,181 initial lumens, and draws 134.9 W for a luminaire efficacy of 61 lm/W. The manufacturer's data sheet lists the luminaire as having 80 1-W LEDs, a nominal CCT of 6000 K, and a CRI of 70, and claims a rated life of 87,000 hours operating in an ambient temperature of 25 °C. The manufacturer's data sheet also states that the luminaire has an IP rating of 66. Figure 2.11 shows both the vertical and horizontal distribution of the luminaire.

Figure 2.10. BetaLED Luminaire

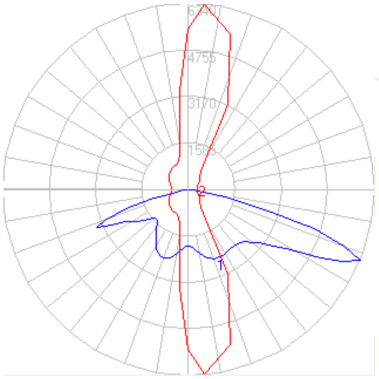

Figure 2.11. Photometric Distribution of BetaLED Luminaire

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[12] www.betaled.com/

2.3.5 Comparison of Luminaires

Table 2.1 provides a comparison of the four LED luminaires with the baseline HPS luminaire, including the percentage of uplight, back light, and forward light in each luminaire's output. Uplight consists of lumens directed above the 90° horizontal plane. Uplight is almost negligible across the LED luminaires, thus offering reduced sky glow compared to the HPS. The HPS luminaire has the highest efficacy but also the greatest amount of uplight (though still quite low) compared to the four LED luminaires.

In general, the greater the amount of forward light, the more light is being directed to the roadway surface and objects in the view of the drivers. However, some forward light is typically emitted at very high angles (80° – 90°) and therefore often extends beyond the roadway surface on the opposite side. The precise amount of light doing so depends on road width, mounting height and arm length, amount of light contained in that very high angle zone to begin with, and other variables. Of the four LED luminaires, the LED Roadway luminaire had the highest percentage of forward light followed by the Elumen luminaire.

Back light is light directed behind the fixture. Back light is desirable for applications where there is a pedestrian walkway, and in situations like this one involving back-to-back mounting along the center of the roadway. In this latter situation, some portion of the back light illuminates the other side of the road (i.e., the opposite lanes), so the back light rating is largely irrelevant in this application for the way it would normally be used, for example, where light trespass is a concern.

Table 2.1. Comparison of LED Luminaires to Baseline High-Pressure Sodium Luminaire[13]

Product	Type	BUG Rating	Luminaire Lumens* (lm)	Input Power (W)	Efficacy (lm/W)	Up-light (%)	Forward light (%)	Back light (%)
HPS	II	B3-U3-G3	13,002	186	81	4.6	66.6	28.8
LED Roadway Lighting	II	B1-U2-G1	6,296	89.4	70	0.0	84.4	15.6
LSI Industries (specified)	II	B2-U1-G2	9,912	139.5	71	0.0	67.0	33.0
Elumen	II	B1-U2-G1	6,462	107.7	60	0.6	76.9	22.5
BetaLED	II	B2-U1-G2	8,181	134.9	61	0.0	61.8	38.2

* Per manufacturer .IES files.
BUG = Back light, uplight, and glare.
HPS = High-pressure sodium.

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[13] Information obtained by analyzing the .IES files of the luminaires in Photometric Toolbox.

2.3.6 Color Characteristics

In terms of lighting quality, the LED luminaires have a higher CRI, 70 or above, while the HPS luminaire has a very low CRI of 21. Even though IES RP-8-00, the IES recommended practice for roadway lighting, does not have a minimum CRI requirement, it acknowledges that low CRI is a disadvantage of HPS lamps (IES 2000) because it may reduce color contrast and with that the driver's ability to discern roadway and traffic features. The LED luminaires selected for this installation were all cool white with CCT of 5000 K or higher. The HPS luminaire emits a warm color of white, with CCT of 2100 K (Table 2.2).

Table 2.2. Comparison of Luminaire Color Characteristics*

Product	CCT (K)	CRI
HPS	2100	21
LED Roadway Lighting	5000	70
LSI Industries	5900	70
Elumen	5000	86
BetaLED	6000	70

CCT = Correlated color temperature.
CRI = Color rendering index.
HPS = High-pressure sodium.

*Per manufacturers literature

Despite a local perspective that "LEDs provide a crisp white light that enables people to see more clearly at night under lower intensity than that provided by HPS luminaires" (NYC 2011), no spectral multipliers were factored into this study. The recently issued 10th Edition of the IES Lighting Handbook (IES 2011) states that spectral multipliers can be used to account for mesopic adaptation;[14] however, "though accounting for mesopic adaptation applies to many outdoor nighttime lighting situations, it should not be used to adjust recommended illuminance or luminances for roadways where the speed limit is greater than 40 kph (25 mph)." As the speed limit on the FDR is 40 mph, spectral multipliers are not considered in this report and all illuminance is thereby based on photopic lumens and adaptation.

2.3.7 Claimed Lifetime of Luminaires

Lifetime predictions based on extrapolations of LED test results have been the subject of much recent scrutiny and debate. In the time since this study began, the IES has published TM-21-11, *Projecting Long Term Lumen Maintenance of LED Light* Sources.[15] TM-21-11 provides a uniform method of

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[14] Mesopic vision (adaptation) is between the photopic and scotopic states. In mesopic vision, both rods and cones are active. Luminance values below approximately 10 cd/m^2 and above approximately 0.001 cd/m^2 produce this state of adaptation. Luminance on the FDR was not measured, but it is safe to assume that drivers on the FDR are operating in mesopic vision.

[15] According to the IES, LED light sources provide a very long usable life but their lumen output gradually depreciates over time as with any other light source. The long potential life of LEDs raises the issue of when they cease to produce a useful level of light, given they tend not to "burn out" when this point is reached. TM-21-11

projecting lumen maintenance based on testing data. Because TM-21-11 was not published before the start of this study, all calculations originally were conducted and remain based on the manufacturers' claimed life ratings.

The claimed LED life rating varies somewhat among manufacturers. Temperature affects the life of the LED and many (but not all) manufacturers provide information related to life with temperature information. The average low temperature is -3 °C (27 °F) in the winter and average high temperature is 29 °C (84 °F) in the summer in NYC (Weather.com 2011).

Individual lifetime claims by each manufacturer used for this study were as follows:

- LSI: (L_{70}) 60,000 to 100,000 hours where the average ambient temperature is below 40 °C (104 °F);[16]
- LED Roadway Lighting: L_{70} at 350 mA (milliamps) at 88,000 hours,[17] and per LRL's website, claims that the power supply has a 20-year design life with high Mean Time Between Failures (MTBF) components;
- Elumen: 90,000 hours without lumen depreciation (Elumen describes this as "light loss factor (LLF)>95%", interpreted here as L_{95});[18] and
- BetaLED: L_{70} at 25 ° C (77 °F) of 87,000 hours.

These estimates pertain specifically to the lumen maintenance of the LEDs, the point that each light source reaches the end of its defined useful life. However, the driver and other components also have impact on life and reliability of the luminaire. Additional information about the life of these other components was not was not available but is discussed further in Section 4.22.

