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THE CLEAN REVOLUTION

NEW YORK CITY FDR DRIVE LED TRIAL: FINAL REPORT

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ACKNOWLEDGEMENTS

The LightSavers global LED trials ran from October 2009 to January 2012 and aimed to provide greater certainty about the state of LED technology. During the trials, lighting managers from nine of the cities independently tested the performance of more than 500 luminaires representing 27 different commercially available LED products, using the same measurement protocol. Key findings of the trials were:

- LEDs achieve the expected 50-to-70 percent energy savings and reach up to 80 percent savings when coupled with smart controls;
- Even with these energy savings, the vast majority of tested products exceeded local lighting standards;
- Many commercial LED products tested show behavior indicative of lifespans of 50,000 hours, though the results from the trials should not be used for predictive purposes;
- LED products generally show very little change in color;
- The ‘catastrophic’ failure rate of LED products over 6,000 hours is around one percent, compared, for example, up to 10 percent for metal halide fixtures over a similar time period;
- In cities where surveys were conducted, the public prefers LED illumination, with about 90 percent of survey respondents supporting a full rollout of LEDs across city street lights.

It should be noted that the LED luminaire product tested in this trial was designed and manufactured several years ago. It would be expected that recent generations of products should exhibit even better performance. The Climate Group’s LightSavers trial concludes that LEDs are now mature enough for scale-up in most outdoor applications, and that LEDs combined with smart controls promise greater savings.

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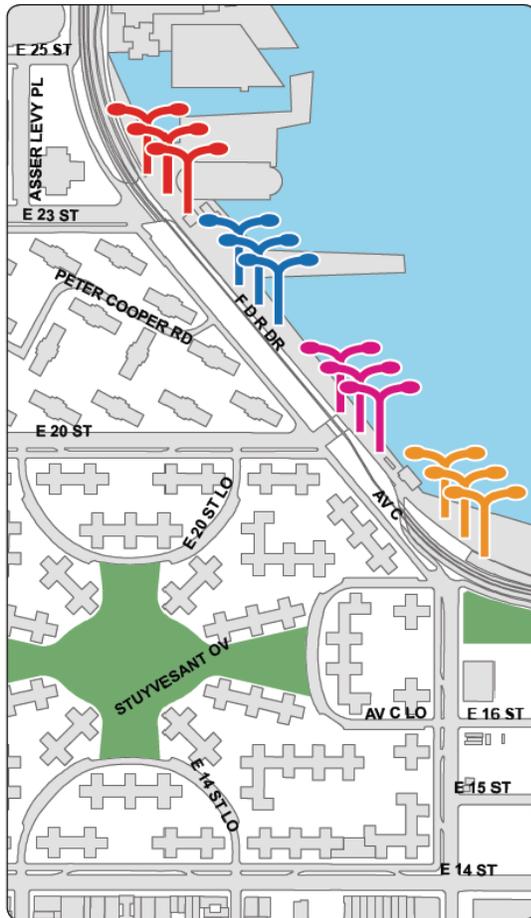
Executive Summary

For the period August 2009 - December 2010, the FDR LED LightSavers trial has yielded valuable data that has enabled a useful comparative evaluation of the performance of four LED products. The trial was a collaborative effort of the New York City Department of Transportation (NYCDOT), The Climate Group, and the US Department of Energy (DOE). Here is a summary of the trial results to date, combining measured values from both the NYCDOT and US DOE monitoring efforts:

1. **Illuminance.** Three LED luminaires exceeded the average illuminance produced by the HPS luminaire and complied initially with the Illuminating Engineering Society of North America's (IESNA) RP-8-00 standard. According to US DOE's measurements, none of the luminaires, including the HPS lamp, complied with the IESNA recommended uniformity ratio of 3.0:1, reflecting perhaps the challenging spatial demands of the site.
2. **Correlated color temperature (CCT).** There was very little change in CCT over the 15 months in either the baseline or all four of the FDR LED luminaires.
3. **Energy.** All of the LED luminaires saved energy ranging from 15 percent to 50 percent, with two luminaires saving in the range of 50 percent. The measured LED luminaire power values were based on the US DOE's laboratory measurements.
4. **Lumen maintenance.** The lumen output of three of the LED luminaires appreciated during the last 11 months of the trial, net of dirt depreciation. The fourth LED luminaire depreciated by 19 percent, but its light output stabilized during the last eight months. These results should not be used to predict the future performance of these products, but they do indicate that after an initial period of volatility of the LED light source due to various factors, lumen output appears to stabilize.
5. **Economic payback.** Since NYC has a five-year payback limit for energy efficiency investments, the capital cost plus installation of the four LED luminaires would need to fall between \$440 and \$590 per unit in order to meet this criterion. One manufacturer quoted a price of \$600/kilo-lumen or \$377 for a single LED luminaire product equivalent to the one in the trial, if purchased in volume. Hence, it appears there is commercial product currently available that would meet the City's economic payback criterion at this time, if the scale of the project is sufficient.

In conclusion, the trial evaluation yielded three LED luminaires that performed quite well with respect to a range of performance parameters in comparison with the baseline HPS luminaire. Meanwhile, the economics of a LED replacement program would likely meet the City's energy efficiency investment criteria, if the tender process were to aim to aggregate most or all of the urban highway lighting assets to create enough volume to reduce prices bid by manufacturers.

Background



The FDR Drive is one of New York City's iconic assets. This busy urban parkway was originally called the East River Drive but was renamed after President Franklin Delano Roosevelt, a former governor of the state of New York. It stretches for 9-1/2 miles along the east side of Manhattan and carries about 150,000 vehicles per day through mid-town Manhattan. Construction of the Drive commenced in 1934, with fiscal stimulus money available during the depression obtained by Mayor LaGuardia. However, construction wasn't completed until 30 years later, due to substantial design and political obstacles.

The New York City Department of Transportation (NYCDOT) plans to upgrade the high pressure sodium (HPS) lighting on the Drive with LED lighting, as potentially a first step towards retrofitting all of the City's expressways. In addition to enhancing the quality of illumination on the parkway, LED lighting should substantially improve operations. Maintenance of the existing lamps on the expressways is costly and a public inconvenience. The City's NYCDOT must shut down portions of the busy parkway every time a lamp needs replacing.

LEDs should last three-to-four times longer, thus cutting maintenance costs and improving public convenience.

The LightSavers FDR LED Trial

The primary aim of the LightSavers FDR trial is to assess the quality and performance of LED illumination over a one-year period on an urban expressway, a demanding application given the typical height and spacing of the poles. In the late summer and fall 2009, the NYCDOT installed four sets of LED luminaire products, a total of 24 units, along FDR Drive stretching from East 16th Street to East 23rd Street on Manhattan's east side adjacent to the East River. The LED luminaires replaced HPS lamps mounted on three consecutive single poles with two arms, mounted back-to-back, that illuminate both north and south bound lanes. Table 1 below summarizes the manufacturers' data on the baseline and LED luminaires obtained by analyzing the .IES files provided by the manufacturers:

TABLE 1: Summary of manufacturers' data from .IES files

Product Reference	Nominal Rating (Watts)	Luminaire Output (lumens)	Luminaire Efficacy (lumens/watt)	Distribution Type
HPS baseline*	164.0	14,490	88.4	II
NYC-2(a)	134.9	8,181	60.6	II
NYC-2(b)	107.7	6,462	60.0	II
NYC-2(c)	139.5	9912	71.1	II
NYC-2(d)	89.4	6,296	70.4	II

Source: M.A. Myer A & O. Hazra, *Demonstration Assessment of Light-Emitting Diode (LED) Roadway Lighting in New York, NY*, US DOE & Pacific Northwest Laboratory, unpublished report, October 2011.

