Lighting Research Center

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Mesopic Street Lighting Demonstration and Evaluation Final Report

for
Groton Utilities
Groton, Connecticut

Prepared by

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Executive Summary

Can a white light source tuned to how humans see at night under low light levels—one with lower wattage and photopic light output—replace a high-pressure sodium (HPS) street lighting system and still provide equal or greater perceptions of visibility, safety, and security? If so, when and where should this lighting system be used? The Lighting Research Center (LRC) conducted research with funding from Groton Utilities that investigated these questions in the context of two installations within the City of Groton, Connecticut. One installation on Meridian Street replaced 100-watt HPS cutoff cobra head street lights with 55-watt induction (electrodeless) lamps and cutoff, cobra head fixtures. A second installation on Shennecossett Road examined the replacement of 100-watt HPS lights with 70-watt ceramic metal halide, cutoff, cobra head street lights. In both installations, the replacement white light sources (induction and ceramic metal halide) were tuned to optimize human vision under low light levels while remaining in the white light spectrum.

The human vision system has two types of receptors in the retina, cones and rods, to transmit visual signals to the brain. The current system of photometry to determine the amount of light needed to perform a task, regardless of the time of day or lighting

conditions, is based on how the eye's cones function. Cones are the dominant visual receptor under photopic (daylight) lighting conditions. Rods function primarily under dark (scotopic) conditions. Under mesopic lighting conditions, which are typically found outdoors at night, a combination of cones and rods perform the vision function. Therefore, outdoor electric light sources that are tuned to how humans see under mesopic lighting conditions can be used to reduce the luminance of the road surface while providing the same or better visibility. This light source must account for how both the cones and rods in the eye see. Light sources with shorter wavelengths, which produce a "cooler" (more blue and green) light, are needed to produce better mesopic vision.[1,2] Based on this understanding, the LRC developed a means of predicting visual performance under low light conditions. This system is called the unified photometry system.[3]

The LRC developed the unified photometry system based on a series of laboratory studies.[4,5] Simulated driving studies verified the validity of the fundamental findings predicted by the unified photometry system.[6,7] but demonstrated that off-axis detection was strongly affected by other visual factors such as target contrast and size. In effect, adopting lighting systems based upon the unified system of photometry would improve visual performance *more* than would be predicted by changes in spectrum and light level alone. A recent field study to examine target detection by subjects driving along a closed track found that targets illuminated by metal halide lamps can be more quickly detected by the subjects than those made visible by HPS lamps.[2] The results from the range of studies conducted to date dramatically underscore the benefits of the unified photometry system for improving visual performance and reducing energy consumption.[8]

Two different lighting technologies were tested during the Groton research on two segments of different roadways. These technologies were selected based on their commercial availability or the ability to commercialize the product, and their ability to reduce energy while maintaining visual performance in accordance with the unified photometry system. The first technology was a 55-watt induction lamp and driver with 6500 K correlated color temperature (CCT). At 6500 K CCT, the lamp has a high scotopic-to-photopic (S/P) ratio (2.88) and optimizes mesopic vision while remaining in the white light spectrum. Induction lamps also are good at retaining their lumen output in both hot and cold ambient temperatures. Their lamp life (60,000 hours) is also good and should reduce street light maintenance costs. The second technology utilized was a 70-watt ceramic metal halide lamp at 4000 K CCT. The S/P ratio is 1.6 and lamp life is 20,000 hours. In both cases, the S/P ratios of the lamps chosen are much higher than that of the HPS lamp with a 0.63 S/P ratio. Based on the unified photometry system, the wattage for both the induction lamp and the metal halide lamp could be less than the HPS system while providing similar visual performance.

Responses to surveys conducted before the installation of the new light sources and after the installations revealed that area residents perceived higher levels of visibility, safety, security, brightness, and color rendering as both drivers and pedestrians with the new lighting systems than with the standard HPS systems. The new lighting systems used

30% to 50% less energy than the HPS systems. These positive results were achieved through tuning the light source to optimize mesopic vision. Using less wattage and photopic illuminance also reduces the reflectance of the light off the road surface. Light reflectance is a major contributor to light pollution (sky glow).[23]

The findings of the research conducted in Groton concur with similar research conducted by the LRC in Easthampton, Massachusetts, and in Austin, Texas, and with research conducted by Fotios et al. in England.[14] This body of research found that drivers and pedestrians perceived they could see better and felt safer with light sources tuned toward the needs of mesopic vision.

Economic analyses were conducted to determine if either the induction or ceramic metal halide street light systems could cost effectively replace the existing HPS street lighting. In the simple payback analysis, the induction lamp has long payback periods of 7.1 years for new installations and 13.9 years for retrofitting existing HPS installations. The ceramic metal halide street lighting provides negative benefits, and therefore produces an infinite negative return primarily because of higher maintenance costs. Utilities normally consider annualized ownership and operating economic analysis to be more appropriate. This type of analysis is similar to how electric rates are set. The annual utility ownership and operating costs for the induction street lighting system is $22.20 less than the 100-watt HPS street lighting it could replace. Similarly, a lifecycle economic analysis shows that the 55-watt induction lamp has a $282.90 savings over its 27-year life compared to the 100-watt HPS. The metal halide street lighting produces negative savings.

Recommendations based on research findings are:

- Efficient white light sources tuned to mesopic vision conditions with high scotopic-to-photopic ratios are recommended as replacements for high-pressure sodium (HPS) street lighting. These light sources should have a correlated color temperature of approximately 6500 K and provide approximately 65 to 70 (photopic) lumens per watt.
- The 55-watt induction street lighting system at 6500 K CCT is an energy-efficient replacement for 100-watt HPS street lighting and should be pursued for new street light installations. It should also be examined as a retrofit for existing 100-watt HPS street lighting.
- The 70-watt ceramic metal halide lighting system is not a good substitution for 100-watt HPS street lighting systems and should not be pursued, primarily because the economics of the metal halide system are poor compared to 100-watt HPS systems.
- White light-emitting diodes (LEDs) should be considered as replacements for HPS street lighting in about three years time when their efficacy is higher and their cost has reached reasonable levels to be economically viable. Groton Utilities may want to consider postponing decisions on street light replacements until white LEDs become economically available.
- The unified photometry system should be used to determine replacement wattages of various size street lights based on lamp S/P ratio and, for new installations, Illuminating Engineering Society of North America (IESNA) recommended

luminance values for the type of street being illuminated. For existing street lighting, measurements of existing luminance values can be calculated by measuring illuminance and roadway surface reflectance. The luminance values can be entered into the unified photometry system to determine appropriate replacement lighting systems that will provide equal visual performance.

Introduction

The LRC conducts research, demonstrations, and evaluations regarding human vision under low light (mesopic) conditions. Mesopic lighting conditions occur at night in areas with lighting such as what is found with many street and area lighting systems. How humans see under this condition is very different than how humans see during the day or in lit buildings (photopic conditions) and how humans see at night in unlit spaces (scotopic conditions).

The human vision system has two types of receptors in the retina, cones and rods, to transmit visual signals to the brain. The current system of photometry to determine the amount of light needed to perform a task, regardless of the time of day or lighting conditions, is based on how the eye's cones function. Cones are the dominant visual receptor under photopic (daylight) lighting conditions. Rods function primarily under dark conditions. Under mesopic lighting conditions, which are typically found outdoors at night, a combination of cones and rods perform the vision function. Therefore, outdoor electric light sources that are tuned to how humans see under mesopic lighting conditions can be used to reduce the luminance of the road surface while providing the same or better visibility. This light source must account for how both the cones and rods in the eye see. Light sources with shorter wavelengths, which produce a "cooler" (more blue and green) light, are needed to produce better mesopic vision.[1,2] Based on this understanding, the LRC developed a means of predicting visibility under low light conditions through comparing luminance levels and a lamp's scotopic-to-photopic spectral ratio. This system is called the unified photometry system.[3] It predicts degrees of visual performance and not perceptions of brightness. Perceptions of brightness are more associated with perceptions of one's safety and security.

Current photometry underestimates the effectiveness of lamps with relatively more short-wavelength output at mesopic light levels. The unified photometry system can more appropriately evaluate the effectiveness of lamps with various spectral power distributions (SPD) by providing "unified" luminance according to the light levels to which human eyes adapt.[1,3]

Table 1 shows photopic illuminance and relative electric power required to obtain criterion levels of off-axis visual performance when illuminated by various SPDs. As the light level decreases, the performance of high-pressure sodium (HPS) lamps, relative to other sources, is reduced. Conversely, metal halide (MH) and fluorescent lamps, which have more short-wavelength components, reduce their relative power requirements to meet criterion visual performance levels.

The LRC developed the unified photometry system based on a series of laboratory studies.[4,5] Simulated driving studies verified the validity of the fundamental findings but underscored the fact that light level as well as target contrast and size affect off-axis detection. Therefore, the visual performance differences between MH and HPS lamps can be even larger than would be predicted by the unified photometry system alone.[6,7] A recent field study to examine target detection by subjects driving along a closed track found that targets illuminated by MH lamps can be more quickly detected by the subjects than those made visible by HPS lamps (Akashi and Rea 2002).[2] The results dramatically underscored the benefits of the unified photometry system.[8]