2.4 Installation

Figure 2.12 shows an image of the FDR with a pair of installed LED luminaires. Six luminaires from each manufacturer were installed on three consecutive poles, mounted similarly back-to-back. The three poles constitute a complete measurement luminaire cycle in accordance with RP-8-00. Between each of the four LED groups, a single pole with two back-to-back 150W HPS (baseline) luminaires was left to delineate each luminaire grouping as shown in Figure 2.13. This allows a clear delineation between each manufacturer. The poles are spaced roughly 165 feet apart, with a pole height of 30 feet, and arm length of 7.5 feet.

The baseline HPS luminaires were cleaned and relamped before baseline measurements were taken to provide a direct initial illuminance comparison with the LED luminaires.

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provides a method for projecting when the "useful lifetime" of an LED will be reached, when the light emitted will have depreciated to a level where it is no longer considered adequate for a specific application.

[16] LSI's data sheet is based on TM-21-08 draft.

[17] LED Roadway luminaire in this study operated at 280 mA. It is assumed that the life claim is at least the same as the claim at 350 mA, if not longer, when operated at the lower drive current.

[18] LLF encompasses lamp lumen depreciation (LLD), luminaire dirt depreciation, and other factors. In terms of LLF for this study, it is assumed all luminaires will experience the same dirt depreciation, so LLF is a surrogate for LLD.

Figure 2.12. FDR Drive Measurement Site (Photo courtesy Ryan Pyle)

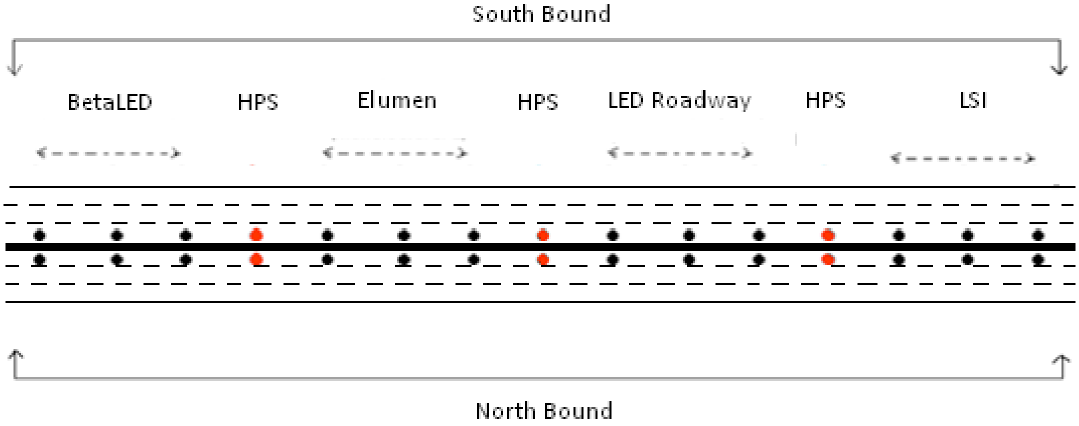

Figure 2.13. Layout of the LED Luminaires
(The figure is not to scale and is shown to illustrate the luminaire placement).

2.5 Power and Energy

2.5.1 Power

Both field and laboratory power measurements were taken for each luminaire type. Voltage and current were measured in the field measurement in 2009 (Appendix A). Electrical measurements for both the HPS and LED luminaires were taken at the same point in the circuit. Table 2.3 provides the average volt-amp values for the luminaires from the roadway. Field power factor (PF) measurements were attempted, but equipment issues and repeated road closures precluded this. However, laboratory tests were later conducted on the luminaires and the PF of each was recorded during these tests.

Except for the HPS luminaire, voltage and current was measured for six of each luminaire type. Five of the six LSI products had a measured current between 0.7 A and 0.8 A (corresponding with volt-amps between 84 and 98 respectively). The voltage was a nominal 120 V (see Appendix A for measured values). Only one LSI product had a current draw of 1.0 A, resulting in a calculated volt-amp of 120, which is closer to the value expected based on the manufacturer's data (see Table 2.5).

Table 2.3. Average Luminaire Field Volt-Amp Measurements

	Volt (V)		Amps (A)		Volt-Amperes (VA)	
Product	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
HPS Luminaire	124.0	N/A*	1.5	N/A*	186.0	N/A*
LED Roadway Lighting	120.8	5.9	0.8	0.1	90.5	5.9
LSI Industries	122.5	2.1	0.8	0.1	93.8	13.8
Elumen	122.2	1.0	0.9	0.1	105.9	6.5
BetaLED	123.0	1.3	1.1	0.0	133.3	5.7

* only one luminaire was measured and thus no average
HPS = High-pressure sodium.
N/A = Not applicable.

Because of this discrepancy between the field-measured power and manufacturer-reported power of one product, laboratory measurements were perceived as crucial to verify the validity of the field measurements. The LED luminaires from the FDR site were carefully removed and sent for laboratory testing in July 2011. Table 2.4 shows the laboratory-measured voltage, current, power, and power factor.

Table 2.4. Laboratory Measurements (July 2011)

Product	Volt (V)	Amps (A)	Power Factor	Power (W)
LED Roadway Lighting	120.0	0.718	0.987	85.0
LSI Industries	120.0	0.697	0.973	81.4
Elumen	120.0	0.894	0.997	107.0
BetaLED	120.0	1.170	0.992	139.3

Table 2.5 lists the power values obtained from the laboratory measurements (offering greater accuracy than the field measurements) and compares them with those reported in the manufacturer data sheets. Except for the LSI luminaire, the measured values and the manufacturer reported power values fell within 5 percent of one another.

Table 2.5. Power Value Comparison

Product	Laboratory Measured Power (W)	Manufacturer Data (W)	Percent Difference (%)
LED Roadway Lighting	85.0	89.4	4.9
LSI Industries	81.4	139.5	41.6[19]
Elumen	107.0	107.7	0.6
BetaLED	139.3	134.9	3.2

2.5.2 Energy

Table 2.6 provides the calculated energy usage of the HPS and the four LED lighting systems as measured in the field. NYC estimates the operating hours of the luminaires are 4,100 hours per year. Compared to the HPS baseline luminaire, all four LED luminaires result in lower energy use, however a couple of the values require additional explanation:

- The LSI Industries product shipped with the incorrect power supply, so does not present an accurate point of comparison for new units going forward. The table therefore lists energy used by the delivered units as well as with the luminaire as originally specified.
- The Elumen product claims to draw 30 percent more power at the end of life and Table 2.6 includes both the initial and end of life energy use of this luminaire.

The LED luminaires use between 17 percent to 51 percent less energy than the HPS electronic baseline.

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[19] Laboratory testing confirmed that neither power nor lumen output of the LSI luminaire matched the specified luminaire. LSI Industries was contacted regarding the significant discrepancy and LSI determined that the five of the six luminaires were manufactured with the wrong driver. They were assembled with their 75-W (nominal) driver instead of the 140-W (nominal) driver.

Table 2.6. Annual Energy Usage

Product	Luminaire Power (W)	Annual Operating Hours	Energy (kWh)	Energy Reduction HPS Ballast (%)
HPS	164.0*	4,100	672	N/A
LED Roadway Lighting	85.0	4,100	349	48.2
LSI Industries – Delivered	81.4	4,100	334	50.4
LSI Industries – Specified	139.5	4,100	572	14.9
Elumen	107.0	4,100	439	34.8
Elumen – End of Life**	139.1	4,100	570	15.2
BetaLED	139.3	4,100	571	15.1

* NYC replaced their magnetic ballasts with electronic ballasts. The value here was obtained via a catalog for HPS electronic ballasts because an HPS luminaire was not removed from the field and sent to the laboratory.[20]

** Manufacturer states that end of life power draw is 30 percent more than initial at end of life. Luminaire power here was the measured power multiplied by 30 percent (107.0 W *1.3 = 139.1 W). See section 4.2for a larger discussion about this luminaire and driver.