*Data from NYCDOT (power consumption measured in the field) and from the Philip's brochure on the Ceramalux 150 wattMog ED28 CL Alto lamp (luminaire output).

Here is an overall summary of the trial:

- The FDR Drive is illuminated by 1,200 HPS Philips Ceramalux 150 wattMog ED28 CL Alto lamps operating 4,100 hours annually;
- The pole height is 30 feet;
- The distance between poles is 160 feet;
- Total annual electricity use for the FDR Drive pole mounted luminaires is 875,760 kWh, which costs \$151,364 annually at 15¢ per kWh, and emits 454 tonnes of CO₂ annually (2009);
- Total annual maintenance costs are approximately \$53 per luminaire for a total of \$63,600 annually (2009), which breaks down as follows:
 - a. \$36,000 for lamp replacement and routine maintenance,
 - b. \$27,600 to close down the FDR Drive for periods of maintenance.
- The NYCDOT follows the Illuminating Engineering Society of North America's (IESNA) RP-8-00 guidance for illuminance for major roads with medium pedestrian conflict, which for FDR Drive (Class A) is as follows: 0.9 foot candles or 9.0 lux average and a uniformity ratio of 3.0 (L_{avg}/L_{min}), to be maintained over the lifetime of the lighting system.

The study area was selected because this stretch of the FDR Drive is relatively straight and long enough to accommodate the four LED luminaire products, as well as a baseline group. Ambient lighting conditions for the trial were good. There appeared to be minimal trespass light coming from nearby buildings, comprising mostly an apartment complex on the west side of the expressway. On the east side of the expressway there is only the river. Although there was some minor spillage of light into the study area from HPS lamps mounted on poles at street level—this section of the FDR Drive is elevated—this was deemed not to materially affect illuminance readings on the roadway.

There were several challenges associated with the trial. For instance, during the spring 2010, a torrential rainstorm accompanied by heavy winds caused a luminaire to fail. The manufacturer expeditiously replaced the luminaire, but gaps in the measurement data exist for that one product.

The Monitoring Protocol and Methodology

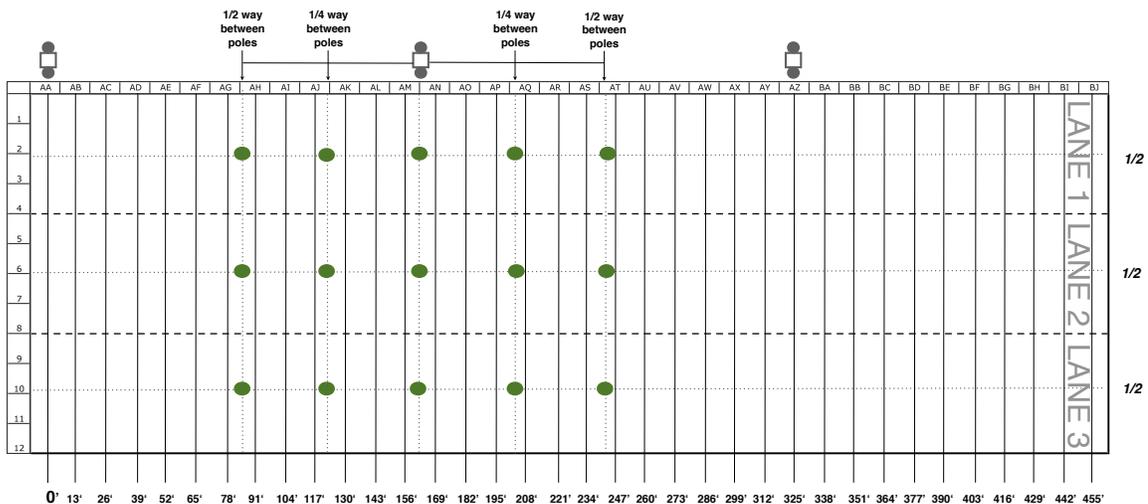
The objective of the trial was to conduct a product evaluation of four LED luminaires in realistic field conditions **over time**. The trial aimed to determine the effects of environment—weather, seasonal changes, dust, grime, etc.—over a period of a year or more on the selected LED luminaire products in real-world conditions, in comparison to the incumbent HPS luminaires now in use on the FDR Drive. In addition, the trial sought to quantify energy savings and potential carbon dioxide emissions reductions with replacement for FDR Drive’s 1,200 luminaires with LED luminaires, as well as calculate financial metrics associated with investment of such a program. NYCDOT staff adopted the following LightSavers protocol in implementing the trial.

1. **Installation.** Five groups containing three consecutive single poles with two arms each were retrofit with four LED luminaire products and a fifth set of new Philips HPS lamps as per normal maintenance procedures.
2. **Burn in period and measurements.** The baseline lamps and LED luminaires were “burned in” for a minimum of 100 hours. For the purpose of this report, the first set of measurements were recorded in August 2009 after the “burn in” period. A second set of measurements was taken in October 2010, a third set in January 2010, and then monthly up until November 2010, for a total of 16 months. The following initial set of measurements were taken for each group of luminaires, baseline and LED:
 - a) Apparent power (VA),
 - b) Photopic illuminance,
 - c) Scotopic illuminance,
 - d) Scotopic/photopic ratio,
 - e) Correlated color temperature (CCT),
 - f) Ambient temperature.

The monitoring team noted date, time, weather, and site conditions when they took measurements.

- Power measurements.** Spot measurements of the baseline group and the LED luminaire group(s) luminaires were taken for voltage and amperage, from which apparent power was calculated. Power factor measurements were not taken. The US DOE also measured power consumption of the LED luminaires in a laboratory test at the end of the trial period and have generously contributed their unpublished data for use in this report. Hence, the US DOE's measured lab values are used in this report, rather than the NYCDOT's field measurements, since they are more accurate. (Lab measurement equipment is inherently more precise than field equipment.)
- Sampling grid.** Figure 1 below shows the sampling grid was selected for this trial, centered on the middle pole in each luminaire product group. This approach was taken to minimize potential spillage of light from the HPS luminaires that separated each LED product group from one another. The sampling points in Lane 3 were eventually dropped, due to the difficulty of shutting down the entire roadway over one evening.

FIGURE 1: NYCDOT FDR Drive trial illuminance sampling grid



- Illuminance measurements.** Both photopic and scotopic illuminance readings were taken on the road surface using the Solar Light SL-3101 radiometer, equipped with photopic and scotopic detectors that follow CIE spectral luminous

efficiency curves. The equipment was calibrated to the National Institute of Standards and Technology (NIST) and has an accuracy of ± 5 percent according to the manufacturer.