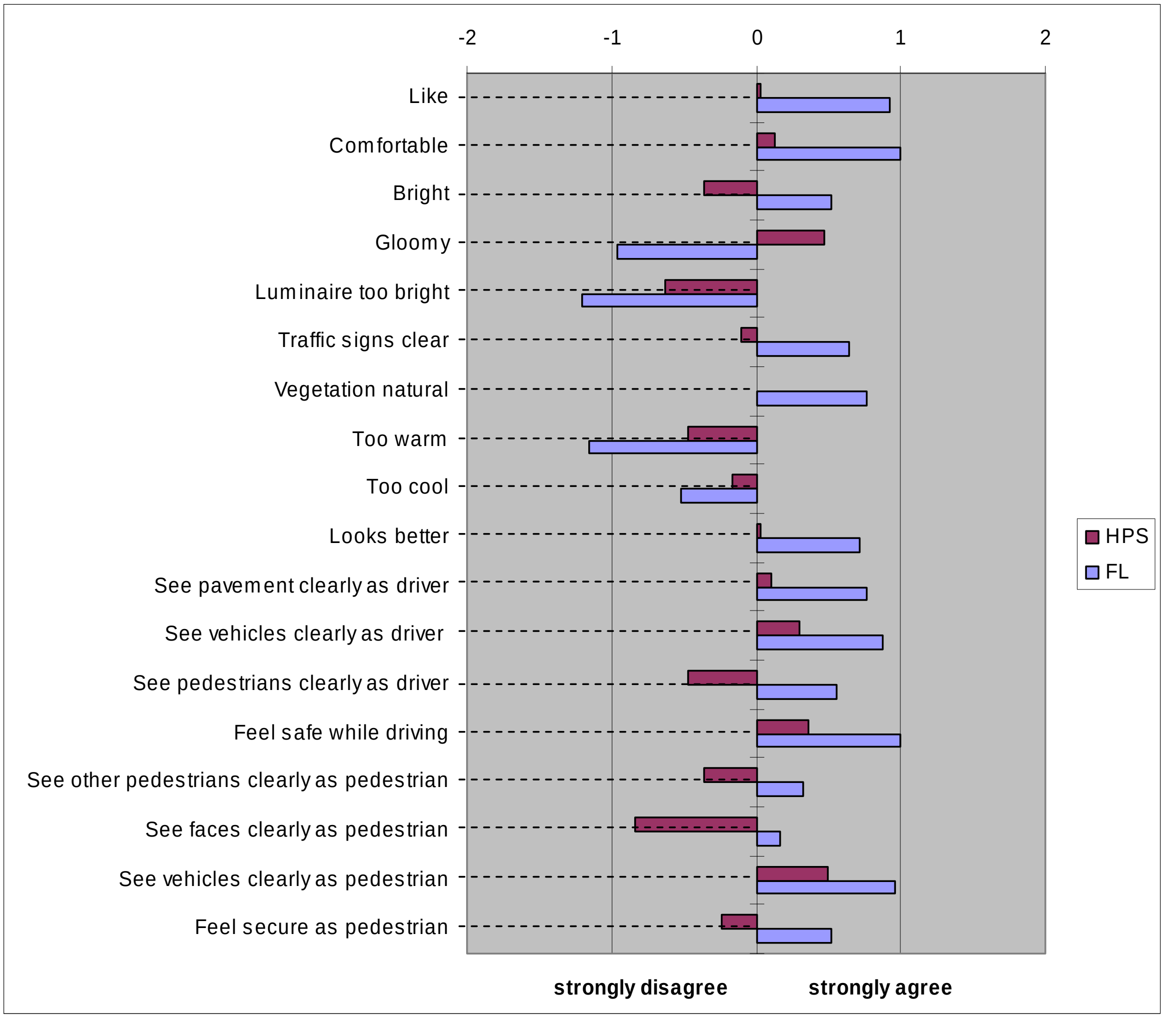
Table 1. Photopic illuminance and relative power required to obtain the same brightness perception and visibility of spaces and objects illuminated by various SPD lamps[8]

Light source	S/P ratio*	0.6 cd/m²		0.3 cd/m²		0.1 cd/m²	
		E (lx)**	Relative power***	E (lx)	Relative power	E(lx)	Relative power
400 W HPS	0.66	26.9	100%	13.5	100%	4.5	100%
1000 W incandescent	4.41	26.9	833%	10.5	648%	2.6	478%
3500 K fluorescent	1.44	26.9	130%	10.4	100%	2.5	73%
400 W MH	1.57	26.9	119%	10.0	88%	2.4	63%
5000 K fluorescent	1.97	26.9	130%	9.0	87%	1.9	57%
6500 K fluorescent	2.19	26.9	130%	8.5	82%	1.8	52%

* S/P ratio: the ratio of scotopic lumens to photopic lumens of each lamp
** E: illuminance measured in lux (lx)
*** Relative power (%) normalized to HPS

To provide further evidence that a light source tuned to how humans see under low light conditions could provide the same or better visibility with lower photopic luminance values, in 2004 the LRC conducted a comparison field study of 70-watt (84 watts with ballast) high-pressure sodium (HPS), semi-cutoff cobra head street light fixtures mounted on utility overhead distribution poles versus 50-watt (54 watts with ballast), 6500 K correlated color temperature (CCT) (a light source tuned to mesopic vision), twin compact fluorescent lamps in a semi-cutoff fixture on a residential street in Easthampton, Massachusetts. The purpose of the experiment was to determine how well the residents saw objects while both driving and walking under the two different lighting conditions. Figure 1 below, which shows residents' responses to survey questions comparing fluorescent and HPS lighting, indicate a strong preference toward the fluorescent lighting for both driving and walking. People said they could see better and felt safer with the fluorescent lighting, which used 30% less energy.[8] The full study is included in Appendix A of this report. These data provided the basis for the LRC to propose a demonstration and evaluation of a mesopically tuned outdoor lighting system to Groton Utilities with the belief that it would have a significant opportunity for success.

Figure 1. Street light comparison results, Easthampton, Massachusetts



Groton Utilities, a municipal electric utility, wished to pursue an evaluation of street lighting that had the potential to reduce energy needs by 30% while maintaining human perceptions of visibility, safety, security, and brightness. To achieve this goal, the utility decided to work with the LRC and its manufacturing partners, Lumec of Montreal, Canada (an outdoor lighting fixture manufacturer), and Philips Lighting (a lamp manufacturer), to demonstrate and evaluate two white light sources designed to reduce energy needs while maintaining visibility. The two white light sources selected were a Philips 55-watt QL induction lamp with a CCT of 6500 K (a white light source optimized for mesopic light conditions) and a Philips 70-watt ceramic metal halide lamp with a CCT of 4000 K (a white light source closer to matching mesopic light condition needs than HPS sources). Lumec provided the cobra head light fixtures with cutoff optics to house these lamps. Parts of two collector-type streets, as defined by the Illuminating Engineering Society of North America (IESNA), were chosen by Groton Utilities as demonstration sites for the two different types of light sources: Meridian Street for the induction lamps and Shennecossett Road for the ceramic metal halide lamps.

Project Goals

The goals of the "Mesopic Street Lighting Demonstration and Evaluation" project were to determine if two white light sources tuned to mesopic conditions could provide similar visibility and human perceptions of safety, security, and brightness as the currently used high-pressure sodium street lighting systems, all the while reducing energy needs by at least 30%. A secondary goal was to determine if mesopically tuned, white light source street lighting systems could be economically deployed within the City of Groton, Connecticut.

Research Methodology

Street Lighting Site Information

Parts of two streets were chosen by Groton Utilities and reviewed by the LRC and its manufacturing partners as sites to demonstrate the induction and ceramic metal halide street lighting systems.

Meridian Street

The Meridian Street neighborhood is a combination of single and multi-family houses with a city-owned park on the south side of the street. It is a two-lane street with parallel parking allowed on both sides. By IESNA standards, it is considered a collector-type road (i.e., side streets empty their traffic onto it and it conveys traffic to larger streets). The roadway is asphalt paved and is approximately 40 feet wide throughout the demonstration section. A concrete sidewalk borders the south side of the street. Because of the higher-than-normal pedestrian traffic generated by park activities, street lights are located on every electric overhead distribution pole and are approximately 120 feet apart. Mounting heights are approximately 25 feet.

Lamp and light fixture information for Meridian Street for both the initial HPS street lighting and for the induction lighting demonstration are listed in Table 2 below. Photographs of the initial HPS and the demonstration induction street light installations are shown in Figures 2 and 3.

Table 2. Street light fixture information (Meridian Street)

	Initial HPS Street Lighting	Induction Demonstration Street Lighting
Lamp Type	HPS	Induction
Lamp Wattage[9]	100 watts (118 watts with ballast)	55 watts including power for driver
CCT[9]	2100 K	6500 K
Mean Lumens[9]	8460	3300*
Lamp Life[9]	30,000 hours non-cycling	60,000 hours
Fixture Type	Cobra Head	Cobra Head
Number of Fixtures	12	12
Light Distribution Type	Type II	Type II
Cutoff Classification	Cutoff	Cutoff
Lighting Control	Photo cell	Photo cell
Mounting Height	25 feet	25 feet
Avg. Illuminance (lux)	8.72 lux*	2.69 lux*

* From LRC test and measurement results

Figure 2. Initial HPS street lighting (Meridian Street)

Figure 3. Induction street lighting demonstration (Meridian Street)

Shennecossett Road

Shennecossett Road has mostly single family homes along its tree-lined street. Both before and after illuminance measurements were taken with the trees full of leaves. By IESNA standards, it is considered a collector-type road (i.e., side streets empty their traffic onto it and it conveys traffic to larger streets). The roadway is asphalt paved and is approximately 30 feet wide throughout the demonstration section. Street lights are installed on every other electric distribution overhead pole and on every pole at an intersection. Poles are approximately 140 feet apart and street lights are approximately 280 feet apart.

Lamp and light fixture information for Shennecossett Road for both the initial HPS street lighting and for the ceramic metal halide lighting demonstration are listed in Table 3 below. Photographs of the initial HPS and the demonstration ceramic metal halide street light installations are shown in Figures 4 and 5.

Table 3. Street light fixture information (Shennecossett Road)

	Initial HPS Street Lighting	Ceramic Metal Halide Demonstration Street Lighting
Lamp Type	HPS	Ceramic Metal Halide
Lamp Wattage[9]	100 watts (118 watts with ballast)	70 watt (92 watts with ballast)
CCT[9]	2100 K	4000 K
Mean Lumens[9]	8460	4150
Lamp Life[9]	30,000 hours non-cycling	24,000 hours
Fixture Type	Cobra Head	Cobra Head
Number of Fixtures	10	10
Light Distribution Type	Type II	Type II
Cutoff Classification	Cutoff	Cutoff
Lighting Control	Photo cell	Photo cell
Mounting Height	25 feet	25 feet
Avg. Illuminance (lux)	3.20 lux*	3.10 lux*

* From LRC measurement results

Figure 4. Initial HPS street lighting (Shennecossett Road)

Figure 5. Ceramic metal halide demonstration street lighting (Shennecossett Road)

Selection of Demonstration Street Light Lamps and Luminaires

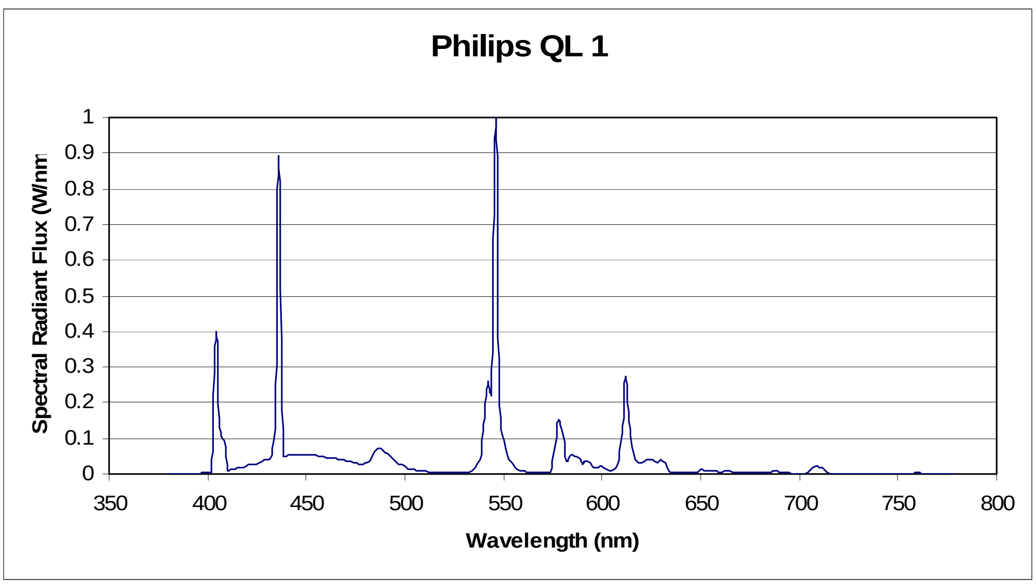
The selection of lamps for the demonstrations were made, in part, based on the unified photometry system's prediction of equal visual performance under mesopic lighting conditions and different lamp spectral power distributions. Selection also was based on lamps that were commercially available or could be reasonably made available by Philips Lighting, the lamp manufacturing partner for this project. The parties decided to examine two different lamp types with two different SPDs, both producing a white light that would be acceptable to city residents and tuned toward optimizing mesopic vision while remaining in the white light zone. The unified photometry system was used in part to develop criteria for the HPS replacement lamp. The system provides the equivalent mesopic luminance for lamps of differing SPDs that will produce equivalent visual performance under low light (mesopic) conditions. The ratio of a replacement lamp's scotopic luminance to photopic luminance (S/P ratio) is used as one of the variables to determine the necessary unified luminance flux equivalent to the HPS lamp. The other variable is the luminance of the road surface.