HPS = High-pressure sodium. N/A = Not applicable.

2.6 Illuminance

2.6.1 New York City Requirement

The illuminance criteria for FDR Drive are based on the recommendations for roadway lighting in RP-8-00. The recommended values for different road types in the RP-8-00 are shown in Table 2.7. FDR Drive falls under the Freeway Class A category, which includes roadways with greater visual complexity and high traffic volumes and R2/R3 pavement classification (asphalt road surface). Thus, 0.9 fc (9.0 lux) average maintained illuminance and a uniformity ratio (average to minimum illuminance) of 3.0:1 are recommended. Because the values recommended are maintained values, light loss factors also have to be considered to be in accordance with the RP-8-00 recommendation.

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[20] Hatch Transformers, Inc MC150-1-F-120U – http://www.hatchlighting.com/product-catalog/findProduct.cmd?partNumber=MC150-1F-120U

Table 2.7. Recommended Illuminance Values (RP-8-00)

Road and Pedestrian Conflict Area Road	Pedestrian Conflict Area	Pavement Classification R1		R2/R3		R4		Uniformity Ratio E_{avg}/E_{min}	Veiling Luminance Ratio L_{vmax}/L_{avg}
		lx	fc	lx	fc	lx	fc		
Freeway Class A		6.0	0.6	9.0	0.9	8.0	0.8	3.0	0.3
Freeway Class B		4.0	0.4	6.0	0.6	5.0	0.5	3.0	0.3
Expressway	High	10.0	1.0	14.0	1.4	13.0	1.3	3.0	0.3
	Medium	8.0	0.8	12.0	1.2	10.0	1.0	3.0	0.3
	Low	6.0	0.6	9.0	0.9	8.0	0.8	3.0	0.3
Major	High	12.0	1.2	17.0	1.7	15.0	1.5	3.0	0.3
	Medium	9.0	0.9	13.0	1.3	11.0	1.1	3.0	0.3
	Low	6.0	0.6	9.0	0.9	8.0	0.8	3.0	0.3
Collector	High	8.0	0.8	12.0	1.2	10.0	1.0	4.0	0.3
	Medium	6.0	0.6	9.0	0.9	8.0	0.8	4.0	0.4
	Low	4.0	0.4	6.0	0.6	5.0	0.5	4.0	0.4
Local	High	6.0	0.6	9.0	0.9	8.0	0.8	6.0	0.4
	Medium	5.0	0.5	7.0	0.7	6.0	0.6	6.0	0.4
	Low	3.0	0.3	4.0	0.4	4.0	0.4	6.0	0.4

Note: RP-8-00 converts to SI (i.e., lux) by multiplying the empirical value (fc) by 10, not 10.76.
fc = Footcandle.
lx = Lux.

2.6.2 Illuminance Calculation

The four LED luminaires were selected based on NYCDOT’s calculation using AGi-32[21] lighting simulation software. Table 2.8 shows the calculated illuminance values of the four LED luminaires. The simulation used a uniform light loss factor of 0.9. NYCDOT’s calculations did not further separate the light loss factors into terms of lamp lumen depreciation or luminaire dirt depreciation, and thus did not incorporate specific expected LLD values for either the HPS or LED luminaires.

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[21] http://www.agi32.com/

Table 2.8. Calculated Illuminance Values by NYCDOT

	Average		Max		Min			
Product	lx	fc	lx	fc	Lx	fc	Avg/Min	Max/Min
HPS	12.0	1.2	33.0	3.3	4.0	0.4	3.0:1	8.3:1
LED Roadway Lighting	7.0	0.7	27.0	2.7	1.0	0.1	7.0:1	27.0:1
LSI Industries	11.0	1.1	32.0	3.2	2.0	0.2	5.5:1	16.0:1
Elumen	6.0	0.6	12.0	1.2	2.0	0.2	3.0:1	6.0:1
BetaLED	10.0	1.0	39.0	3.9	3.0	0.3	3.3:1	13.0:1

fc = Footcandle.
lx = Lux.

2.6.3 Measurements

The measurement protocol was developed based on the recommendations on roadway lighting in LM-50-99 (IES 1999)[22]. The grid starts at a point one half of the grid cell size from the luminaire. In the longitudinal direction the distance between grid lines is one tenth of the spacing between luminaires. There are two grid lines per lane located one quarter of the distance from the edge of each lane. FDR Drive is an important transit route and could not be completely closed for measurement; therefore only one and a half lanes were measured. Weather conditions also were noted.

Initial illuminance measurements were taken on the roadway during the night of August 3, 2009. Approximately 60 points were measured for each luminaire type. Table 2.9 shows a summary of the measured illuminance values; the full set of values is provided in Appendix C. Three of the four LED products exceeded the average initial illuminance of the HPS, and two of the LED systems along with the HPS system met the uniformity criterion of Avg/Min being less than or equal to 3.0:1.

None of the uniformities in the table are of particular concern. The fact that the other two LED systems exceed the criterion at 3.3:1 reveals more about the sensitivity of this metric to small changes (and perhaps errors) in the minimum values than it does about performance of the luminaires themselves. The average values in this case were each based on at least 60 points whereas the minimum might consist of as little as a single value measured at a single point. Moreover, given its place in the denominator, even a small change in the measured minimum has large effects on the ratio (e.g., going from 0.1 fc to 0.2 fc is a small increment, but represents a 100 percent increase that halves the resulting ratio). The lower illuminance levels of the minimums are approaching the sensitivity of the light meter and so even a small measurement error here can result in large apparent variations in uniformity.

In actuality, an observer would be hard-pressed to distinguish such minor variations in measured uniformities, by eye alone. The fairly consistent values in the table should be viewed in that context.

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[22] Although LM-50-99 has since been officially withdrawn by the IES due to the document's passing the official 10-year lifespan, this project started in 2009 and the document was still in use at the time.

Table 2.9. Measured Illuminance Values

Product	Average		Max		Min		Avg/Min	Max/Min
	Lx	Fc	lx	fc	lx	fc		
HPS	9.0	0.9	25.0	2.5	3.0	0.3	3.0:1	8.3:1
LED Roadway Lighting	12.0	1.2	24.0	2.4	4.0	0.4	3.0:1	6.0:1
LSI Industries	10.0	1.0	22.0	2.2	3.0	0.3	3.3:1	7.3:1
Elumen	6.0	0.6	19.0	1.9	2.0	0.2	3.0:1	9.5:1
BetaLED	13.0	1.3	40.0	4.0	4.0	0.4	3.3:1	10.0:1

fc = Footcandle.
HPS = High-pressure sodium.
lx = Lux.
N/A = Not applicable.

Measured values would be normally expected to slightly exceed the calculated values, due to the latter incorporating LLFs of 0.90 for the LED and 0.78 for the HPS in the NYCDOT calculations whereas the measured (initial) values would not yet show any actual light losses (i.e., initially they have an LLF of 1.0). There are a few notable variations in the results from this location, however.

The original HPS cobra head measured average illuminance is lower than its corresponding calculated value, in reverse of the expected norm. There are multiple possible reasons for this effect:

1. The model differs from reality – Any real-world deviation from the “ideal” conditions assumed in the model will in turn vary the measured results. For example, the current model assumes a flat planar surface, while in reality the roadway slopes away from the center for water drainage and for traffic needs. Many other such real-world variations are possible as well, and are commonly encountered when comparing modeled to measured results.
2. Luminaire condition – the HPS lamps were replaced, but the lenses were not. Having been in the field for an unknown number of years, the lenses may be yellowed, etched or otherwise aged with significant effects to their transmission rate and distribution. Such changes are complex to model and are thus typically neglected in calculated values.
3. Variability in production – For a variety of reasons, it is not uncommon to find that performance of even well-established products varies from the manufacturer’s spec, and occasionally even from one sample to the next.