6. **Correlated color temperature (CCT).** CCT was measured using the Konica Minolta CL-200 Chroma Meter at the beginning of the trial. A second set of CCT readings was taken in December 2010. The meter has an accuracy of ± 2 percent according to the manufacturer.
7. **Ambient temperature.** Ambient temperature measurements were taken with a Blackberry.
8. **Periodic testing.** After the initial set of baseline measurements were taken and recorded, illuminance (photopic and scotopic) and ambient temperature readings were taken at random monthly intervals over a period of 12 months in Lanes 1 and 2—the monitoring session did not allow enough time in the evening to take readings in Lane 3. Over the course of this period a total of approximately 390 measurements were recorded for each luminaire product, excepting the baseline, for which 330 measurements were taken and NYC-2(d), for which 330 measurements were taken—two months were missed when a defective luminaire was replaced after the rainstorm noted above.
8. **Dirt depreciation test.** In order to assess the impact of luminaire dirt depreciation (LDD) on lumen maintenance, the NYCDOT provided the US DOE with one of each of the LED products, which were tested before and after cleaning at a qualified laboratory in the summer 2011. The US DOE generously allowed us to use their unpublished data in this report. Results are reported below.
9. **Lumen maintenance.** LED streetlight luminaire manufacturers claim their products will typically maintain lumen output at 70 percent or above (L_{70}) their original output for 50,000 hours or more. Indeed, the five LED luminaire manufacturers in this trial claimed lifetimes ranging from 50,000 - 75,000 hours for their products. It is challenging to evaluate such claims in a real world trial. The IESNA TM-21 Working Group, during the recent course of its evaluation of 40 sets of laboratory data on LED light source lumen maintenance over 6,000 hours or more, concluded that lumen depreciation can change in various ways that are difficult to model or predict, especially during the first 1,000 hours of operation when rapid variations have been observed.¹ Ideally, in order to have predictive value, a field trial should be 10,000 hours or more, i.e., three years, with the last 5,000 hours yielding the most consistent and reliable information. While ideal, such a trial is not practicable in a municipal context given limited resources, as well as the need to make procurement decisions in a shorter time frame. In this trial, data was collected approximately monthly over a period of 16 months, or 5,466 hours.

¹ IESNA, *Projecting Long Term Lumen Maintenance of LED Light Sources*, TM-21-11, August 2011.

The lumen maintenance results from the trial provide a useful snapshot of how the five LED products performed relative to each other during this period. However, the results should not be used to predict how these products will perform in the future.

The US DOE conducted a single set of measurements at the FDR trial site on the evening of August 3, 2009, using a more comprehensive sampling grid based on the recommendations on roadway lighting contained in IESNA LM-50-99 in order to determine compliance of the HPS and LED luminaires with IESNA's recommended roadway lighting standards. Approximately 60 sampling points were measured for each luminaire product. In this report, we use the DOE's illuminance results for a snapshot of relative comparative performance of the products, while we use the NYC DOT's 15-month measurements to provide a snapshot of lumen maintenance over that period of time.

Results

Illuminance comparisons

The results reported below are excerpted from the US DOE's report on this trial.² Key purposes of illuminance measurements are to:

- Compare the illumination performance LED products with each other and with the baseline HPS lamp;
- Determine whether the luminaires surveyed comply with recommended values for the relevant different road type in IESNA's RP-8-00, *Roadway Lighting: American National Standard Practice for Roadway Lighting*, to which NYCDOT adheres.

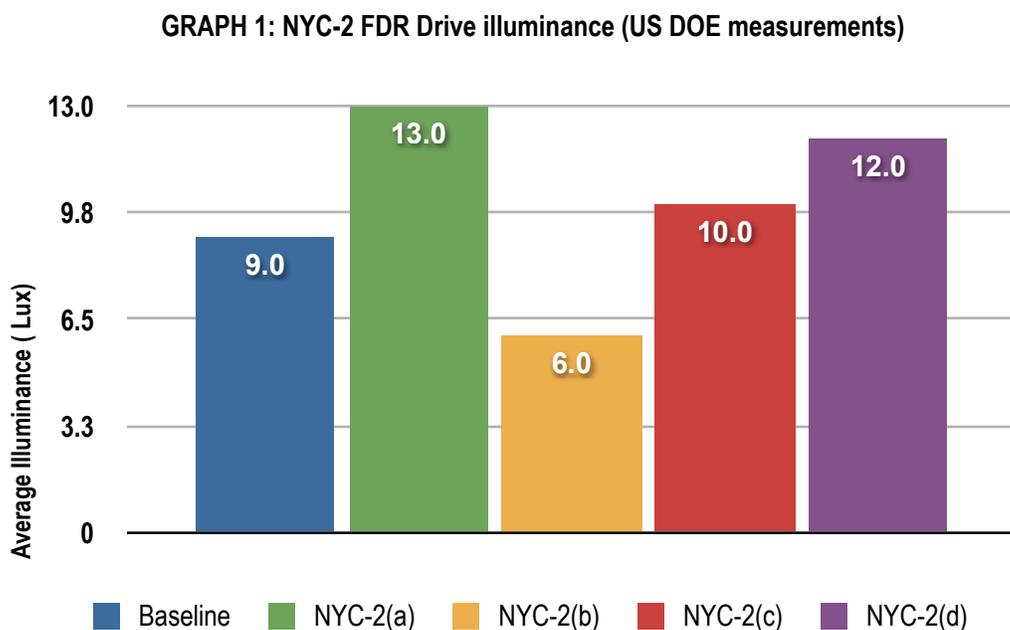
The FDR Drive falls into Freeway Class A, for which recommends 0.9 foot-candles (fc) or 9.0 lux as the average maintained illuminance value over the lifetime of the luminaire. A maximum uniformity ratio of 3.0:1 (average to minimum illuminance) is also recommended.

Graph 1 below shows that three LED luminaires, NYC-2(a), NYC-2(c), and NYC-2(d) exceeded the average illuminance produced by the HPS luminaire and complied initially with RP-8-00. According to US DOE's measurements, none of the luminaires, including the HPS lamp, complied with the IESNA recommended uniformity ratio of 3.0:1, reflecting perhaps the challenging spatial demands of the site. The HPS luminaire came with

² M.A. Myer and O. Hazra, *Demonstration Assessment of Light-Emitting Diode (LED) Roadway Lighting—Host Site: FDR Drive, New York, New York*, US DOE & Pacific Northwest Laboratory, December 2011.

three percent of the recommended value (3.1:1), and LED luminaires NYC-2(a), NYC-2(b), and NYC-2(d) came within 13 percent (3.4:1) of the recommended value.

The end of lifetime of a LED luminaire, or L_{70} , is defined by IESNA when its lumen output declines to 70 percent of its initial value.³ Since RP-8-00 recommended values are based on their maintenance over the lifetime of the luminaire, it would be expected that 70 percent of the LED average illuminance would be equal to or above 9.0 lux value at the end of its lifetime. Only one LED luminaire, NYC-2(a), would thus comply accordingly, with its end of lifetime average illuminance calculated at 9.1 lux.



Source: Table 2.9, M.A. Myer and O. Hazra, *Demonstration Assessment of Light-Emitting Diode (LED) Roadway Lighting—Host Site: FDR Drive, New York, New York*, US DOE & Pacific Northwest Laboratory, December 2011, page 2.16.