To eliminate multiple variables for determining whether the demonstration white light sources could provide similar perceptions of visibility, safety, security, and brightness, luminaires similar to those in use with the existing HPS lighting system were used for the demonstration lighting. The HPS system used a semi-cutoff, cobra head street light fixture. This fixture employed a drop lens. LRC testing of similar fixtures manufactured by the same company indicated that the existing fixture's optical characteristics perform as a cutoff fixture. Lumec provided cobra head fixtures with cutoff optics and a drop lens for both the induction lamp and metal halide lamp installations. Lumec has a kit it installs within its cobra head fixtures to accept the induction lamp. We recognize that these demonstration fixtures do not meet the Connecticut law requiring full cutoff optics for all new street light fixtures where the municipality is paying for the installation. However, the desire to not introduce another variable into the evaluation by changing fixture types outweighed following precisely the Connecticut law. This is a research project and not necessarily a permanent installation. In accordance with Connecticut law, Groton Utilities should only install full cutoff fixtures for new or replacement street light installations.

Meridian Street Lamp Choice (Induction Lamp)

The S/P ratio of the Philips induction lamp with 6500 K CCT phosphors is 2.88 (compared to 0.63 for the existing HPS lamps). Mesopic efficacy improves with higher S/P ratio lamps. Figure 6 shows the SPD of the Philips induction lamp with 6500 K CCT phosphors. These phosphors are not commercially available in the Philips induction lamp line. However, Philips produced these lamps for this demonstration project using phosphors found in its 6500 K CCT linear fluorescent lamps. It is believed these phosphors can be commercialized for induction lamps if a market for mesopic street lighting develops.

Figure 6. SPD of the 6500 K CCT induction lamp



Note: SPD recorded from LRC lamp testing

The luminance values for the HPS street lighting along Meridian Street were calculated using the road surface illuminance measurements and a 7% asphalt roadway reflectance (Gillet and Rombauts 2001).[10] Average photopic illuminance under HPS conditions for the test site on Meridian Street was 8.72 lux. The average photopic luminance of the roadway surface was approximately 0.21 cd/m^2.

The unified photometry system predicted a need for the induction lamp to provide a luminous flux of 3620 lumens to have an equivalent visual performance to the 9500-lumen, 100-watt HPS lamp source it replaced. Table 4 below provides the results of the power and luminance calculations. When the photopic luminance of the roadway pavement under HPS lighting (S/P = 0.63) is 0.21 cd/m^2, the equivalent mesopic luminance under the same lighting condition is 0.17 cd/m^2. Conversely, when the equivalent mesopic luminance of the pavement under induction lighting (S/P = 2.88) is 0.17 cd/m^2, the photopic luminance is 0.08 cd/m^2. Hence, only 3620 photopic lumens are required for each new induction luminaire to create a mesopic luminance of 0.17 cd/m^2, while an HPS luminaire needs 9500 photopic lumens to create the same mesopic luminance.

Table 4. Comparison between HPS and induction systems in photopic and mesopic luminances

	Mesopic luminance (cd/m^2)	S/P ratio	Photopic luminance (cd/m^2)	Luminous flux (lm)	Lamp input power (W)
HPS	0.17	0.63	0.21	9500	100
Induction	0.17	2.88	0.08	3620	60

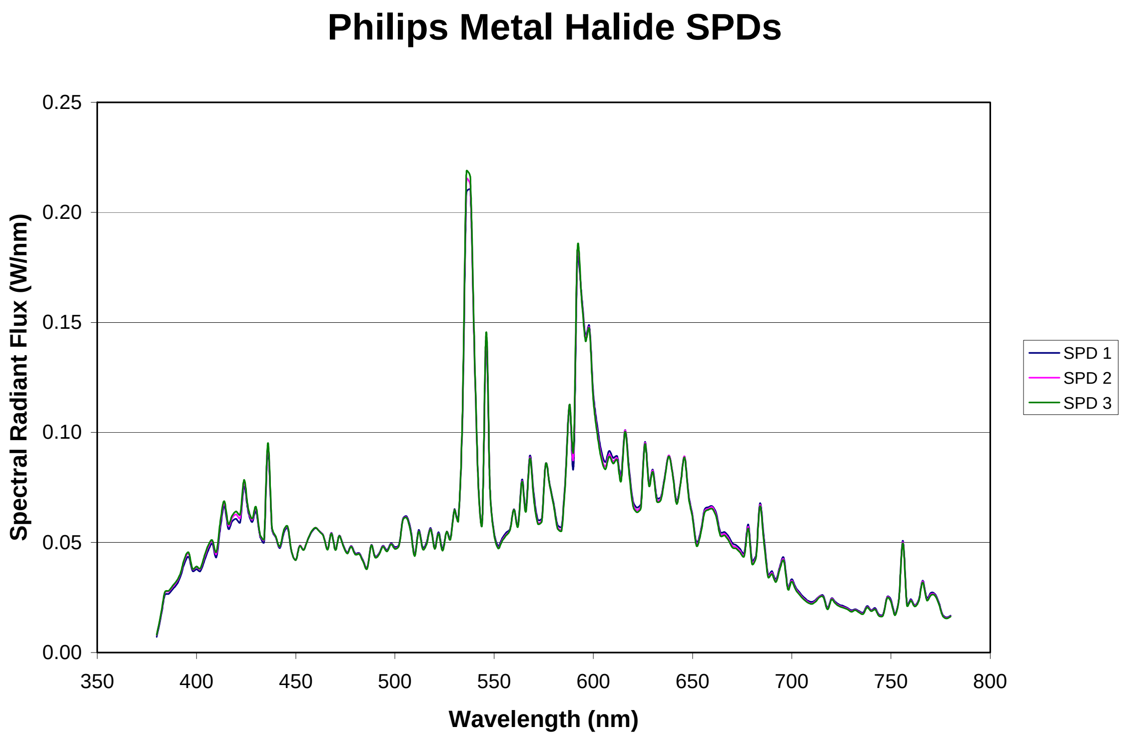
Philips, the lamp partner for this project, manufactures 55-watt (3300 lumens) and 85-watt (6300 lumens[11]) induction lamps that entered the short list of choices for replacing the 100-watt HPS lighting on Meridian Street. The 85-watt version provides more light than was needed according to the unified photometry system. While the 55-watt induction lamp provides slightly less light than needed, it was felt that this lamp would provide a better test of a white light source tuned to mesopic vision than the higher wattage lamp. The 55-watt induction lamp provides an average photopic luminance of 0.06 cd/m^2, based on illuminance measurements and road surface reflectance along Meridian Street measured after the installation of the induction lamps and fixtures.

Shennecossett Road Lamp Choice (Ceramic Metal Halide Lamp)

A fluorescent light source at 6500 K CCT was tested at the Easthampton, Massachusetts, test site in 2004. An induction lamp at 6500 K CCT was demonstrated as part of the Groton research project. The other white light source commercially available for street lighting is metal halide. To complete the research into possible lamp replacements for HPS that have mesopic characteristics, the project partners decided to test a metal halide lamp with a 4000 K CCT. While 4000 K is less mesopically efficacious than 6500 K, it is certainly mesopically better than the HPS lamp at 2100 K. The 4000 K CCT ceramic metal halide lamp is commercially available today. It would have been extremely difficult (and expensive) for Philips to take an existing metal halide lamp and change its correlated color temperature to match the needs of a white light mesopic lamp.

Figure 7 shows the SPD of three Philips ceramic metal halide lamps with 4000 K CCT phosphors tested at the LRC. The S/P ratio of these lamps is 1.6.

Figure 7. SPD of 4000 K CCT ceramic metal halide lamps



The unified photometry system predicted a need for the ceramic metal halide lamp to provide a luminous flux of 4070 lumens to have an equivalent visual performance to the 9500-lumen, 100-watt HPS lamp source it replaced. Table 5 below provides the results of the power and luminance calculations. When the photopic luminance of the roadway pavement under HPS lighting (S/P = 0.63) is 0.07 cd/m^2, the equivalent mesopic luminance under the same lighting condition is 0.05 cd/m^2. Conversely, when the equivalent mesopic luminance of the pavement under ceramic metal halide lighting (S/P = 1.6) is 0.05 cd/m^2, the photopic luminance is 0.03 cd/m^2. Hence, only 4070 photopic lumens are required for each new metal halide luminaire to create a mesopic luminance of 0.05 cd/m^2, while an HPS luminaire needs 9500 photopic lumens to create the same mesopic luminance.

Table 5. Comparison between HPS and metal halide systems in photopic and mesopic luminances

	Mesopic luminance (cd/m^2)	S/P ratio	Photopic luminance (cd/m^2)	Luminous flux (lm)	Lamp input power (W)
HPS	0.05	0.63	0.07	9500	100
Metal Halide	0.05	1.60	0.03	4070	70

The 70-watt ceramic metal halide lamp provided an average photopic luminance of 0.07 cd/m^2, based on illuminance measurements and road surface reflectance along Shennecossett Road measured after the installation of the metal halide lamps and fixtures. This far exceeds the 0.03 cd/m^2 photopic luminance needed to provide equal visual performance to the initial HPS system. However, it must be pointed out that the illuminance measurements were taken shortly after the metal halide lamps were installed. Metal halide lamps have high lumen depreciation over their life. Ceramic metal halide lamps, as were used in this demonstration, have less lumen depreciation (5900 initial lumens versus 4150 mean lumens) than probe-start metal halide lamps, but higher lumen depreciation than HPS lamps. Therefore, over time, the photopic luminance of the ceramic metal halide lamps is expected to decrease from that measured during this project.