Variations were also found among some of the LED products. The measured LSI Industries values similarly showed reverse results from those otherwise expected based on calculations, in this case reflecting an anomaly that most of the luminaire samples contained an incorrect, lower-wattage driver than was specified. The LED Roadway Lighting measured average illuminance was almost twice (and the minimum a factor of four) its corresponding calculated value. A sample of this luminaire removed and tested in the laboratory after 19 months of operation suggests that the correct .IES file was used for the original calculations. To date the source of this latter difference between the calculated and measured values has been indeterminate.

3.0 Economics

The initial cost of LED luminaires is generally higher than that of conventional luminaires. However, the low power draw and expected long life of LED luminaires may result in substantial energy and maintenance savings, thus making them an attractive alternative.

3.1 Cost Inputs

The pricing of the luminaires used in the demonstration was obtained from each manufacturer's representative in NYC. Electricity and maintenance costs were obtained from NYCDOT.

3.1.1 Electricity Tariff

According to NYCDOT, NYC's comprehensive and complex street lighting system uses approximately 295.5 million kWh at a cost of $50 million at their current rate, which calculates to an overall tariff of $0.169/kWh (NYC 2011). However, that same document includes different scenarios from which differing rates can be derived, with results varying from $0.120 to $0.169 per kWh. (Billing invoices combine elements of multiple sites and demand charges, etc., and so do not resolve this issue.) General calculations in this study are based on the $0.169/kWh rate, but some tables include a range of tariffs to illustrate sensitivity of the results to this particular input.

3.1.2 Initial Luminaire Prices

Initial luminaire prices were obtained from manufacturer representatives in the NYC area. Typically, prices offered for luminaires are affected by order quantity, location of the site, and the number of participants in the supply chain, which greatly complicates the comparison of prices paid in one situation to another somewhere else. As only six luminaires from each vendor were ordered for this study, for example, estimating what the corresponding price would be for an order of 50, 100, or 1,000 units involves some degree of speculation.

In addition, luminaires for sites in NYC typically cost more than in other geographic areas. There are a number of reasons for this trend, including luminaire construction requirements, labor costs, and other factors.

The length of the supply chain also affects the purchase price. Buying directly from the manufacturer is typically cheaper than procuring luminaires through a supply chain where electrical distributors and contractors, manufacturer representatives, etc., are involved. Manufacturers often sell directly to municipalities, but that may not be the case for all luminaires in all quantities.

Final prices to individual users can thus vary considerably from the values obtained here.

3.1.3 Maintenance

Luminaire and lamp maintenance costs are calculated separately by NYCDOT. The annual maintenance budget for NYC street lighting is approximately $40 million for the HPS luminaires currently in use. The average maintenance cost per HPS fixture includes lamp maintenance of approximately $35 per year, luminaire maintenance of approximately $35 per year, and photo-electrical controls (photocell) maintenance of approximately $30 per year (NYC 2011). A NYCDOT contractor patrols FDR Drive every ten days and performs any standard maintenance required. Costs associated with pole maintenance are not included in the annual maintenance cost because they should be the same regardless of light source.

3.1.4 Discount Rate

The discount rate is the economic rate at which a site discounts future expenditures to establish their present value. For the life-cycle cost analysis, discount rates of 0 percent, 3 percent, and 7 percent were used to provide a range of values that other sites might encounter.

3.2 Cost-Effectiveness

3.2.1 Simple Payback

The simple payback is initially calculated using 4,100 annual operating hours and melded electricity rate of $0.169/kWh. The longer life of the LEDs reduces the lamp replacement costs for LED systems, although regular luminaire and lighting control maintenance remains the same for both HPS and LED luminaires.

3.2.1.1 Simple Payback for Measured Values

The simple payback periods shown for the LED luminaires in Table 3-1 range from roughly 7 to 15 years, with longer payback periods principally due to higher initial luminaire cost. The LED Roadway luminaire showed the shortest payback period due to both the lower initial cost and lower power draw compared to the other LED luminaires.

Table 3.1. Simple Payback of LED Luminaires

	Powe r (W)	Hours	Cost of Power ($/kWh)	Equipment Price ($)*	Annual Energy Cost ($)	Maintenance Savings ($)	Payback (Years)
LED Roadway Lighting	85.0	4,100	0.169	695.00	60.41	35	7.7
LSI Industries (Delivered)[23]	81.4	4,100	0.169	795.00	57.85	35	8.6
LSI Industries (Specified)[24]	134.9	4,100	0.169	795.00	93.47	35	14.4
Elumen	107.0	4,100	0.169	719.10	76.04	35	9.7
BetaLED	139.3	4,100	0.169	1,022.63	98.99	35	19.6

* Note: 2009 prices

HPS = High-pressure sodium. N/A = Not applicable.

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[23] The power value is the power value from the luminaire delivered with the wrong driver.

[24] The power value is the power value from the manufacturer’s data sheet and the expected value.

3.2.1.2 Simple Payback for Other Scenarios

NYC pays a higher electricity tariff than many other places in the U.S. This is due to the mixture of fuel used to generate electricity, the constraints of deploying new infrastructure in the City, and overall significant electric demand. Furthermore, as previously noted NYC's own documentation includes multiple scenarios where the rates can be calculated and vary from \$0.120 to \$0.169 (NYC 2011) per kWh. Table 3.2 provides the simple payback period (SPB) for each of the LED luminaires at a few alternative electricity rates, ranging from \$0.12/kWh to \$.153/kWh.

Table 3.2. Simple Payback Period of LED Luminaires at Varying Electricity Tariffs

	Electricity Rate ($/kWh)	SPB Period (years)	Electricity Rate ($/kWh)	SPB Period (years)	Electricity Rate ($/kWh)	SPB Period (years)	Electricity Rate ($/kWh)	SPB Period (years)
LED Roadway Lighting	0.120	9.4	0.130	9.0	0.150	8.3	0.153	8.2
LSI Industries (Delivered)	0.120	10.5	0.130	10.1	0.150	9.3	0.153	9.2
LSI Industries (Specified)	0.120	16.1	0.130	15.7	0.150	15.0	0.153	14.9
Elumen	0.120	11.4	0.130	11.0	0.150	10.3	0.153	10.2
BetaLED	0.120	21.7	0.130	21.2	0.150	20.4	0.153	20.3

HPS = High-pressure sodium. N/A = Not applicable.
PBP = Payback period.

The results in the table show that, in this installation, each \$0.01 increase in electricity tariff translates into a roughly 0.5 year reduction in the period required for the LED products to achieve simple payback. This relationship appears to hold true in this location regardless of power or luminaire price, though note that locations elsewhere would likely show somewhat different results.

3.2.1.3 Life-Cycle Cost

The analysis period for evaluating the life-cycle cost (LCC) of the luminaires was selected by taking the claimed life rating of the LED luminaire with the longest expected life among those used in the demonstration. According to manufacturer claims, the LSI luminaire had the highest expected life with a rating of 100,000 hours[25]. A corresponding analysis period of 24.4 years was therefore used in the LCC calculation, obtained by dividing the expected life (100,000 hours) by the annual operating hours of 4,100 hours. Software available from the National Institute of Standards and Technology, BLCC5.3[26] was used to calculate the LCCs for the different luminaires under a variety of scenarios.