The US DOE report presents additional detailed analysis of illuminance maintenance relative to RP-8-00 and includes discussions of NYCDOT’s calculated illuminance values of the four LED luminaires, as compared with the respective values measured by US DOE.

³ IESNA, *Measuring Lumen Maintenance of LED Light Sources*, LM-80-08.

Correlated color temperature (CCT)

Changes in color temperature of the illumination produced by LED luminaires over time may indicate a number of problems stemming from degradation of the components of the LED device, especially the materials that encapsulate and cover the LED diode.

As the Table 2 below indicates, differences in measured CCT ratings for each product when compared with its manufactured nominal rating ranged from 2.6 percent for NYC-2(d) to as much as 32 percent for NYC-2(a). Hence, the nominal CCT ratings may have been misstated by several manufacturers in their product literature. However, there was very little change in CCT over the 15 months in either the baseline or LED devices in all four of the FDR Drive LED luminaires, an excellent result. Note that the measured results are less than the ± 2 percent accuracy of the meter, so it is difficult to ascertain if the measured changes are due to the LEDs or meter error.

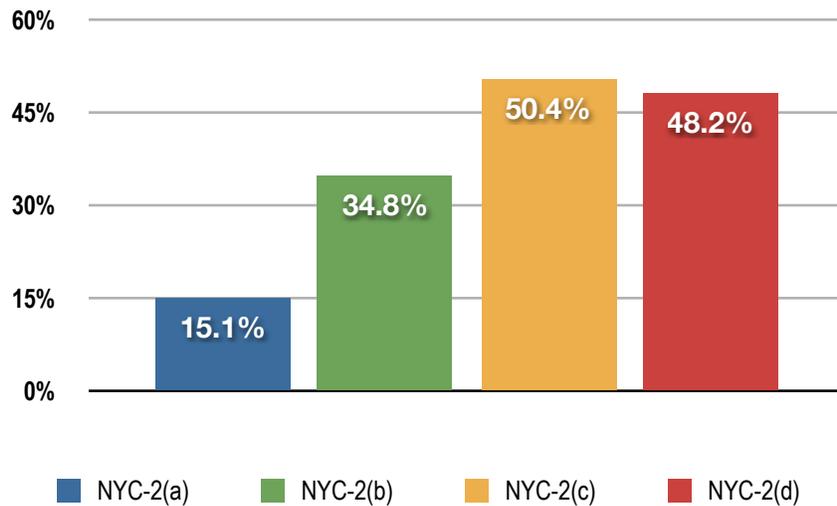
TABLE 2: Summary of color temperature results

Product Reference	Manufacturer's Nominal CCT (Kelvin)	Measured CCT Aug-2009 (Kelvin)	Measured on Aug-2009 vs. Nominal	Measured CCT Nov-2010 (Kelvin)	% Measured Change
Baseline	2100	2780	32.4%	2812	1.15%
NYC-2(a)	6000	6474	7.9%	6456	-0.28%
NYC-2(b)	5000	6039	20.8%	6017	-0.36%
NYC-2(c)	5000	6582	31.6%	6506	-1.15%
NYC-2(d)	5000	4851	-3.0%	4823	-0.58%

Energy savings

As seen in the Graph 2 below, all of the LED luminaires saved energy, measured as apparent power (VA), ranging from 15 percent to 50 percent, with NYC-2(c) reducing electricity consumption from the baseline by the largest amount. The HPS power use was based on NYCDOT's field measurements. Meanwhile, as noted above, the measured LED luminaire power values were based on the US DOE's laboratory measurements. The manufacturer of NYC-2(b) states that the end of life power draw for its product is 30 percent more than at beginning of its life, so the snapshot given here is not indicative of lifetime energy savings for this particular product.

GRAPH 2: LED energy savings from baseline HPS



Note: The energy savings reported from laboratory measurements for NYC-2(c) are not consistent with the nominal power rating derived from .IES files (see Table 1). This is likely due to incorrect .IES files being provided by the manufacturer.

Luminaire site-specific system effectiveness

A key advantage that LED luminaires hold over conventional HID luminaires is that the light they produce is more directional. Thus, more of the light produced by the LED luminaire is directed to the surface where it is needed. However, there does not currently exist a standard lighting metric for measuring how effective luminaires are projecting light on a specific surface in a field trial.

We propose a “site-specific system effectiveness” metric that is calculated for each LED luminaire simply by dividing its average photopic illuminance measured on a sampling grid by its apparent power value. The calculated value of lumens per watt is then indexed to the comparable baseline value, which is normalized to the value 1.0. This metric does not take into account uniformity.

Ascertaining how much apparent power it takes for a luminaire to deliver its light to a surface grid compared with a baseline product can assist lighting asset managers in understanding the directional effectiveness of different LED luminaire products at illuminating a surface, compared with conventional lamps such that rely more on luminaire lens optics to direct and shape their light output. The figures below characterize this metric and compares the LED luminaires to the baseline.

FIGURE 2: System on-site effectiveness indexed to the baseline HPS lamp (normalized value = 1.0 lumen/watt)

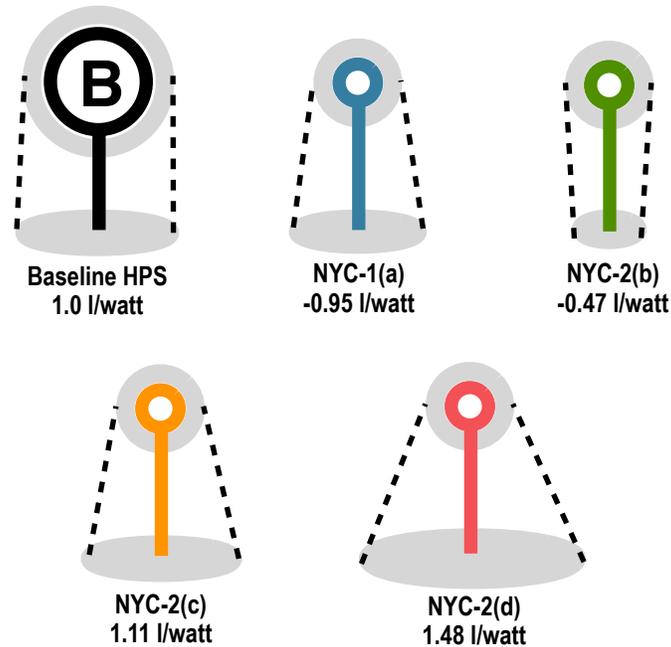


Figure 2 above shows that LED luminaire NYC-2(a) is equivalent to the HPS luminaire at directing light to the road surface. Meanwhile, NYC-2(c) is 11 percent more efficient, and NYC-2(d) is 48 percent more efficient at directing light to the road surface than the baseline HPS luminaire. LED luminaire NYC-2(b) is about half as efficient as the HPS baseline. The relatively high on-site system effectiveness of NYC-2(d) helps to explain the ability of this LED luminaire to produce nearly 29 percent more illuminance than the HPS baseline luminaire on the US DOE’s sampling grid, while consuming only half the energy as the HPS luminaire. According to the US DOE report, 84 percent of the light produced by this LED luminaire is expressed as forward light on the road, versus 67 percent for the HPS luminaire, which further helps to explain the comparative optical advantage of this product compared with the other LED products in the trial.