Light Illuminance Measurements

Illuminance measurements were taken by LRC personnel using a Hagner model E2 illuminance meter calibrated against the LRC meter standard. For the street lighting on both Meridian Street and Shennecossett Road, horizontal illuminance measurements were taken at the road surface every 20 feet along the length of the road and every 10 feet for the width of the road for a representative section of each road. For Meridian Street, the length of roadway section measured was 260 feet and incorporated three utility poles, all of which have street lights. For Shennecossett Road, the length of roadway section measured was 300 feet and incorporated three utility poles. Only the first and third pole had street lights.

Table 6 and Figure 8 provide the illuminance measurements and spatial light distribution for Meridian Street with the HPS lamps, and Table 7 and Figure 9 provide the illuminance measurements and spatial light distribution for Meridian Street with the induction lamps.

Table 6. Meridian Street, HPS illuminance measurements (lux)

Distance Along Street (feet)	Edge of Payment	10 feet	20 feet	30 feet	Far Edge of Payment
0	5.1	9.5	13.9	5.9	3.7
20 (light)	9.6	15.0	17.9	10.6	5.8
40	3.9	6.5	8.0	8.4	5.8
60	4.2	7.5	8.5	7.2	5.1
80	4.0	6.6	8.3	7.9	5.1
100	6.3	9.8	11.8	7.2	8.1
120	6.5	14.3	16.0	6.5	6.3
140 (light)	9.3	19.3	17.4	6.0	5.8
160	5.8	12.4	15.8	8.6	4.8
180	4.6	9.0	10.7	9.2	5.2
200	4.6	7.6	11.3	11.1	5.6
220	7.7	15.8	18.7	10.7	5.8
240 (light)	7.9	19.8	34.0	15.0	5.6
260	6.5	13.6	20.1	11.4	6.9

Table 7. Meridian Street, induction illuminance measurements (lux)

Distance Along Street (feet)	Edge of Payment	10 feet	20 feet	30 feet	Far Edge of Payment
0	5.3	4.8	3.0	1.7	0.9
20 (light)	5.9	5.7	3.7	2.0	1.2
40	3.2	4.2	2.8	1.6	1.0
60	1.7	1.5	1.1	0.8	0.8
80	1.7	1.8	1.2	1.2	1.2
100	3.7	3.3	2.5	1.8	1.5
120	4.7	4.9	3.4	2.1	2.0
140 (light)	4.7	4.7	3.5	2.2	1.6
160	4.2	4.9	3.5	2.4	1.7
180	3.0	2.7	2.0	1.4	1.1
200	2.8	2.6	2.0	1.5	1.1
220	4.2	2.6	3.6	2.4	1.3
240 (light)	4.4	4.6	3.7	2.4	1.2
260	3.6	3.9	3.0	1.9	1.2

Figure 8. Meridian Street, HPS spatial light distribution (in lux)

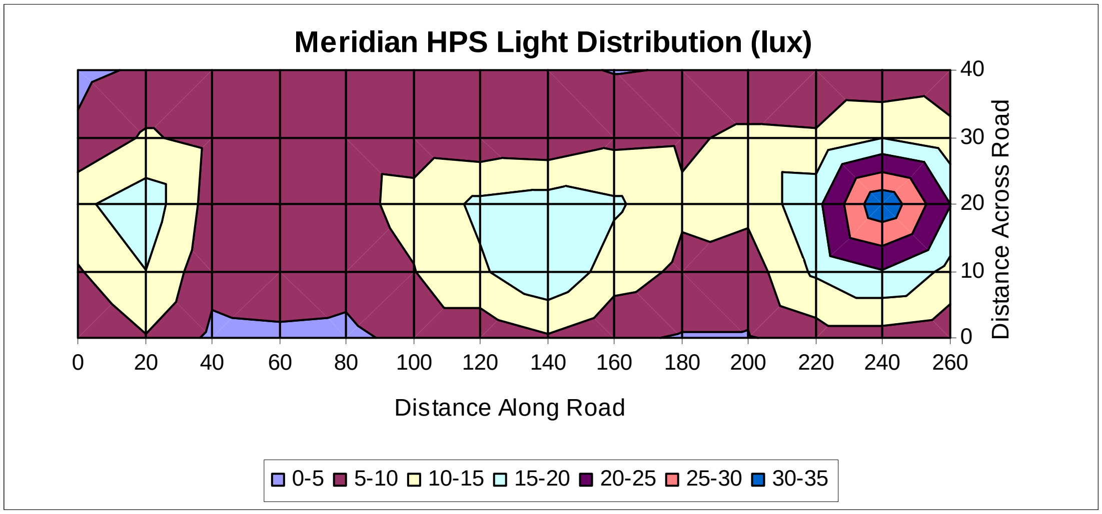


Figure 9. Meridian Street, induction spatial light distribution

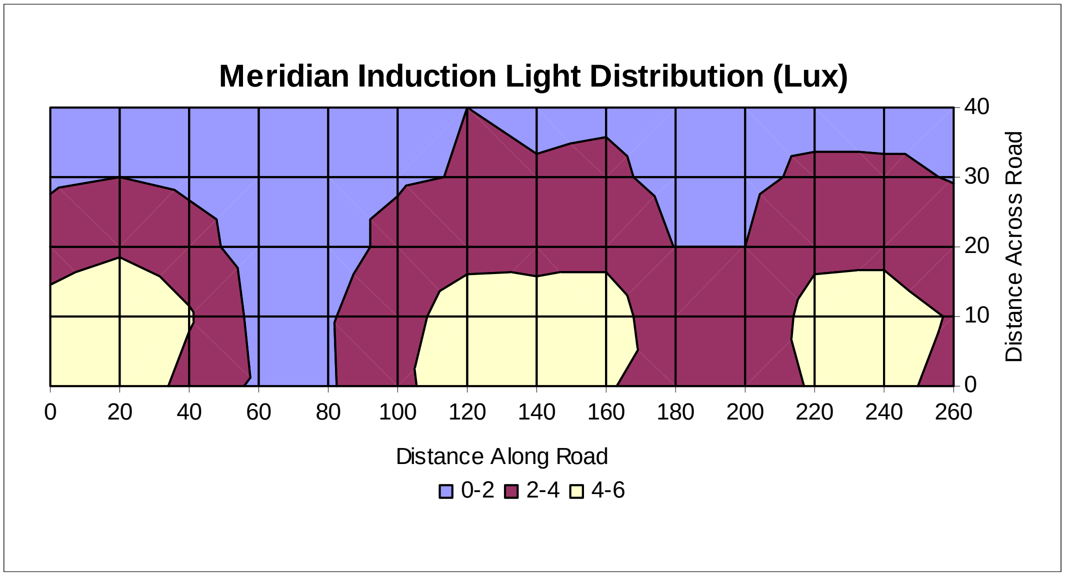


Table 8 and Figure 10 provide the illuminance measurements and spatial light distribution for Shennecossett Road with the HPS lamps, and Table 9 and Figure 11 provide the illuminance measurements and spatial light distribution for Shennecossett Road with the ceramic metal halide lamps.

Table 8. Shennecossett Road, HPS illuminance measurements (lux)

Distance Along Street (feet)	Edge of Payment (closest to lights)	10 feet	20 feet	Far Edge of Pavement
0	1.9	2.8	4.9	2.9
20 (light)	3.1	4.3	5.2	3.8
40	1.7	2.8	4.2	2.8
60	0.8	1.2	1.6	1.8
80	0.3	0.4	0.4	1.4
100	0.2	0.4	0.4	0.6
120	0.1	0.2	0.3	0.2
140	0.1	0.2	0.2	0.2
160 (pole, no light)	0.1	0.1	0.2	0.2
180	0.1	0.1	0.1	0.2
200	0.2	0.2	0.2	0.4
220	0.5	0.5	0.7	1.3
240	1.2	1.6	2.0	3.4
260	5.7	7.8	14.7	9.5
280 (light)	12.9	16.6	23.6	9.1
300	9.6	13.7	12.2	4.9

Table 9. Shennecossett Road, ceramic metal halide illuminance measurements (lux)

Distance Along Street (feet)	Edge of Payment (closest to lights)	10 feet	20 feet	Far Edge of Pavement
0	3.4	8.4	5.6	2.6
20 (light)	8.6	15.5	8.9	3.3
40	4.0	10.7	5.5	2.4
60	1.5	6.7	3.2	1.3
80	1.5	2.5	1.7	1.2
100	0.8	1.3	0.6	0.4
120	0.2	0.5	0.3	0.2
140	0.1	0.3	0.2	0.1
160 (pole, no light)	0.0	0.0	0.1	0.1
180	0.0	0.0	0.1	0.1
200	0.0	0.1	0.4	1.0
220	0.4	0.6	1.7	1.6
240	1.0	2.2	5.6	2.8
260	3.2	5.8	5.5	1.3
280 (light)	10.7	23.3	5.7	2.1
300	9.8	5.3	2.7	1.4

Figure 10. Shennecossett Road, HPS spatial light distribution

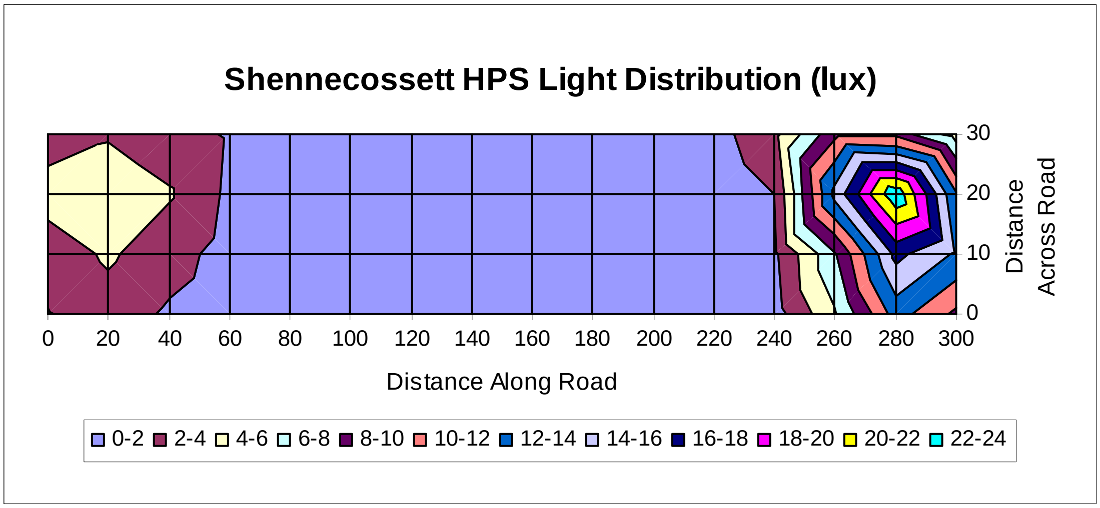
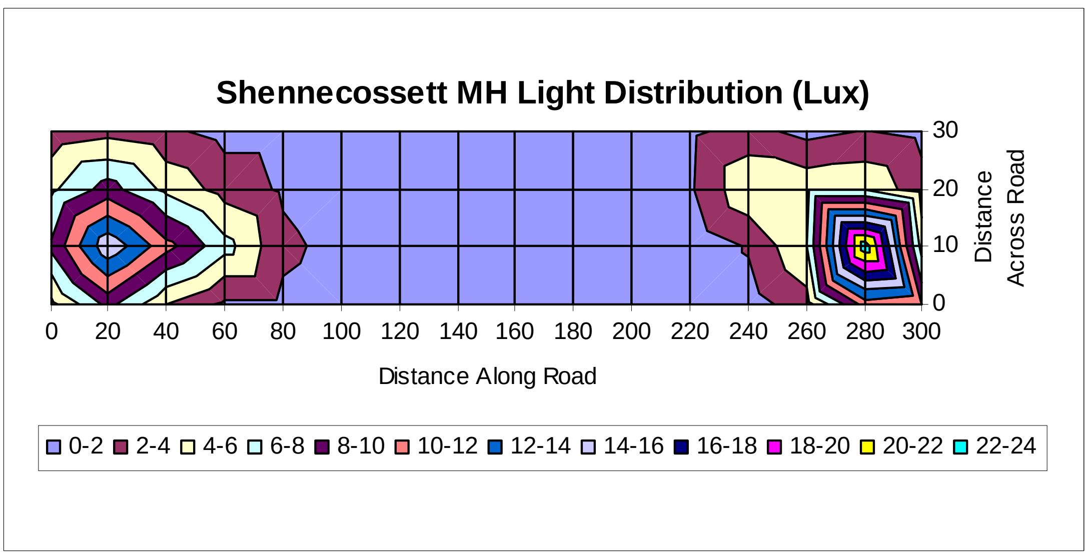