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[25] Manufacturers in this study claimed expected lives (defined as when the LED reaches a specified fraction of initial output) between 87,000 and 100,000 hours. If the LED luminaires were operated 24 hours per day, it would take about 10 years to reach the lowest claimed expected life (87,000 hours). No LED system has been operating this long, so these life claims cannot be verified. The claims were furthermore made at a time before the industry standardized on a methodology of predicting lumen maintenance (IES TM-21-11). In the absence of such alternatives, the manufacturer values were simply accepted as given.

[26] http://www1.eere.energy.gov/femp/information/download_blcc.html

Table 3.3 provides the LCC for the different products across a range of discount rates and is based on an HPS lamp life of 5.7 years, which is the typical rated life of HPS lamps given the annual hours of operation. For contracting reasons, NYCDOT could not provide the price of the HPS lamp, but because these lamps are procured in large quantities, the cost was estimated at a conservative $10. Values are compiled for the two electricity tariffs at the ends of the potential range discussed earlier.

Table 3.3. Life-Cycle Cost Calculation of LED Luminaires Compared to Baseline High-Pressure Sodium Luminaire with a Lamp Life of 5.7 Years

	DR (0%)	**DR (3%)**	**DR (7%)**	**DR (0%)**	**DR (3%)**	**DR (7%)**
	$0.120 / kWh			$0.169 / kWh		
HPS	$4,566	$3,163	$2,102	$5,392	$3,730	$2,476
LED Roadway Lighting	$3,468	$2,628	**$1,977**	$3,896	$2,923	**$2,171**
LSI Industries – Delivered	**$3,425**	**$2,618**	$2,008	**$3,836**	**$2,900**	$2,194
LSI Industries - Specified	$4,141	$3,111	$2,332	$4,844	$3,594	$2,650
Elumen	$3,744	$2,824	$2,115	$4,284	$3,194	$2,359
BetaLED	$4,519	$3,460	$2,635	$5,211	$3,942	$2,952

HPS = High-pressure sodium.
LCC = Life-cycle cost.
N/A = Not applicable.
DR = Discount rate.

This LCC analysis factors in the initial cost and the replacement cost of the LED luminaires, but only the replacement cost of HPS lamps since the HPS fixtures were already installed.

The systems with the lowest LCCs (indicated in bold in Table 3.3) were the LED Roadway Lighting and the LSI Industries product that was delivered with the incorrect power supply. The low initial price and the low power draw which leads to lower energy use which helps drive the lowest LCC in both cases. However, the delivered LSI system was an anomaly, which also rendered its lighting performance unsuitable as a replacement for the HPS. Note that, in the absence of the incorrect LSI product, the LED Roadway Lighting product offered the lowest LCC across the board.

In a few scenarios, at least one LED system has the same LCC or a greater LCC than the HPS system. However, in the majority of cases the LED products have lower overall costs when considered over the longer term.

4.0 Discussion

A few issues surfaced during the course of the study that are not original or unique to the project and deserve separate attention:

- The estimated cost effectiveness of LED systems improves with longer assumed lifetimes. The lifetimes of most LED systems are simply quoted in terms of lumen maintenance by the LEDs, however, and do not take into account the other components in the system.
- Similarly, other components of light loss (e.g., dirt depreciation) are often overlooked as contributors to hastening the end of a product's useful life.
- BUG (backlight, uplight, glare) ratings are a useful tool in evaluating suitability of a luminaire for a given application but should not be viewed in isolation of other information, and should be considered in their proper context.

4.1 Extrapolated Illuminance Values

NYC references RP-8-00 for its roadway lighting, which sets an average **maintained** illuminance of 9.0 lux (0.9 fc), meaning that light loss factors must be taken into account in systems designed to meet the specification. Although numerous types of light loss factors exist, lamp lumen depreciation and luminaire dirt depreciation (LDD) are probably most significant for this application[27].

Lumen maintenance factors are individual to each product, and corresponding multipliers need to be applied to the **initial** illuminance values to evaluate how each system performs compared to RP-8-00. During its life, the HPS system will only depreciate by 10 to 15 percent[28] and then burn out. Of the tested LED luminaires, three defined life in terms of L_{70} and one, Elumen, defined their end of life at "LLF >95%". Illuminance values at the respective ends of life were calculated for the LED luminaires, multiplying each initial measured illuminance by the corresponding manufacturer-claimed lumen depreciation (see Table 4.1). Based on the results extrapolated from measured (initial) illuminance, only BetaLED would be expected to meet the maintained illuminance requirements of RP-8-00 at their claimed end of life. Note that the HPS system has dropped below the maintained RP-8-00 value in Table 4-1 and the LED Roadway Lighting value shows a similar result.

However, all values in Table 4-1 neglect dirt depreciation. LDD is driven primarily by external factors and was thus assumed to be the same for the four LED and the HPS luminaires. RP-8-00 provides a means for estimating the LDD for different dirt categories (ranging from very dirty to very clean environments) as a function of time[29]. At eight years, the maximum period estimated in RP-8-00, the corresponding LDD values for moderate and very clean environments are roughly 0.77 and 0.92, respectively. Note that if either of these values is applied to the extrapolated illuminance values, none of the systems in Table 4.1 meet RP-8-00.

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[27] NYCDOT used a total LLF value of 0.90 (LED) and 0.78 (HPS) in their calculations – see section 2.6.2.

[28] For the Philips Ceramalux HPS lamps, the difference between the mean and initial lumens (often used as a surrogate for lamp lumen depreciation) is 10 percent. The general value used for HPS lamp lumen depreciation is typically between 10 and 15 percent at 40% of rated life.

[29] Consult RP-08-00, Figure A5.

The extrapolated illuminance in Table 4.1 therefore uniformly incorporates a luminaire dirt depreciation (LDD) factor of 1.0, which allows the evaluation to focus instead on extrapolating the lamp lumen depreciation of the different systems.

Table 4.1. Extrapolated Illuminance Value over the Life of the Luminaires

	Life (hours)	Extrapolated Average Illuminance	
Product	Hours	Lux	Footcandles
HPS	24,000	8.7	0.9
LED Roadway Lighting	88,000	9.0	0.9
LSI Industries (delivered)	100,000	7.5	0.8
Elumen	90,000	6.1	0.6
BetaLED	87,000	9.8	1.0

HPS = High-pressure sodium.

The LEDs in the table show extremely long claimed lives, having been estimated by the individual manufacturers prior to the official release of TM-21-11. The TM-21-11 methodology would not allow such lengthy claims without sufficient testing data (e.g., a minimum of 15,000 hours of LM-80-08 data for most of the luminaires in this study) to back them up, an unlikely situation in the near term given the continuing dynamic nature of the LED industry and consequent steady introduction of new products. Future evaluations should incorporate values that are based on life projections using TM-21-11.

Of related note is that the original TM-21-11 methodology assumes the LEDs operate at constant current over their entire lifetime. Elumen claims a proprietary algorithm that increases current (along with power) to maintain light output over time. TM-21-11 could not presently be used to estimate the lifetime of the Elumen luminaire accurately since the current is not static over the lifetime of the luminaire[30].

4.2 Life of Other Components

Lumen maintenance is often used interchangeably with expected lifetime of the luminaire, or at least as the usual proxy for it. However, all of the other components in the luminaire also play a role in reliability and lifetime. A structural failure in the luminaire housing or power supply failure may well end a luminaire’s functional operation even though years remain in the LEDs themselves.