Lumen maintenance

A key purpose of the LightSavers trial was to determine how the LED luminaires performed over a period of time. For the purposes of this study, lumen maintenance factors affecting LED luminaires can be divided into two groups:

- Factors that can be reversed or recovered through maintenance, such as luminaire cleaning to remove dust and grime from its lens;

- Factors that cannot be reversed or recovered, such as the gradual fading of the LED device's lumen output or dramatic changes in its correlated color temperature (CCT).

In the first category, luminaire dirt depreciation (LDD) is the most significant factor. It results from the accumulation of dust and grime on the luminaire lens over time. This varies significantly from one locale, climate, or season to another. Air pollution is obviously an important variable. Also, an electrostatic charge on the plastic lens of a LED luminaire attracts particles floating in the air. The dryer the environment, the higher the charge and attraction of particles to the lens. Conversely, higher humidity reduces the static charge and particle attraction. Finally, design of the LED luminaire affects dust buildup. Some manufacturers incorporate self-washing features into their luminaire design, so that precipitation removes dust that has adhered to the luminaire lens. The effectiveness of such designs varies significantly from one product to another.

Note that LDD is not linear. Dust buildup on a newly installed luminaire may be rapid at the start, depending on humidity and temperature, and then decline in rate as the amount of dirt on the luminaire lens reaches a level that dampens its static charge.

NYCDOT washed the luminaires being tested, in accordance with the LightSavers trial testing protocol, so it is assumed they were relatively dust free at the start of the trial.⁴ The LightSavers trial protocol also specifies washing the luminaires just before and after the last measurement session, in order to determine a locale-specific LDD for the trial.

Fortunately, the US DOE GATEWAY program offered to test the FDR LED trial luminaires in a laboratory, so NYCDOT staff removed them from the field in March 2011 and provided them to the US DOE. Its unpublished laboratory test results are shown in Table 3 below.⁵ The total LDD for the four LED luminaires over a 19 month period ranged from 2.3 percent to 5.7 percent, likely reflecting significant differences in design that affected dirt buildup. For comparison, Table 3 below also includes laboratory depreciation tests for four other LED luminaire products removed from US DOE GATEWAY trials in Minneapolis and Oakland.

⁴ The Climate Group, *LightSavers Technology Monitoring Protocol*, Version 1.2, November 12, 2009

⁵ E-mail from Michael Myers, US DOE

TABLE 3: Summary of US DOE dirt depreciation analysis

DOE GATEWAY Trial	Luminaire	Period (Months)	Total LDD Over Period	Annualized LDD
Minneapolis I-35W	No. 1	15	4.6%	3.7%
Minneapolis I-35W	No. 2	15	3.8%	3.0%
Oakland	No. 3	24	10.6%	5.3%
Oakland	No. 4	18	6.3%	4.2%
New York City	NYC-2(a)	19	4.3%	2.7%
New York City	NYC-2(b)	19	2.3%	1.8%
New York City	NYC-2(c)	19	4.0%	2.5%
New York City	NYC-2(d)	19	5.7%	3.6%
Average All Cities		18.5	5.2%	3.4%
Average NYC		19	4.1%	2.7%

Sources: Bruce Kinzey, *LEDs in the Real World*, Panel Presentation at the DOE SSL R&D Workshop 2010, Raleigh, N.C. and M.A. Myer A & O. Hazra, *Demonstration Assessment of Light-Emitting Diode (LED) Roadway Lighting in New York, NY*, US DOE & Pacific Northwest Laboratory, unpublished report, October 2011.

The Municipal Solid-State Street Lighting Consortium’s *Model Specification for LED Roadway Luminaires* recommends using a LDD value of 0.9 or 10 percent depreciation over four years and assumes the luminaires are washed at 4 year intervals.⁶ This LDD factor when annualized is 0.975 or 2.5 percent depreciation annually. This value by coincidence is close to the 2.7 percent average LDD for the four LED products in this trial, as measured by the US DOE GATEWAY lab analysis and shown in Table 3 above.

In the second category of lumen maintenance factors, LED devices, unlike HPS lamps, do not typically burn out. Instead, the light they produce gradually fades over a long period of time in a non-linear fashion. As noted above, the end of lifetime of a LED device occurs when its light output declines to 70 percent of its original output. Since the luminaires on FDR Drive operate 4,100 hours annually, a LED luminaire rated at 50,000 hours of operation would reach L₇₀ at 12 years and two months after its initial start of operation, implying a calculated rate of approximately three percent depreciation *per annum* simply averaged over the lifetime of the product. Note that the manufacturers’

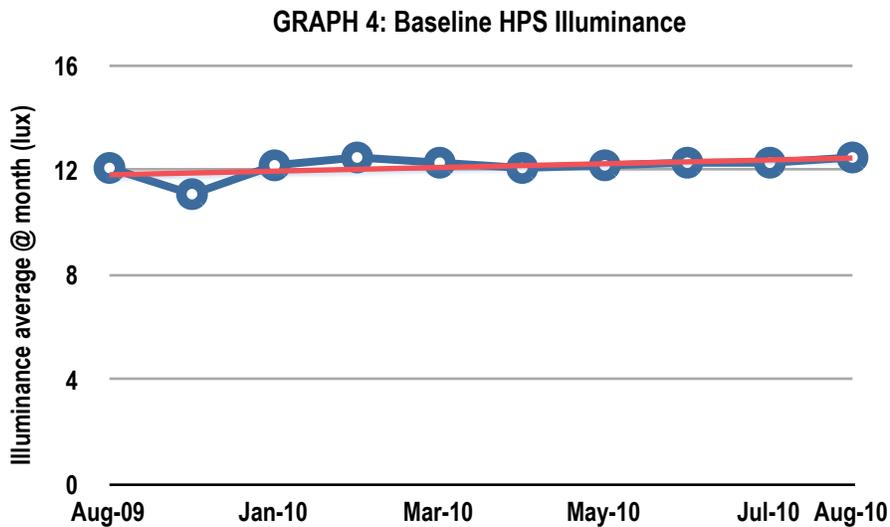
⁶ US DOE Municipal Solid-State Streetlighting Consortium, *Model Specification for LED Roadway Luminaires*, Version 1.0, October 2011.