Figure 11. Shennecossett Road, ceramic metal halide spatial light distribution



Street Lighting Evaluation Methodology

Mail surveys were conducted to garner residents' opinions of the initial HPS street lighting and of the demonstration induction and metal halide street lighting. A survey was sent to approximately 30 residents living on or near the Meridian Street demonstration site and to approximately 50 residents living on or near the Shennecossett Road demonstration site prior to changing the HPS street lights to either the induction or ceramic metal halide lights. This survey was conducted between March 20, 2007 and

April 20, 2007. Residents were asked to provide their perceptions of visibility, safety, security, brightness, and color rendering as both pedestrians and drivers. This survey set the baseline for residents' perceptions under the original HPS street lighting conditions. A copy of the "before" survey can be found in Appendix B. Residents were offered a supermarket gift certificate of $10 if they completed both the before and after surveys.

Forty-seven percent of the Meridian Street residents provided responses to the before survey, while 68% of Shennecossett Road residents responded. This high percentage of responses allowed for statistically sound analysis to be conducted.

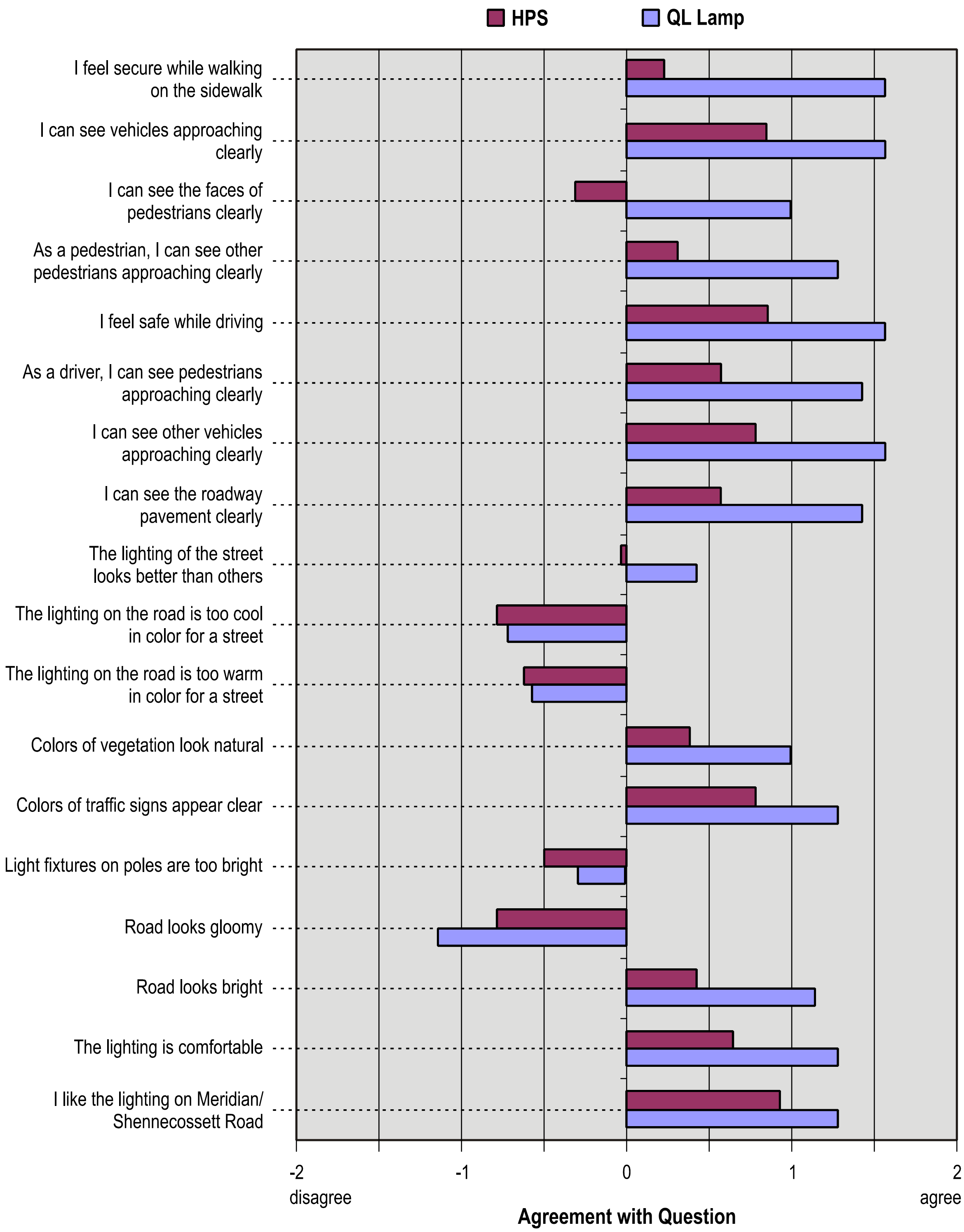
The induction and metal halide light fixtures were installed in June 2007. An anomaly was noticed in July 2007 with the light distribution of the metal halide fixtures. Replacement parts were provided by Lumec and installed in August 2007. The post-installation survey was mailed to residents who completed the pre-installation survey on or about September 20, 2007, with requests to return the surveys by October 20, 2007. Fifty percent of Meridian Street residents who completed the initial survey also completed the post-installation survey. Sixty-eight percent of Shennecossett Road residents who completed the pre-installation surveys also completed the post-installation survey. This survey allowed the researchers to compare residents' perceptions between the original HPS lighting and the new demonstration lighting. A copy of the post-installation survey is included in Appendix C. The survey questions were identical to the pre-installation survey. Sending the post-installation survey to only residents that responded to the pre-installation survey allowed for within-subject analysis to be conducted.

Research Results

Meridian Street HPS versus Induction Lamp

Figure 12 illustrates the results of comparing the induction and HPS street lighting on Meridian Street. Graph bars tracking to the right toward the positive end of the scale indicate agreement with the survey statement, while bars tracking to the left toward the negative end of the scale indicate disagreement with the statement.

Figure 12. Street light comparison on Meridian Street: HPS and induction (QL)



The results depicted in Figure 12 show a strong preference for the induction lamp at 6500 K CCT. Survey respondents indicated that they felt safer and could see better with the 55-watt induction lamp at 6500 K CCT than with the 100-watt HPS at 2100 K CCT.

On the questions of visibility—as a pedestrian seeing vehicles approaching clearly, seeing faces of other pedestrians clearly, and seeing other pedestrians approaching clearly; and as a driver seeing pedestrians approaching clearly, seeing other vehicles approaching clearly, and seeing the roadway pavement clearly—the induction street lighting showed residents' agreement with these statement to score between 1.0 and 1.6 on a scale of –2.0 to +2.0. The HPS street lighting for the same questions had agreement scores of 0.3 to 0.8. This shows a clear preference for the induction street lighting providing higher perceptions of visibility for both drivers and pedestrians.

On the questions of safety and security, including feeling secure while walking and feeling safe while driving, the induction street lighting again outscored the HPS system. The scores for the induction lighting for these questions were 1.6 in agreement with the survey statements, again using the –2.0 to + 2.0 scale. The HPS lighting system had agreement scores of 0.2 and 0.8.

On the questions on brightness, including the road looks bright and the lighting is comfortable, again the induction street lighting had higher scores of residents' agreement with the statements. Neither light source was viewed as being too bright.