The driver has a life rating and is separate from the life of the LEDs, yet the data sheets for the four products in this study only published the life of the LEDs. In contrast, information available on the drivers ranged and was rather limited. Elumen claimed a driver life in terms of years, while LED Roadway Lighting stated the statistical reliability in the form of mean time between failures. The other two manufacturers stated the warranty of the drivers. While each of these data points is helpful and informative, perhaps stating all three is best from a user’s perspective.

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[30] Variable drive current is also the case for many systems that incorporate dimming, though not applicable in this instance.

The Municipal Solid-State Street Lighting Consortium (MSSLC) has issued the Model Specification for LED Roadway Lighting[31] that contains suggested requirements for all of the components in the luminaire. The reader is referred to that document for a rapid tutorial on the various items of concern.

4.3 BUG Values

The IES has officially rescinded the cutoff classification system in favor of the new "BUG" rating system[32]. BUG improves on the old system[33] in that it now evaluates each component (backlight, uplight, and glare) separately instead of combining the lighting output information into a single metric. Although a marked improvement over the old system, BUG itself is still not without potential shortcomings.

BUG ratings range from zero to five for each component (B, U, and G). The lumen output contained within each zone generates the rating given to a luminaire in that zone (See Figures 4.1 through 4.3). Within each component, there are further sub-sections (e.g., uplight is bifurcated into uplight low [UL] and uplight high [UH]), with specific lumen thresholds for each rating. Higher values indicate that somewhere in that zone more lumens are emitted than in a lower value. Higher ratings are not necessarily negative, however, and in fact may be desirable in certain locations (e.g., Times Square) where more light is required. Local zoning codes often set specific BUG criteria.

As discussed in Section 2.3.5, in this particular application the backlight rating is largely irrelevant because the poles are located along the center of the roadway and all downward light is thus either contributing to illumination on one side of the roadway or the other. In contrast, uplight contributes to skyglow and may be of greater concern[34]. The original HPS fixtures have a rating of U3 whereas the LEDs had values of either U1 or U2, reducing the corresponding contribution to uplight significantly.

The glare rating for the HPS is G3 whereas the LEDs again all offer G values of 1 or 2. In general, the LED products can therefore be expected to produce fewer glare issues for drivers than the HPS. It should be noted, however, that the BUG system sets a maximum lumen limit on more than one angular zone, so although there is a single Glare rating for a luminaire, the rating that results from the angular zone producing the worst case performance governs the final rating. In other words, a luminaire emitting lumens at a G2 level in any angular zone is rated as a G2 luminaire everywhere, even if all the other zones would qualify under a G1 rating.

The limited scope of this study precluded the collection of subjective feedback from FDR users on glare of the various products.

Table 4-2 shows the applicable thresholds for glare ratings per TM-15-11. Under these values, LED Roadway Lighting and Elumen both are characterized as G1 and BetaLED was characterized as G2. Notice that Elumen actually emits more lumens in the FH zone(1554) than either of the other two luminaires, but that the BetaLED emits more lumens in the BH zone (766) and this pushes the luminaire

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[31] http://www1.eere.energy.gov/buildings/ssl/specification.html

[32] http://www.ies.org/PDF/Erratas/TM-15-11BUGRatingsAddendum.pdf

[33] The former IES cutoff classifications were based only on intensities at or above 80°, rather than on luminaire lumens.

[34] Street lights are admittedly only a small contributor to the total uplight emitted in New York City, but this would not necessarily be the case in other locations.

to a G2 rating. This result highlights the fact that the G value provides some level of useful information, but users need to evaluate all of the secondary solid angles if overly concerned about glare or other value.