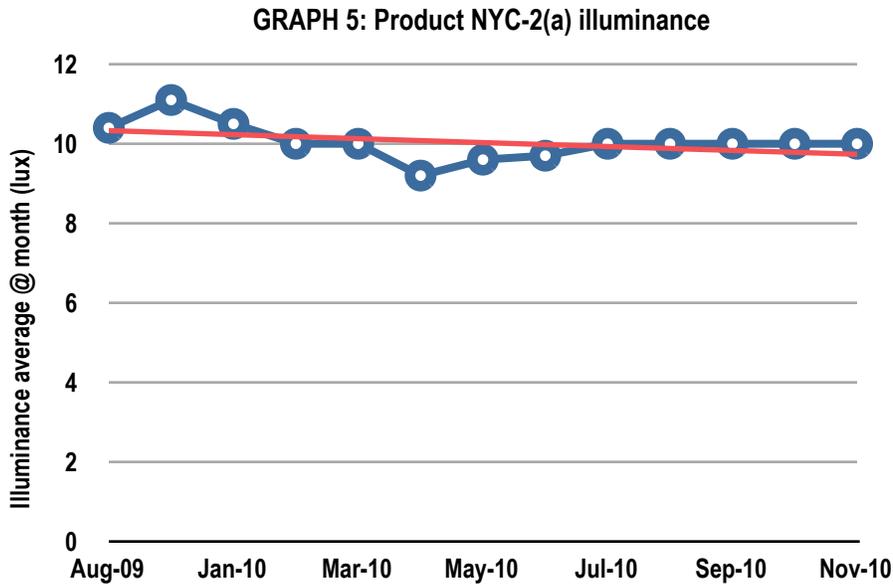
claimed lifetime of LED products in this trial range from 87,000 to 100,000 hours, or a maximum of 24+ years.

For the purpose of easy product comparison in this trial and study, we assume a lifetime of 50,000 hours for all the LED products, notwithstanding manufacturer claims. Thus, lumen depreciation significantly exceeding three percent in the first year of the trial, *net of LDD*, would be less desirable than a value in the range of three percent or less.

It should be noted again, in respect of the IESNA's TM-21 Working Group's recent findings, that the lumen depreciation metric for the first year has no predictive value. However, comparing first-year lumen output performance of multiple products in a trial can offer insights that enable lighting asset managers in a practical way to better differentiate products from one another.

The graphs below show the monthly averaged photopic illuminance values (lux) for each luminaire over a period of 15 months (blue line) subjected to Excel's exponential trendline function (red line), which uses the LOGEST function to generate an exponential least squares fit of the individual observed values to a curved line. (This is the equivalent of performing an Excel LINEST linear least squares fit on the logarithms of the observed values, the slope of the generated straight line equalling the logarithm of the depreciation rate of the exponential fit.) The graphs do not take into account LDD.

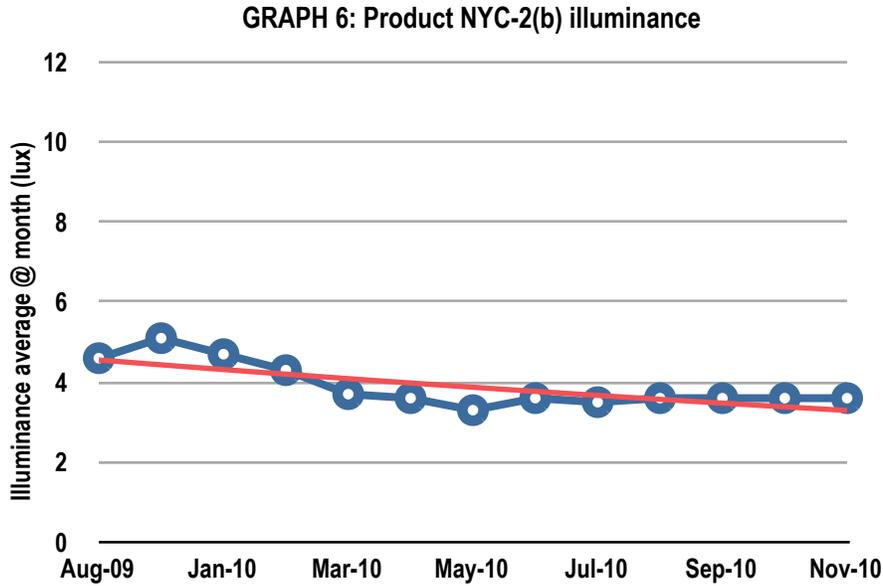




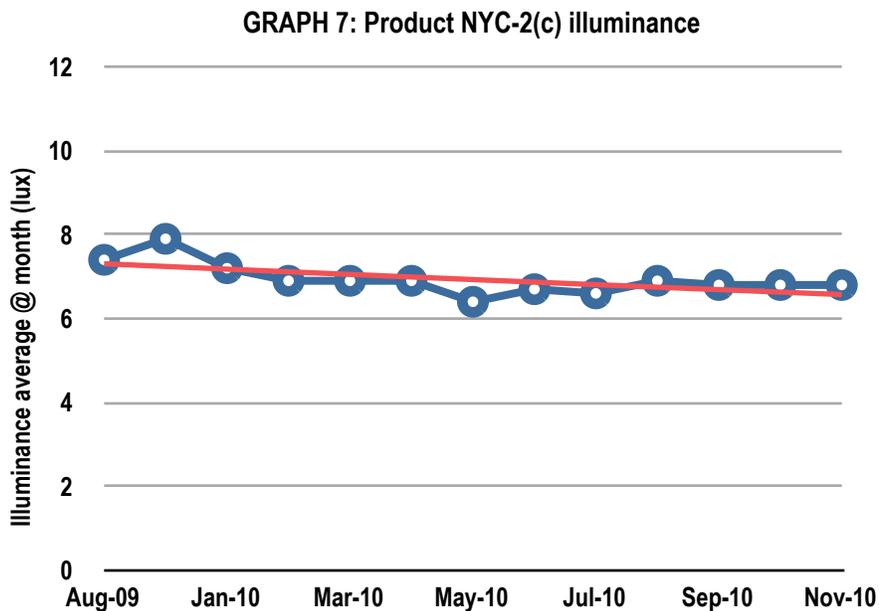
As shown by Graph 4 above, the illuminance produced by the baseline HPS lamps increased by 6.2 percent over the first year. However, it is expected the HPS lamp will burn out after 20,000- 24,000 hours and then be replaced by a new lamp. Given significant long-term experience with HPS products, it is also expected that it will depreciate about 10 - 14 percent over that period of time, before relamping is required.

As shown by Graph 5 above, Product NYC-2(a) exhibited 5.7 percent depreciation in the first year, or three percent net of LDD as measured by the US DOE GATEWAY in a laboratory. During the hot months of July and August, 2010, no decline in illuminance was observed.

As shown by Graph 6 below, Product NYC-2(b) exhibited the most depreciation, with 25.1 percent depreciation in the first year, or 23.3 percent net of LDD as measured by the US DOE GATEWAY in a laboratory. Note, however, that after an initial period of high volatility, lumen output stabilized after the first six months of the trial, so over time this product's lumen output may exhibit much lower depreciation than indicated here. During the hot months of July and August, 2010, no decline in illuminance was observed.



As shown by Graph 7 below, product NYC-2(c) exhibited 9.5 percent depreciation in the first year, or seven percent net of LDD as measured by the US DOE GATEWAY in a laboratory. During the hot months of July and August, 2010, no decline in illuminance was observed.