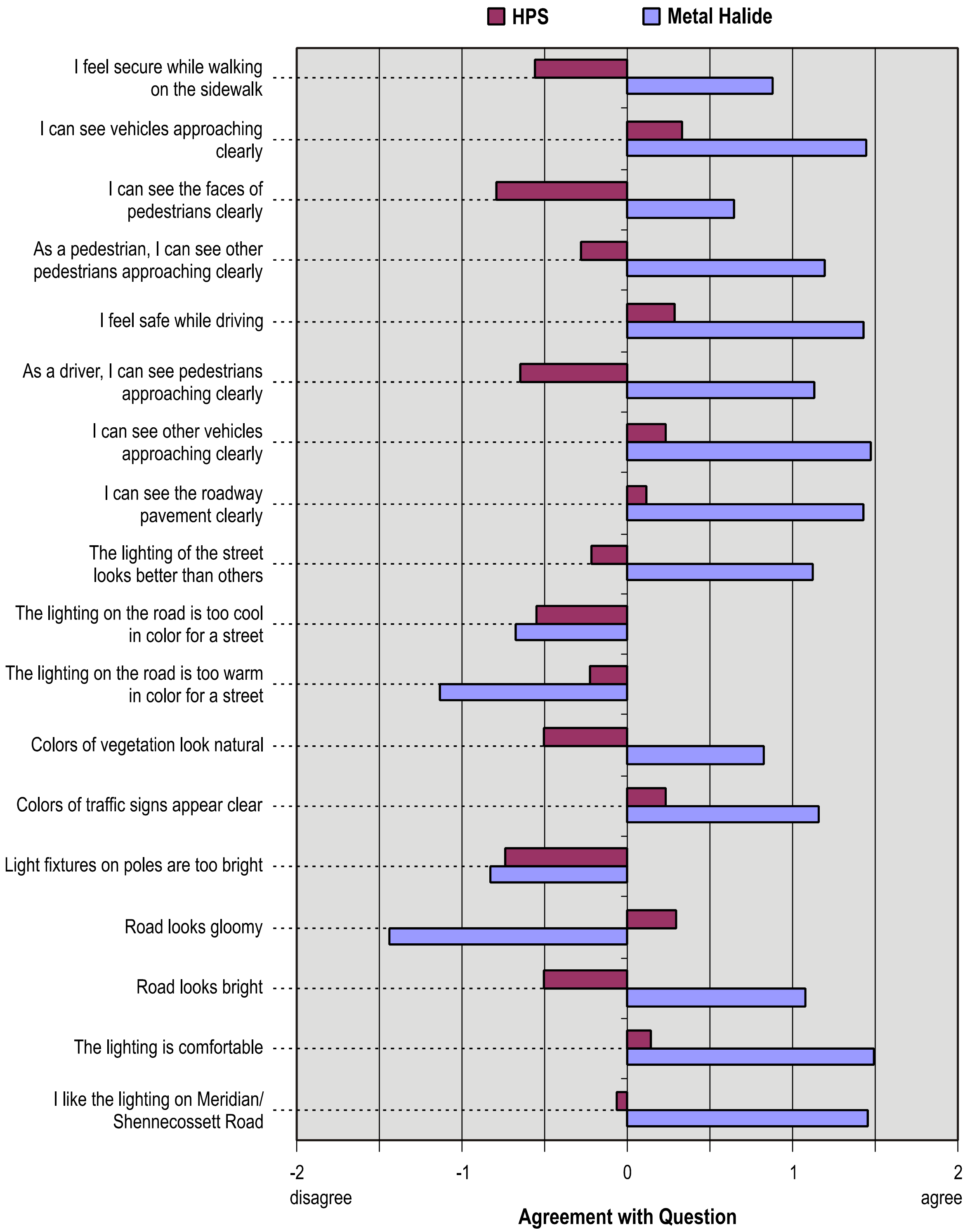
Color rendering also favored the induction lighting. However, neither light source was perceived as being too cool or warm in color.

Possibly the best comparison of visibility, brightness, and color rendering can be seen in Figures 2 and 3 above. These photographs were taken on the same section of Meridian Street with HPS lighting and after the installation of the induction lighting. The photos exposures are similar with regards to a combination of F-stop, exposure time, and ISO speed. The resident with the white car had it parked in identical positions for both photos, even though Figure 2 was taken on April 27, 2007 and Figure 3 on August 27, 2007. Please examine closely the details of the white car in both photos and the visibility and color of the vegetation. It is clear from these photos why residents' perceptions of visibility, brightness, and color rendering were higher with the induction lighting at 6500 K CCT. However, one must take into account that Figure 2 was taken with some fog moving into the area.

Shennecossett Road HPS versus Ceramic Metal Halide

Figure 13 below illustrates the results of comparing the ceramic metal halide and HPS street lighting on Shennecossett Road. Graph bars tracking to the right toward the positive end of the scale indicate agreement with the survey statement, while bars tracking to the left toward the negative end of the scale indicate disagreement with the statement.

Figure 13. Street light comparison on Shennecossett Road: HPS and ceramic metal halide



In analyzing the results of the two street light types, it must be remembered that the high luminance and illuminance values for the metal halide lighting will decrease over time as the lamp ages. The survey of residents occurred while the metal halide lamp was at its peak light output. The results from the unified photometry system analysis would indicate the metal halide lamp should outperform the HPS street lighting at the current photopic luminance values for the metal halide. At mean lumen output, the metal halide lamp should provide approximately the same visual performance as the HPS it replaced.

All this said, the results depicted in Figure 13 show a strong preference for the metal halide lamp at 4000 K CCT. As predicted by the unified photometry system, survey respondents indicated they felt safer and could see better as both drivers and pedestrians with the 70-watt metal halide street lighting than with the 100-watt HPS.

On the questions of visibility—as a pedestrian seeing vehicles approaching clearly, seeing faces of other pedestrians clearly, and seeing other pedestrians approaching clearly; and as a driver seeing pedestrians approaching clearly, seeing other vehicles approaching clearly, and seeing the roadway pavement clearly—the metal halide street lighting showed residents' agreement, on average, with these statements to score between 0.6 and 1.45 on a scale of –2.0 to +2.0. The HPS street lighting for the same questions had agreement scores of –0.75 to 0.3. This shows a clear preference for the metal halide street lighting providing higher perceptions of visibility for both drivers and pedestrians.

On the questions of safety and security, including feeling secure while walking and feeling safe while driving, the metal halide street lighting again outscored the HPS system. The scores for the metal halide lighting for these questions were 0.8 and 1.4 in agreement with the survey statements, again using the –2.0 to + 2.0 scale. The HPS lighting system had agreement scores of –0.55 and 0.3.

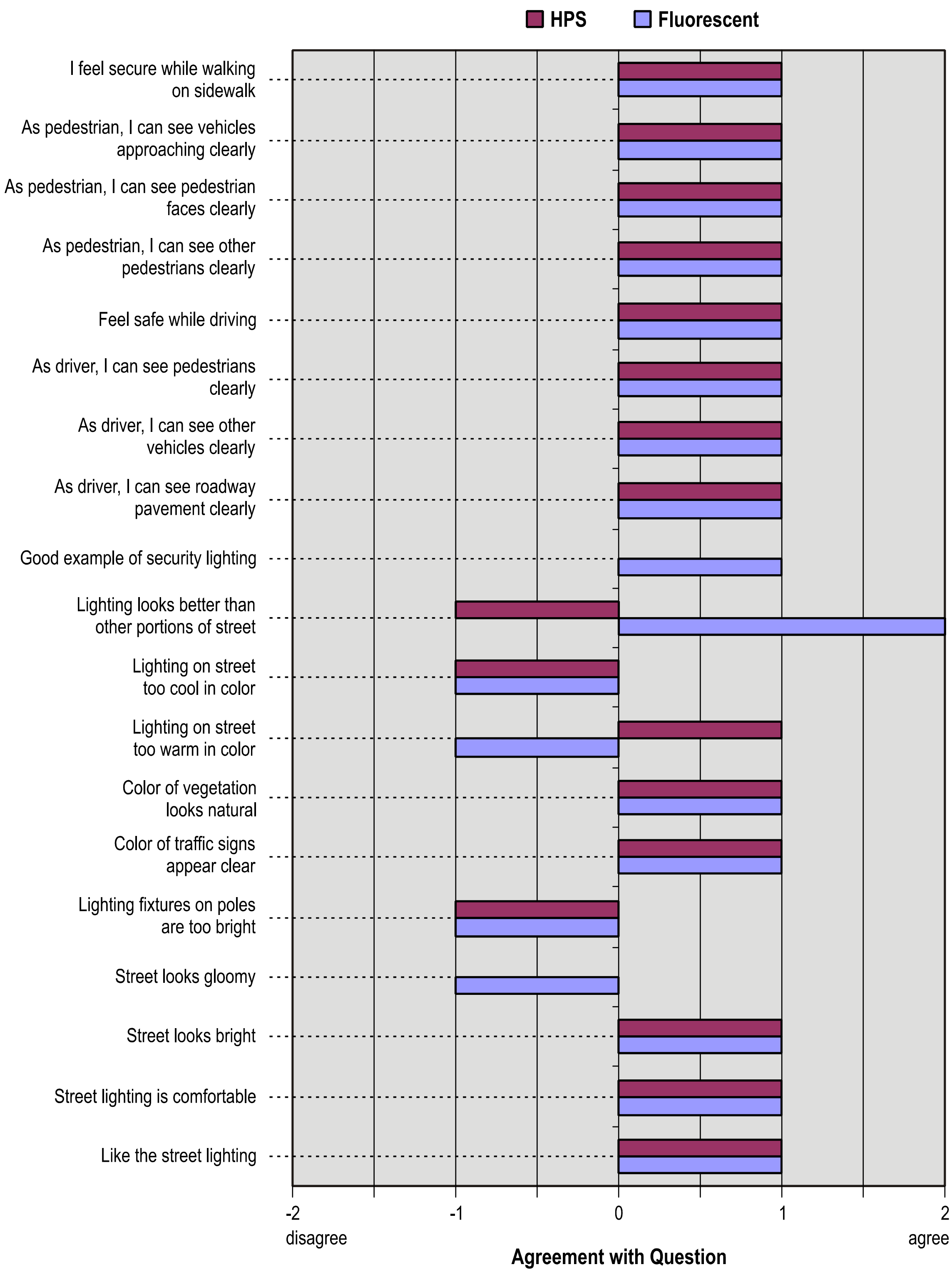
On the questions on brightness, including the road looks bright and the lighting is comfortable, again the metal halide street lighting had higher scores of residents' agreement with the statements. Neither light source was viewed as being too bright.

Color rendering also favored the metal halide lighting. However, neither light source was perceived as being too cool or warm in color.

Comparison of Groton Mesopic Street Lighting Results with Other LRC Research

The LRC has conducted demonstration and evaluation research regarding mesopic street lighting at other locations. The results of the Easthampton, Massachusetts, research are summarized in the introduction to this report, including Figure 1 above and in Appendix A. Another mesopic project was conducted in Austin, Texas. The results of residents' perceptions of visibility, safety, security, brightness, and color rendering from the Groton research are very similar to those found in other LRC mesopic research.[12] Although very few subjects completed the survey, Figure 14 depicts the limited results from the Austin street lighting study.

Figure 14. Austin, Texas Mesopic Research Results[12]



The Austin street lighting compared HPS with two fluorescent T5 twin-tube, 50-watt lamps at 4000 K CCT. Median (rather than average) values of residents responses were used because of the limited number of responses.

Given residents' overwhelming positive perceptions for street lights tuned toward optimizing mesopic vision as compared to HPS street lighting in multiple research studies, one must conclude that mesopic street lighting has the ability to increase perceptions of visibility, safety, security, brightness, and color rendering while reducing photopic luminance and lamp wattages. This outcome is consistent with the unified photometry system's predicted visual performance.

City Police Perceptions of Newer Street Lighting

LRC personnel interviewed City of Groton Police Chief Bruno Giulini and night-shift patrol personnel. Chief Giulini supports the use of street lights to reduce accidents and deter crime. He believes the new lighting on Meridian Street and Shennecossett Road appears to be brighter than the HPS it replaced. It also has better color rendering properties. Patrol personnel believe the new street lights make objects look more natural. They believe HPS lighting changes the color of objects.