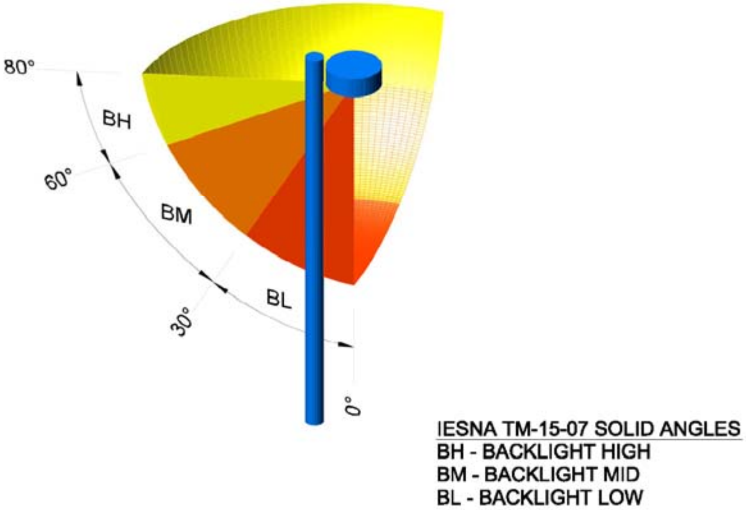

Figure 4.1. BUG Zones – B (Backlight) Graphic Courtesy Clanton & Associates

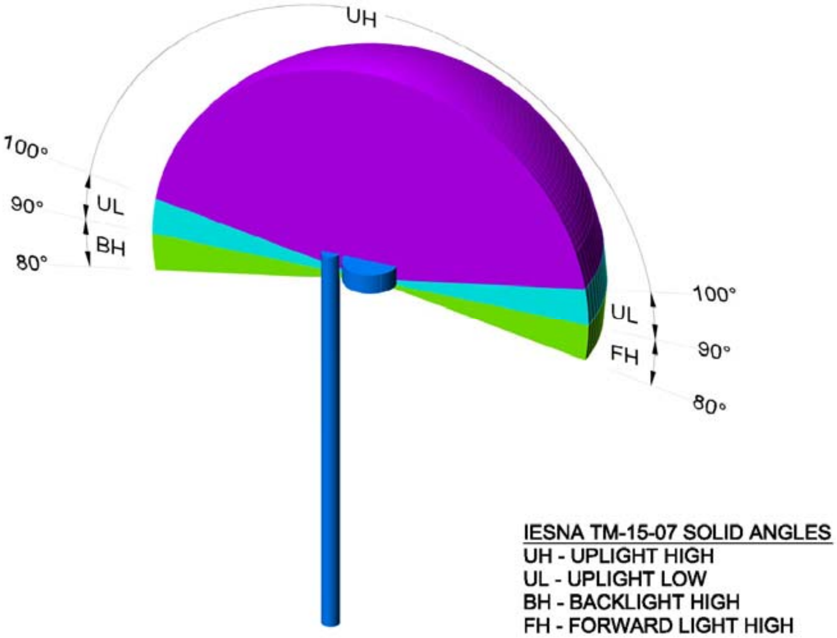

Figure 4.2. BUG Zones – U (Uplight) Graphic Courtesy Clanton & Associates

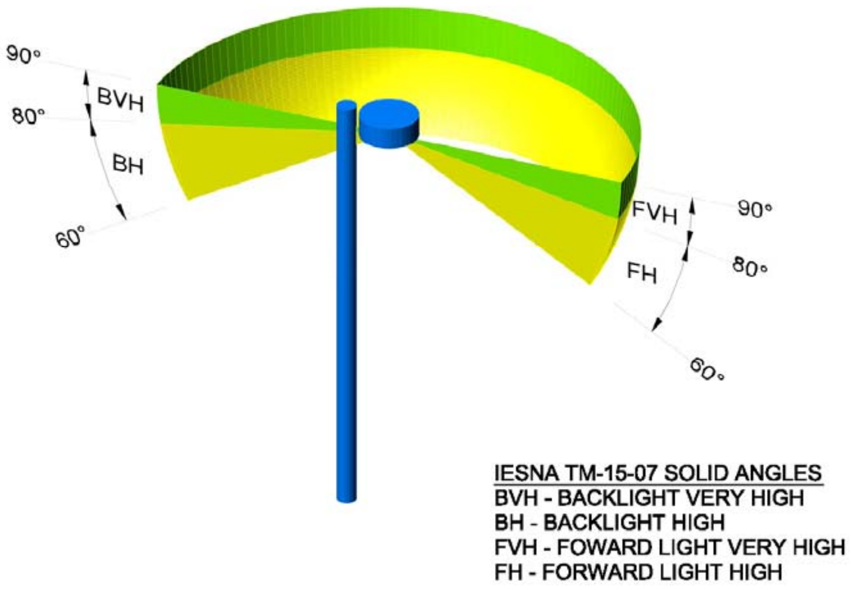

Figure 4.3. BUG Zones – G (Glare) Graphic Courtesy Clanton & Associates

Table 4.2. BUG Values

Secondary Solid Angle	Angle from vertical	G1 Limits (lumens)	G2 Limits (lumens)	**LED Roadway Lighting** G1	**Elumen** G1	**BetaLED** G2
FH	(60°-80°)	1800	5000	1449.2	1554.6	1425.0
FVH	(80°-90°)	100	225	87.5	74.2	21.1
BH	(60°-80°)	500	1000	209.2	388.6	766.0
BVH	(80°-90°)	100	225	13.5	54.7	9.6

5.0 Conclusions

The goal of the GATEWAY Demonstration Program is to install and evaluate LED products in general illumination applications that save energy, match or improve the quality of illumination, and are genuinely cost-effective according to the user's own criteria.

Aside from product performance, success of a given installation largely depends on the particulars of the site and the specific information included in the evaluation. In the FDR Drive installation, significant levels of energy savings were achieved. All of the evaluated LED luminaires had lower energy usage than the incumbent baseline HPS luminaire, using 26 to 57 percent less energy. In terms of illuminance, three luminaires matched the initial illuminance, but only two LED systems would meet the required maintained illuminance values identified in RP-8-00 (though note that those also do not meet the maintained illumination at their stated ends of life if dirt depreciation is included, although they still outperform the incumbent HPS).

In regard to non-illuminance lighting metrics, the LED systems all offered better color rendering and emitted no uplight compared to the HPS system. The improved color rendering resulting from the broader spectrum of the LED may bring with it better identification and contrast for improved visual acuity and reading of signs and license plates.

The cost-effectiveness of the FDR Drive installation depends on high electricity rates and deferred costly maintenance. Lighting system maintenance in limited-access installations like elevated roadways, tunnels, and heavily traveled urban highways can be quite expensive because it generally requires lane closures and multiple staff charging overtime labor rates, and even then the work must be carried out in close proximity to moving traffic. Safety issues increase as the speed of travel and traffic volume increase, both of which are significant at this location.

The actual annualized cost of having to re-lamp HPS fixtures primarily depends on the number of vehicles and staff required to close the lane and conduct the work, and the associated frequency of this activity. Not all issues can be directly monetized, however, such as the difficulty in scheduling lane closures on a major elevated freeway located in a large metropolitan area, or the inconvenience of closures to motorists (many of whom may vocalize their displeasure in letters to the mayor's office or local newspaper, etc.).

In this installation, the cost effectiveness for the lighting systems is also highly dependent on the manufacturer's claimed lifetimes of the LED light output (70 percent or greater lumen maintenance for 87,000 – 100,000 hours). If the luminaires in fact have a shorter useful life, the cost effectiveness will be reduced. At the time, the higher initial cost already comprised a formidable initial obstacle to SSL roadway lighting when these luminaires were purchased, although taking a longer life-cycle perspective found the LEDs potentially competitive even then due to anticipated maintenance advantages and savings of costly electricity in NYC.

Most importantly, the initial costs of the luminaires in this project reflected the small quantities purchased and 2009 pricing and performance levels, and should be viewed in that context with respect to decisions being made today. Nevertheless, despite the near certain achievement of energy savings and potential improvement in illumination quality, it remains likely at present that a longer-term life-cycle perspective is required to economically justify an investment in solid-state lighting for many roadway lighting applications.

6.0 References

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Appendix A – Power Measurements

Table A.1. Field Power Measurements (August 2009)

Products		Voltage (V)	Amperage (A)	Power (VA)
HPS		124.0	1.5	186.0
LSI Industries		120.0	1.0	120.0
LSI Industries		125.0	0.7	87.5
LSI Industries		123.0	0.8	98.4
LSI Industries		124.0	0.7	86.8
LSI Industries		123.0	0.7	86.1
LSI Industries		120.0	0.7	84.0
	Average	122.5	0.8	93.8
	Std. Dev	2.1	0.1	13.8
LED Roadway		123.0	0.7	86.1
LED Roadway		115.0	0.8	92.0
LED Roadway		112.0	0.8	89.6
LED Roadway		125.0	0.7	87.5
LED Roadway		123.0	0.7	86.1
LED Roadway		127.0	0.8	101.6
	Average	120.8	0.8	90.5
	Std. Dev	5.9	0.1	5.9
Elumen		121.0	0.9	108.9
Elumen		123.0	0.9	110.7
Elumen		121.0	0.8	96.8
Elumen		123.0	0.8	98.4
Elumen		123.0	0.9	110.7
Elumen		122.0	0.9	109.8
	Average	122.2	0.9	105.9
	Std. Dev	1.0	0.1	6.5
BetaLED		123.0	1.1	135.3
BetaLED		124.0	1.1	136.4
BetaLED		124.0	1.1	136.4
BetaLED		122.0	1.0	122.0
BetaLED		121.0	1.1	133.1
BetaLED		124.0	1.1	136.4
	Average	123.0	1.1	133.3
	Std. Dev	1.3	0.0	5.7

Appendix B – Laboratory Luminaire Output Data

In March of 2011, one of the six luminaires from each manufacturer was removed from the field and shipped to a laboratory. Table B.1 lists the lumen output of one luminaire per manufacturer. For the LSI Industries luminaire, it was one of the luminaires with the 75W driver.

Table B.1. Laboratory Measurements of Lumen Output of the LED Luminaires (July, 2011)

Luminaire	Lumen Output
LED Roadway Lighting	5,772
LSI Industries	5,637
Elumen	5,870
BetaLED	7,097

Appendix C – Detailed Illuminance Data

Table C.1. Illuminance Measurement of HPS Luminaire

Illuminance Grid Measured in Footcandles			
	X-Axis		
Y-Axis	1	2	3
1	1.27	1.52	1.59
2	1.13	1.34	1.47
3	0.56	0.75	0.91
4	0.37	0.53	0.53
5	0.35	0.44	0.54
6	0.30	0.43	0.46
7	0.35	0.44	0.49
8	0.45	0.49	0.53
9	0.82	1.17	1.42
10	1.17	1.29	1.54
11	1.34	1.28	1.30
12	1.11	1.12	1.35
13	0.64	0.67	0.84
14	0.48	0.63	0.53
15	0.42	0.42	0.52
16	0.46	0.49	0.54
17	0.72	0.90	1.01
18	1.40	1.44	1.54
19	1.92	2.22	2.54