As shown by Graph 8 below, Product NYC-2(d) exhibited 7.4 percent depreciation in the first year, or 3.8 percent net of LDD as measured by the US DOE GATEWAY in a labo-

ratory. Note that measurements were not taken during June and July, after a torrential rainstorm and heavy winds damaged a luminaire, which took several months to replace. Given the gap in measurements and the fact that a new luminaire was installed towards the last quarter of the monitoring period, it is suggested that the lumen maintenance analysis for this product be interpreted with additional caution

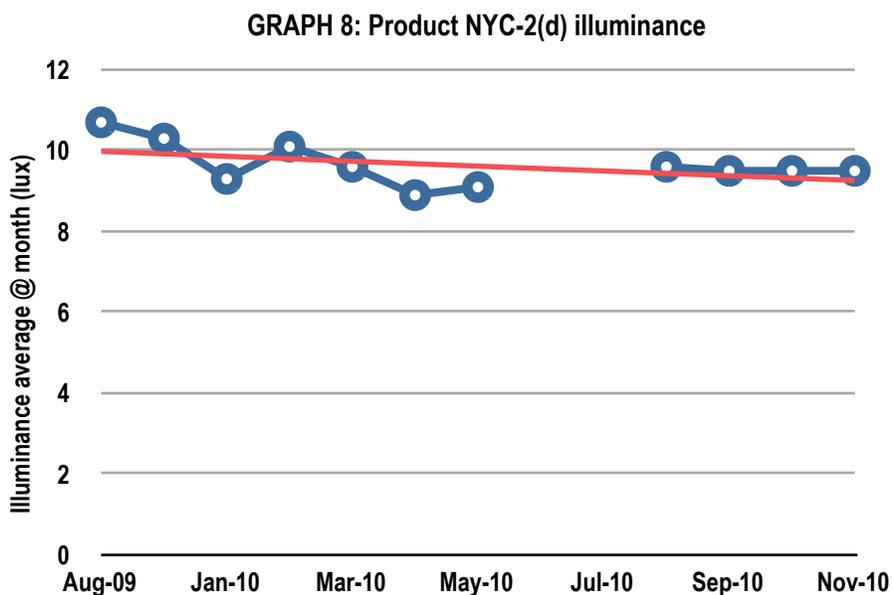


Table 4 below summarizes the information displayed in the above lumen maintenance graphs. One of the four LED luminaires falls into the desirable range of three percent or less lumen depreciation in the first year.

TABLE 4: Summary of annualized lumen maintenance results

Trial Reference	First Year Exponential Trendline* (Excel)	Field Lamp Lumen Depreciation (LLD*)	Laboratory Luminaire Dirt Depreciation (LDD)	Net LLD One Year	Net Lumen Depreciation First Year
Baseline	+6.2 percent	1.062	n.a.	1.062	+6.2%
NYC-2(a)	-5.7 percent	0.943	0.973	0.970	-3.0%
NYC-2(b)	-25.1 percent	0.749	0.982	0.767	-23.3%
NYC-2(c)	-9.5 percent	0.905	0.975	0.930	-7.0%
NYC-2(d)	-7.4 percent	0.926	0.964	0.962	-3.8%

*The LLD is calculated from the figures in the first year exponential trend column.

All of the luminaires, baseline HPS luminaire included, exhibited considerable volatility in lumen output during the early months of the trial, confirming recent findings by the IESNA's TM-21 Working Group. In the case of the LED products, this may be due to factors such as curing of the phosphors and the encapsulate that encase the LED diodes, as well as multiple other factors. Hence, a reanalysis for each product was conducted that omits data collected during the the first five months or 1,700 hours or three months of data. (NYCDOT did not collect data in September 2009, November 2009, and December 2009— months two, four, and five.) Hence, the Excel exponential trendline function was applied to data from the consecutive months of January 2010 to November 2010. Table 5 below provides the results, with the US DOE's LDD factors applied as well to yield 11 months of net lumen depreciation.

This reanalysis is shown in Table 5 below. Omitting the first 1,700 hours of trial data, it shows that three of the four LED luminaires fall into the more desirable lumen maintenance range of three percent or less depreciation in the first year. Indeed, lumen output increased from all three luminaires for the last 4,250 hours of the trial.

TABLE 5: Summary of annualized lumen maintenance results omitting first 1,000 hours

Trial Reference	First Year Exponential Trendline* (Excel)	Field Lamp Lumen Depreciation (LLD)	Laboratory Luminaire Dirt Depreciation (LDD)	Net LLD One Year	Net Lumen Depreciation First Year
Baseline	+1.0 percent	1.01	n.a.	1.010	+1.0%
NYC-2(a)	-0.4 percent	0.996	0.973	1.023	+2.3%
NYC-2(b)	-20.4 percent	0.796	0.982	0.810	-19.0%
NYC-2(c)	-3.8 percent	0.962	0.975	1.002	+0.02%
NYC-2(d)	-0.2 percent	0.998	0.964	1.035	+3.6%

**Note: Data is based on the last 12 months of the trial, with the first three months of data omitted from this calculation.*

One product exhibited a 19 percent decline in lumen output, January 2010 - November 2010. However, it should be noted that during the second half of the trial, illuminance stabilized from this product, which showed only 2.7% decline in lumen output from March 2010 - November 2010 (LDD not factored). The significant volatility of this product during the first 2,000 hours of the trial is perhaps indicative of the unpredictable be-

havior of LED light sources early in their lifetime. Hence, the above analysis should not be used to predict long-term performance of any of these products.

Finally, ambient temperature measurements were also taken in the FDR study by the NYCDOT monitoring team at the same time that they made illuminance measurements in the trial. The intent was to ascertain whether changes in illuminance recorded might correlate with changes in ambient temperature. Since LED devices are very sensitive to temperature, some reduction in output on hot summer days might be expected. Also, if a LED luminaire’s lumen output were to vary with ambient temperature, this might indicate that the thermal management system in the luminaire is not well designed to dissipate heat and protect the LED devices.

In the foregoing analysis, no correlation was observed between the higher summer temperatures recorded in July and August (in the range of 25°C) and lower lumen output from the LED luminaire products.

Summary Product Assessment

Table 6 below summarizes the results of the product evaluation. Three products achieved 16 stars or better out of a possible 18 in performance: NYC-2(a), NYC-2(c), and NYC-2(d), though as noted earlier the lumen maintenance information for NYC-2(d) should be interpreted with caution due to the replacement of a luminaire towards the end of the trial. Note that due to the unpredictability of lumen maintenance performance during the initial months of the trial, we have omitted an assessment of that parameter from the table.