Other Research into Perceptions of Brightness

Brightness, more so than illuminance, will guide people's perceptions of safety and security. In reports by Rea[13] and Fotios et al.[14], it was found that metal halide and fluorescent outdoor lighting provided perceptions of higher brightness than HPS. This allows photopic luminance to be less for the whiter light sources while providing the same degree of brightness. Therefore, white light sources can be of less wattage than an HPS source. Rea, through experimentation, estimated the ratio of HPS luminance to metal halide luminance to be 1.4 to provide perceptions of equal brightness at a background luminance of 0.1 cd/m^2 to 1.0 cd/m^2, and a ratio of 1.8 at a background luminance of 0.01 cd/m^2 to 0.1 cd/m^2.

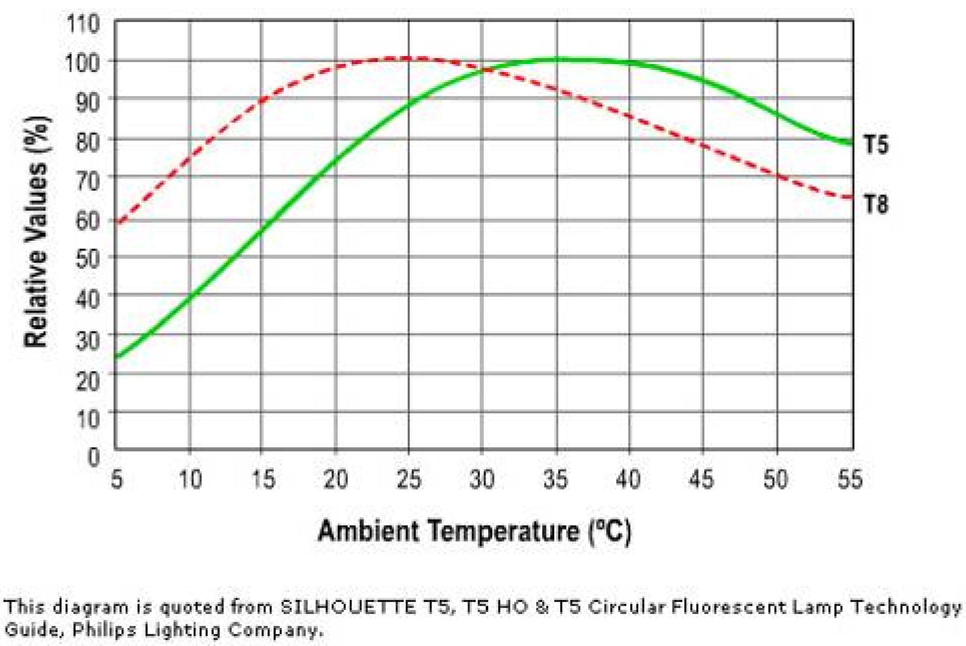
The background photopic luminance of Shennecossett Road (0.07) falls within these ranges. The ratio of the HPS luminance to the metal halide luminance is currently 1.0. Therefore, Rea's outcome would predict that subjects viewing the lighting on Shennecossett Road would have higher perceptions of brightness with the metal halide lighting than with the HPS lighting. The outcome from the subject surveys verified that people perceive the brightness to be higher with the metal halide lighting.

Performance and Economics Considerations

Outdoor temperatures vary throughout the year. Lamps enclosed in water-tight light fixtures located outdoors will experience changes in the ambient temperature in which they operate. Changes in ambient temperature will affect the lamp efficiency and total lumen output. This is truer for fluorescent-type lamps than for HPS lamps. The induction lamp is a fluorescing lamp source. HPS and metal halide lamps experience minimal losses in lumen output as the ambient temperature changes. Fluorescent-type lamps are rated for maximum lumen output at a certain ambient temperature, 25°C for T8 and 35°C for T5. The LRC, through its lamp testing, has found the Philips induction lamp has a maximum light output at approximately 25°C. Fluorescing lamps operated at either higher or lower temperatures will experience lumen losses.

The LRC's National Lighting Product Information Program has published a *Lighting Answers* publication that discusses the effects of ambient temperature on fluorescent lighting systems.[15] Figure 15 illustrates the effects of ambient temperature on T5 and T8 lamps. An ambient temperature of 50°C (122°F) within a totally enclosed outdoor light fixture during summer months will reduce T5 light output by approximately 14%. Conversely, an ambient temperature within the light fixture of 10°C (50°F) will reduce light output by approximately 60% for a T5 lamp..

Figure 15. Light output and ambient temperature[15]



The LRC tested the Philips 55-watt induction lamp at low and high ambient temperatures using a freezer or a lab oven and a 1 ft × 1 ft × 1 ft foamcore box to represent the light fixture. The lamp was placed within the box in a base-up operating position. The lamp driver was placed outside the box. A thermocouple on the inside bottom of the box measured the ambient temperature within the box. A small hole on the side of the box was cut to measure illuminance with a Hagner EC1 meter. The temperature within the freezer was –15.3°C (4.5°F). The lab oven was controlled and testing was performed at 40°C (104°F), 50°C (122°F), and 60°C (140°F).

Table 10 below illustrates the testing results at both low and high ambient temperatures for the induction lamp.

Table 10. Induction lamp performance at varying ambient temperatures

Situation	Lamp base temp (°C)	Box temp (°C)	Illuminance (lx)	% illuminance *
Lamp outside of box, ambient 26.7°C	86.0	--------	--------	
Lamp in box, on bench, ambient 26.7°C	100.0	28.8	50,400	100.0%
Lamp in box, in freezer, ambient –15.3°C	68.0	10.2	49,800	98.8%
Lamp in box, in oven, ambient 40°C	108.7	39.0	47,900	95.0%
Lamp in box, in oven, ambient 50°C	113.5	46.3	45,200	89.7%
Lamp in box, in oven, ambient 60°C	121.3	58.4	42,000	83.3%

** These percentages represent the illuminance amount in comparison to the stable lamp in the box, on bench, in room temperature environment (50,400 lx).*

The lamp base temperature was measured at the junction of the lamp base to the lamp. The box temperature was the temperature at the bottom of the inside of the foam core box and represents the ambient temperature of the lamp environment.

The induction lamp performs better than either a T5 or T8 fluorescent lamp in both cold and hot ambient environments. Lumen reduction was less than 2% at a box temperature of 10°C and slightly more than 10% at 46°C. The small amount of light output loss confirms the induction lamp as a good choice for outdoor lighting applications.

Replacing a 100-watt HPS light source (118 watts with ballast) with a 55-watt induction light source[14] or a 70-watt metal halide lamp (85 watts with ballast) saves considerable amounts of energy.[9] Assuming 4,160 hours of operation per year, the 100-watt HPS system will use 491 kilowatt-hours (kWh), compared to the 55-watt induction system at 229 kWh and the metal halide system at 354 kWh.[16] This is a 53% reduction in annual energy use for the induction system and a 28% reduction for the metal halide system. Cost savings to the user of the induction system at 15.4977 cents per kWh for energy purchases would be $40.62 per year ($76.08 for 100-watt HPS versus $35.46 for 55-watt induction).[17] The metal halide system also saves money for energy. Cost savings for this system would be $21.28 per year ($76.08 for 100-watt HPS versus $54.80 for metal halide).

Using either the induction lamp or the metal halide lamp will increase maintenance costs. For the induction lamp, annual maintenance costs are increased slightly by $0.97per lamp because of the higher cost for the replacement lamp and driver. This higher cost is offset by doubling the life expectancy of the induction lamp compared to an HPS lamp. Adding to the cost of the induction lamp replacement is the need to replace the lamp driver at the time of lamp replacement.

Currently, the cost of a ceramic metal halide lamp is high. Given this and the shorter life (30,000 hours for HPS and 20,000 for metal halide) of the metal halide lamp compared to the HPS lamp, annual maintenance costs would greatly increase by $24.06 per lamp.

Three methods of analysis can be used to determine the economic viability of alternatives to high-pressure sodium street light systems. The first looks at simple payback where any additional capital costs must be offset with annual savings. The second economic analysis examines alternative street lighting scenarios from a utility's annual ownership and operating perspective or rate-making analysis. The third method is lifecycle cost.

The following assumptions were used for all economic analyses:

- Capital cost for HPS system less lamp is $75[*,17]
- Capital cost for the induction system less lamp and driver is $200[*,18]
- Capital cost for the metal halide system less lamp is $80[17]
- Labor to install a new street light is $150[19]
- The outdoor lighting system operates 4,160 hours per year[16]
- Lamp costs are $43[20] for a 100-watt HPS non-cycling, $200[21] for 55-watt induction with driver, and $111[20] for 70-watt ceramic metal halide
- Labor to change a lamp on an existing outdoor fixture is $100[19], including travel time to the site and use of bucket truck
- Lamp life is 30,000 hours[9] for the 100-watt HPS non-cycling, 60,000 hours[11] for 55-watt induction, and 24,000 hours[21] for 70-watt ceramic metal halide
- Energy cost is $0.154977 per kWh[22]
- Total system wattage for HPS 118 watts[16], for induction 55 watts[11] and for metal halide 85 watts[9]
- Street light fixture amortization is 27 years[19]

*Note: Approximate costs of the different outdoor lighting fixtures are subject to price changes due to the ever-changing prices of raw materials.

To determine the simple payback of using either the induction or metal halide lighting systems, the capital cost of the induction, metal halide, and HPS systems must be determined and the savings from using the induction or metal halide system must be included in the calculation. Two different scenarios exist for simple payback, one for newly designed/installed lighting systems and one for retrofitting existing HPS lighting systems. For new outdoor lighting, the differential capital cost of the induction or metal halide versus the HPS lighting system is used. For retrofit situations, the full cost of the induction or metal halide system plus the labor costs to install the system must be considered.

Simple Payback: New Outdoor Induction Lighting Installations

Differential Capital Cost, Induction versus HPS = (Induction fixture cost + lamp costs + labor cost) – (HPS fixture cost + lamp cost + labor cost)
= ($200 + $200 lamp + $150) – ($75+$43 + $150)
= $550 – $268
Differential Capital Cost = $282

Annual Energy Savings, Induction versus HPS = (HPS wattage – Induction wattage)/1000 × 4,160 hours of operation × $0.154977 per kWh
= (118 W – 55 W)/1000 × 4,160 × $0.154977
Annual Energy Savings = $40.62

Annual Maintenance Savings, Induction versus HPS = (HPS lamp cost + labor cost) × (annual operating hours / lamp life) – (Induction lamp costs + labor cost) × (annual operating hours / lamp life)
= ($43 + $100) × (4,160/30,000) – ($200 + $100) × (4,160/60,000)
Annual Maintenance Savings = $19.83 – $20.80 = –$0.97

Simple Payback = Differential Capital Cost / (Annual Energy Savings + Annual Maintenance Savings)
= $282 / $39.65
Simple Payback = 7.1 years

Simple Payback: New Outdoor Metal Halide Lighting Installations

Differential Capital Cost, Metal Halide versus HPS = (Metal Halide fixture cost + lamp costs + labor cost) – (HPS fixture cost + lamp cost + labor cost)
= ($80 + $111 lamp + $150) – ($75+$43 + $150)
= $280 – $268
Differential Capital Cost = $73

Annual Energy Savings, Metal halide versus HPS = (HPS wattage – Metal Halide wattage)/1000 × 4,160 hours of operation × $0.154977 per kWh
= (118 W – 85 W)/1000 × 4,160 × $0.154977
Annual Energy Savings = $21.28

Annual Maintenance Savings, Metal Halide versus HPS = (HPS lamp cost + labor cost) × (annual operating hours / lamp life) – (Metal Halide lamp costs + labor cost) × (annual operating hours / lamp life)
= ($43 + $100) × (4,160/30,000) – ($111 + $100) × (4,160/24,000)
Annual Maintenance Savings = $19.83 – $30.00 = –$16.74

Simple Payback = Differential Capital Cost / (Annual Energy Savings + Annual Maintenance Savings)
= $73 / $4.54
Simple Payback = 16.1 years

Simple Payback: Retrofit Outdoor Induction Lighting Installations

Capital Cost of Induction System = Fixture cost + lamp costs + labor
= $200 + $200 lamp. + $150
Capital cost = $550

Annual energy savings and maintenance savings will be the same as new induction lamp installations described above.