Illuminance Grid Converted to Lux			
	X-Axis		
Y-Axis	1	2	3
1	12.7	15.2	15.9
2	11.3	13.4	14.7
3	5.6	7.5	9.1
4	3.7	5.3	5.3
5	3.5	4.4	5.4
6	3.0	4.3	4.6
7	3.5	4.4	4.9
8	4.5	4.9	5.3
9	8.2	11.7	14.2
10	11.7	12.9	15.4
11	13.4	12.8	13
12	11.1	11.2	13.5
13	6.4	6.7	8.4
14	4.8	6.3	5.3
15	4.2	4.2	5.2
16	4.6	4.9	5.4
17	7.2	9.0	10.1
18	14.0	14.4	15.4
19	19.2	22.2	25.4

Table C.2. Illuminance Measurement of LED Roadway Luminaire

Illuminance Grid Measured in Footcandles			
		X-Axis	
Y-Axis	1	2	3
1	1.86	2.18	2.10
2	1.99	2.15	1.96
3	1.35	1.49	1.19
4	0.59	0.72	0.66
5	0.40	0.42	0.45
6	0.36	0.37	0.42
7	0.45	0.50	0.60
8	0.74	0.87	1.00
9	1.24	1.56	1.51
10	1.21	1.99	1.48
11	1.02	2.18	2.18
12	1.11	1.89	2.01
13	1.17	1.18	1.43
14	0.46	0.93	1.07
15	0.35	0.50	0.58
16	0.40	0.51	0.58
17	0.46	0.61	0.70
18	0.79	0.98	1.10
19	1.47	1.78	1.68
20	1.87	2.37	1.85
21	1.33	2.28	2.25

Illuminance Grid Converted to Lux			
		X-Axis	
Y-Axis	1	2	3
1	18.6	21.8	21.0
2	19.9	21.5	19.6
3	13.5	14.9	11.9
4	5.9	7.2	6.6
5	4.0	4.2	4.5
6	3.6	3.7	4.2
7	4.5	5.0	6.0
8	7.4	8.7	10
9	12.4	15.6	15.1
10	12.1	19.9	14.8
11	10.2	21.8	21.8
12	11.1	18.9	20.1
13	11.7	11.8	14.3
14	4.6	9.3	10.7
15	3.5	5.0	5.8
16	4.	5.1	5.8
17	4.6	6.1	7.0
18	7.9	9.8	11.0
19	14.7	17.8	16.8
20	18.6	21.8	21.0
21	19.9	21.5	19.6

Table C.3. Illuminance Measurement of LSI Luminaire

Illuminance Grid Measured in Footcandles			
	X-Axis		
Y-Axis	1	2	3
1	1.68	1.69	1.61
2	1.66	1.74	1.73
3	0.84	0.81	0.73
4	0.47	0.50	0.44
5	0.37	0.34	0.33
6	0.34	0.31	0.41
7	0.58	0.60	0.57
8	1.00	1.11	1.07
9	1.61	1.71	1.76
10	1.77	1.73	1.62
11	1.80	2.13	2.17
12	1.21	1.14	1.09
13	0.70	0.69	0.67
14	0.39	0.40	0.38
15	0.32	0.26	0.25
16	0.31	0.34	0.28
17	0.52	0.52	0.50
18	0.94	0.93	0.88
19	1.67	1.26	1.78
20	1.78	1.77	1.66
21	1.33	2.28	2.25

Illuminance Grid Converted to Lux			
	X-Axis		
Y-Axis	1	2	3
1	16.8	16.9	16.1
2	16.6	17.4	17.3
3	8.4	8.1	7.3
4	4.7	5.0	4.4
5	3.7	3.4	3.3
6	3.4	3.1	4.1
7	5.8	6.0	5.7
8	10	11.1	10.7
9	16.1	17.1	17.6
10	17.7	17.3	16.2
11	18	21.3	21.7
12	12.1	11.4	10.9
13	7.0	6.9	6.7
14	3.9	4.0	3.8
15	3.2	2.6	2.5
16	3.1	3.4	2.8
17	5.2	5.2	5.0
18	9.4	9.3	8.8
19	16.7	12.6	17.8
20	16.8	16.9	16.1
21	16.6	17.4	17.3

Table C.4. Illuminance Measurement of Elumen Luminaire

Illuminance Grid Measured in Footcandles			
	X-Axis		
Y-Axis	1	2	3
1	1.10	1.08	1.09
2	0.60	0.83	1.06
3	0.34	0.41	0.49
4	0.22	0.37	0.41
5	0.26	0.28	0.26
6	0.26	0.28	0.24
7	0.22	0.26	0.31
8	0.30	0.38	0.51
9	0.54	0.68	0.99
10	0.96	0.97	0.93
11	1.17	1.07	0.94
12	0.63	0.64	0.75
13	0.39	0.47	0.60
14	0.28	0.33	0.46
15	0.19	0.22	0.30
16	0.21	0.19	0.26
17	0.33	0.29	0.39
18	0.51	0.67	0.76
19	0.95	1.43	1.46
20	1.06	1.26	1.89
21	1.23	1.19	1.05

Illuminance Grid Converted to Lux			
	X-Axis		
Y-Axis	1	2	3
1	11.0	10.8	10.9
2	6.0	8.3	10.6
3	3.4	4.1	4.9
4	2.2	3.7	4.1
5	2.6	2.8	2.6
6	2.6	2.8	2.4
7	2.2	2.6	3.1
8	3.0	3.8	5.1
9	5.4	6.8	9.9
10	9.6	9.7	9.3
11	11.7	10.7	9.4
12	6.3	6.4	7.5
13	3.9	4.7	6.0
14	2.8	3.3	4.6
15	1.9	2.2	3.0
16	2.1	1.9	2.6
17	3.3	2.9	3.9
18	5.1	6.7	7.6
19	9.5	14.3	14.6
20	11.0	10.8	10.9
21	6.0	8.3	10.6

Table C.5. Illuminance Measurement of BetaLED Luminaire

Illuminance Grid Measured in Footcandles			
	X-Axis		
Y-Axis	1	2	3
1	3.35	3.67	2.77
2	1.21	1.75	1.98
3	0.65	0.88	1.13
4	0.51	0.77	0.89
5	0.47	0.54	0.68
6	0.45	0.54	0.57
7	0.47	0.53	0.63
8	0.48	0.70	0.76
9	0.86	1.22	1.32
10	2.65	3.04	2.36
11	3.94	3.54	2.48
12	1.54	2.12	2.11
13	0.74	1.05	1.07
14	0.61	0.86	0.97
15	0.54	0.56	0.61
16	0.42	0.46	0.54
17	0.38	0.43	0.54
18	0.42	0.47	0.60
19	0.74	0.71	1.00
20	1.96	1.92	2.27
21	3.96	2.54	1.99

Illuminance Grid Converted to Lux			
	X-Axis		
Y-Axis	1	2	3
1	33.5	36.7	27.7
2	12.1	17.5	19.8
3	6.5	8.8	11.3
4	5.1	7.7	8.9
5	4.7	5.4	6.8
6	4.5	5.4	5.7
7	4.7	5.3	6.3
8	4.8	7.0	7.6
9	8.6	12.2	13.2
10	26.5	30.4	23.6
11	39.4	35.4	24.8
12	15.4	21.2	21.1
13	7.4	10.5	10.7
14	6.1	8.6	9.7
15	5.4	5.6	6.1
16	4.2	4.6	5.4
17	3.8	4.3	5.4
18	4.2	4.7	6.0
19	7.4	7.1	10.0
20	33.5	36.7	27.7
21	12.1	17.5	19.8