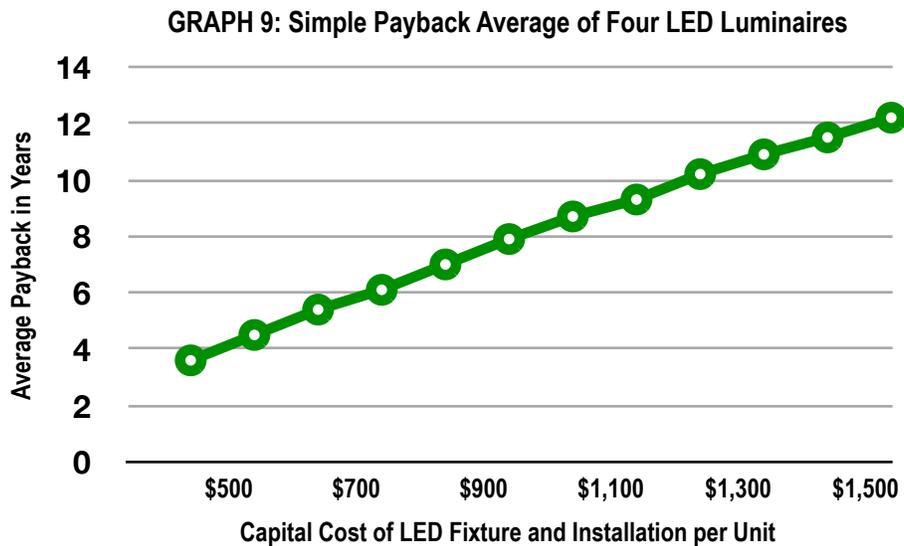
TABLE 6: Summary Product Evaluation

Trial Ref.	Illuminance Exceeds Baseline	Illuminance Initially Meets RP-8-00	Illuminance Maintained to Meet RP-8-00	Energy Savings	Luminaire Site-Specific System Effectiveness	Color Temp Change After 1 Year	Total Stars (18 maximum)
NYC-2(a)	***	***	***	**	**	***	16
NYC-2(b)	*	*	*	***	*	***	10
NYC-2(c)	***	***	*	***	***	***	16
NYC-2(d)	***	***	**	***	***	***	17

Economic payback

Graph 9 below shows the simple payback for all four LED luminaire products averaged together up to 12 years and \$1,500 capital expenditure per unit. The analysis shows that at a capital expenditure of approximately \$800 per unit, for example, a LED replacement program on FDR Drive would pay back in 5.4 years. Here is a summary of the assumptions underlying the analysis:

- Total annual electricity costs of \$151,364 for 1,200 luminaires,
- Electricity cost of \$0.15/kWh (2009), with an annual inflation rate of 3 percent, which results in \$0.16.kWh in 2011,
- Energy savings as indicated by Graph 2,
- Annual maintenance costs of \$63,600 or \$53 /luminaire, no annual inflation,
- Cost savings calculations are based on energy savings data collected by the US DOE in a laboratory using scientific equipment with low error tolerances.



Here are some caveats. The possible cost of replacing the LED device driver is not factored into the analysis. Further, the analysis does not include potential borrowing costs that the NYCDOT might incur to raise capital on its own for a retrofit.

Table 7 below gives a breakdown of cost each LED fixture plus installation to meet a five-year simple payback threshold, the limit required to meet criteria for NYC’s internal energy efficiency fund.

TABLE 7: Summary Product Evaluation

Trial Ref.	Total capital cost to meet 5 year payback
NYC-2(a)	\$440
NYC-2(b)	\$540
NYC-2(c)	\$580
NYC-2(d)	\$590

Capital costs would likely be lowered if a potential tender were to encompass a larger volume of LED replacements on other roadways similar to the FDR Drive, such as the Brooklyn Queens Expressway and Harlem River Drive. This was confirmed when we surveyed the manufacturers to determine the potential price of new LED luminaires equivalent to those provided in the trial. One manufacturer replied, indicating that their product could be provided in the range of \$600/kilo-lumen in “volume”, meaning in the range of 5,000 units. For this particular product, the current price would be approximately \$377, given its lumen output rating in this trial. This product would fall into the range noted in Table 8, with installation costs added.

According to TrendForce, Inc., high brightness white LED package prices have declined 54 percent globally over the past two years.⁷ It is expected that over the next year prices will continue to decline and will be reflected in rapidly declining LED luminaire prices. Clearly, NYC DOT would have some leverage in reducing prices offered in a tender situation if it commits to a staged plan of replacing all or most of its urban roadway HPS luminaires.

Summary

For the period August 2009 - December 2010, the FDR LED LightSavers trial has yielded valuable data that has enabled a useful comparative evaluation of the performance of four LED products. However, the information presented in the report should be interpreted keeping in mind the usual caveats that may affect field trials, such as error uncertainties associated with measurement equipment or environmental variables at the

⁷ See: www.ledinside.com for more information.

trial site from one month to another. However, it is expected that the voluminous amount of data collected by NYCDOT staff over 15 months, reinforced by the field illuminance and laboratory energy data generously provided by US DOE staff, should ameliorate these uncertainties. Here is a summary of the trial results to date, combining measured values from both the NYCDOT and US DOE efforts:

1. **Illuminance.** Three LED luminaires, NYC-2(a), NYC-2(c), and NYC-2(d) exceeded the average illuminance produced by the HPS luminaire and complied initially with IESNA RP-8-00. According to US DOE's measurements, none of the luminaires, including the HPS lamp, complied with the IESNA recommended uniformity ratio of 3.0:1, reflecting perhaps the challenging spatial demands of the site. The HPS luminaire came with three percent of the recommended value (3.1:1), and LED luminaires NYC-2(a), NYC-2(b), and NYC-2(d) came within 13 percent (3.4:1) of the recommended value.
2. **Correlated color temperature (CCT).** Differences in measured CCT ratings for each product when compared with its manufactured nominal rating ranged from -3.0 percent for NYC-2(d) to as much as 32 percent for NYC-2(c). The nominal CCT ratings may have been misstated by several manufacturers in their product literature. However, there was very little change in CCT over the 15 months in either the baseline or all four of the FDR LED luminaires.
3. **Energy.** All of the LED luminaires saved energy ranging from 15 percent to 50 percent, with NYC-2(c) and NYC-2(d) reducing electricity consumption from the baseline by the largest amount. The HPS power use was based on NYCDOT's field measurements and documentation. Meanwhile, as noted above, the measured LED luminaire power values were based on the US DOE's laboratory measurements.
4. **Lumen maintenance.** The lumen output of three of the LED luminaires appreciated during the last 11 months or 3,800 hours of the trial, net of dirt depreciation as measured in the laboratory by the US DOE. The fourth LED luminaire depreciated by 19 percent over the same period, but it should be noted that its light output stabilized considerably during the last eight months of the trial, albeit at a level significantly below its initial lumen output. These results should not be used to predict the future performance of these products. However, they do indicate that after an initial period of volatility of the LED light source due to various factors, lumen output appears to stabilize. A trial lasting three years or 10,000 hours would be needed to yield data that could be used for predictive purposes, in accordance with IES TM-21.
5. **Economic payback.** The simple payback for all four LED luminaire products was averaged together up to 12 years and \$1,500 capital expenditure per unit. The analysis shows that at a capital expenditure of approximately \$600 per unit, for example, a LED replacement program on FDR Drive would pay back in 5.4 years.

Since there is a five-year payback limit for energy efficiency investments, the capital cost plus installation of the four LED luminaires would need to fall between \$440 and \$590 per unit in order to meet this criterion. One manufacturer quoted a price of \$600/kilo-lumen or \$377 for a LED luminaire product equivalent to the one in the trial, if purchased in volume. Hence, it appears there is commercial product currently available that would meet the City's economic payback criterion at this time.

In conclusion, the trial evaluation yielded three LED luminaires, NYC-2(a), NYC-2(c), and NYC-2(d), that performed very well with respect to a range of performance parameters in comparison with the baseline HPS luminaire, scoring 16 out of a possible 18 points in the evaluation. Meanwhile, the economics of a LED replacement program would likely meet the City's energy efficiency investment criteria, if the tender process were to aim to aggregate most or all of the urban highway lighting assets to create enough volume to reduce prices.