Simple Payback = Capital Cost / (Annual Energy Savings + Annual Maintenance Savings)
= $550 / $39.65
Simple Payback = 13.9 years

Simple Payback: Retrofit Outdoor Metal Halide Lighting Installations

Capital Cost of Metal Halide System = Fixture cost + lamp costs + labor
= $80 + $111 lamp. + $150
Capital cost = $341

Annual energy savings and maintenance savings will be the same as new metal halide lamp installations described above.

Simple Payback = Capital Cost / (Annual Energy Savings + Annual Maintenance Savings)
= $341 / $4.54
Simple Payback = 75.1 years

Utility annual ownership and operating perspective or rate-making analysis includes the annual cost of maintenance, energy, and capital. The accepted amortization period for street lights is 27 years.[19] This is an approximation of the life of a street light fixture. The other costs that must be recovered through street light rates are the business overheads, taxes, and any profits. For purposes of this analysis, these other costs will be the same for all types of street lighting. Based on Groton Utilities' current street light rate and purchased power adjustment for a 100-watt HPS system, the "other" annual costs are $25.81.

The annualized capital cost for each street lighting system is the cost of the fixture plus cost of the lamp plus installation cost divided by the amortization period of 27 years. The annualized capital cost for the 100-watt HPS system is $75 fixture + $43 lamp + $150 installation ÷ 27 years = $9.93. The induction annualized capital cost is $200 fixture + $200 lamp + $150 installation ÷ 27 years = $27.37. The annualized capital cost for the metal halide system is $80 fixture + $111 lamp + $150 installation ÷ 27 years = $13.37

Total annual ownership and operating costs for each street light system analyzed is included in Table 11 below.

Table 11. Comparison of street light annual ownership and operating costs

	HPS	Induction	Metal Halide
Annual Capital Cost	$9.93	$27.37	$13.37
Annual Energy Cost	$76.08	$35.46	$54.80
Annual Maintenance Cost	$19.83	$20.80	$36.57
Annual "Other" Costs	$25.81	$25.81	$25.81
Total Annual Cost	**$131.64**	**$109.44**	**$130.55**

Lifecycle costs examines the capital cost of the street lighting made in Year 1 and all annual energy and "other" costs and maintenance costs as they occur over the 27-year life of the street light fixture. For this analysis, there is no salvage value or disposal costs at the end of life. A 6% annual discount rate was used to determine present value of all costs. Table 12 shows the lifecycle cost of each of the three street light systems evaluated.

Table 12. Street light systems lifecycle costs

	HPS	Induction	Metal Halide
Capital Cost	$268.00	$550.00	$341.00
Lifecycle Energy Cost	$1005.06	$468.45	$723.94
Lifecycle Maintenance Cost	$218.63	$190.34	$418.31
Lifecycle "Other" Cost	$340.96	$340.96	$340.96
Total Lifecycle Cost	**$1832.65**	**$1549.75**	**$1824.21**

Conclusions

Residents' perceptions of visibility, safety, security, brightness, and color rendering improved considerably under both the induction and ceramic metal halide street lighting compared to their perceptions with the HPS street lighting. Photopic illuminance levels were lower for both the induction and metal halide street lighting compared to the original HPS lighting. On Meridian Street, the average photopic illuminance with HPS street lighting was 9.58 lux as compared to 2.70 lux with the induction lighting. On Shennecossett Road, the average photopic illuminance with HPS street lighting was 3.20 lux as compared to 3.10 lux with the ceramic metal halide lighting.

The unified photometry system developed by the LRC is a good predictor of visual performance under different lamp scotopic-to-photopic ratios and varying photopic luminance values. The unified photometry system predicts that the visual performance should be about the same when 55-watt induction lamps at 6500 K CCT are used to replace 100-watt HPS street lighting on Meridian Street. For Shennecossett Road, the unified photometry system predicts increases in visual performance when the 70-watt ceramic metal halide lighting replaces the 100-watt HPS street lights. While the residents' survey responses on visibility are not the same as visual performance testing, they are an indicator of preferred lighting sources to enhance visibility. The unified photometry system results comparing the 100-watt HPS street lighting with the 55-watt induction and the 70-watt metal halide with regard to visibility agree with the perceptions of survey respondents.

The survey results obtained at both Meridian Street and Shennecossett Road with regard to perceptions of visibility, safety, security, brightness, and color rendering compare favorably with results from similar research conducted in Easthampton, Massachusetts, and Austin, Texas. In all cases, residents responding to similar surveys indicated they could see better and felt safer as both drivers and pedestrians with street lights that were tuned to favor mesopic vision while remaining in the white light zone.

Utilization of high scotopic-to-photopic ratio lamps under low photopic luminance conditions can reduce lamp wattage while maintaining, or improving visual performance. For luminance conditions as found on Meridian Street and Shennecossett Road, a 6500 K CCT lamp with its higher S/P ratio, such as the induction lamp used at Meridian Street, allows lower wattage lamps to be used than a lamp with a lower S/P ratio, as found with the metal halide lamp at 4000 K CCT. Using lamps with even higher S/P ratios could further reduce lamp wattages while maintaining visual performance. However, it is uncertain whether residents would accept a street light that essentially emits a green light. Therefore, a lamp with around a 6500 K CCT that remains a white light source optimizes both mesopic vision and residents' acceptance.

The induction lamp, while still considered a fluorescing light source, performed better than most linear or compact fluorescent lamps at both low and high lamp ambient temperatures. The light loss of the induction lamp at approximately 37°F was only 1% compared to a T8 lamp at 25% loss and T5 lamp with 60% loss of light output. More light is lost at high ambient temperatures than cold temperatures for the induction lamp; however, it still outperforms the T8 fluorescent lamp. For a lamp ambient temperature of approximately 115°F, the induction lamp loses approximately 10% of its light output. The T8 fluorescent lamp loses 21% at this temperature and the T5 lamp loses 5%.

The energy-saving potential is substantial with the use of either the 55-watt induction or 70-watt metal halide street lighting systems to replace 100-watt HPS street lighting. The 55-watt induction street light uses 228 kWh annually, while the 70-watt metal halide lighting uses 354 kWh annually. These are compared to 491 kWh for the 100-watt HPS system. The induction street light reduces energy use by 263 kWh annually or a 53.6% reduction. The metal halide system has an annual reduction in energy use of 137 kWh or 27.9%. These energy savings translate into annual cost savings of $40.62 for the induction street lighting and $21.28 for the metal halide. All energy costs are based on $0.154977 per kWh.[22]

Annual maintenance costs are important to any utility that must maintain a street lighting system. These costs are the second highest cost (after energy) in owning and operating a street light system. Any street lighting system that reduces maintenance costs will be favorably considered by a utility. Maintenance costs are a function of labor costs to change a burned out lamp, the cost of the lamp, and life of the lamp. In the case of the HPS street lighting system, lamp costs are relatively low and lamp life is good at 30,000 hours for non-cycling HPS lamps. Induction street lighting has double the life at 60,000 hours but both the lamp and the driver must be replaced at the end of life. These components are much more expensive than the 100-watt HPS lamp. Therefore, the annualized maintenance cost for the induction system is slightly higher ($0.97 annually) than the HPS system it would replace. Ceramic metal halide lamps currently are expensive at $111 each[20] and their life (24,000 hours[21]) is shorter than that of HPS lamps. This combination increases annualized maintenance costs for the metal halide street lighting by $16.74 above the HPS street lighting system it would replace.

The economics of replacing existing HPS street lighting systems with either the induction or metal halide street lighting must be considered before recommendations can be made. Simple paybacks are long for both new street light installations and for retrofitting existing street lighting with the induction street lighting system and even longer for the metal halide system. New induction lighting installations where just the differential capital cost is considered require the energy savings to pay off the additional capital cost in 7.1 years. Retrofitting existing HPS street lights with the induction lighting requires the energy savings to pay off the entire capital cost in 13.9 years. The metal halide system offers minimum annual savings ($4.54) compared to the HPS system because of the large increase in annual maintenance costs. Therefore, the metal halide street lighting has longer paybacks than the induction system.

There are other economic analyses used by utilities to analyze capital expenditures besides simple payback. One such analysis is utility rate-making economics where the capital costs are amortized over the useful life of the street light and are added to the annual operating, overhead, taxes, and profits costs. The accepted life of street lights is 27 years.[19] Using this economic method, the 55-watt induction street light reduces annual utility ownership and operating costs by $22.20 per street light from the existing 100-watt HPS street lighting system. There is a small decrease ($1.09) in annual utility ownership and operating costs for the metal halide lighting.

Lifecycle costing is another means of examining the economics of the different street lighting systems. All ongoing costs are brought back to a present value and added to the initial capital cost. Any salvage value or disposal costs at the end of the street light life are subtracted or added. The discount rate used for this analysis was 6%, which reflects the approximate cost of money to Groton Utilities. The 55-watt induction street lighting has the lowest lifecycle cost of the three street lighting systems examined at $1,549.75. The 70-watt metal halide system is next at $1824.21 and the 100-watt HPS system is last at $1,832.65.

Recommendations

Efficient white light sources tuned to mesopic vision conditions with high scotopic-to-photopic ratios are recommended as replacements for high-pressure sodium street lighting. These light sources should have a correlated color temperature of approximately 6500 K and provide approximately 65 to 70 photopic lumens per watt. At low luminance levels of 0.1 cd/m^2, energy savings of 40% to 50% are possible. At slightly higher luminance levels of 0.3 cd/m^2, energy savings are approximately 30%.

The 55-watt induction street lighting system at 6500 K CCT is an energy-efficient replacement for 100-watt HPS street lighting and should be pursued for new street light installations. It should also be examined as a retrofit for existing 100-watt HPS street lighting. Induction lamps perform well in both cold and hot ambient conditions. The utility ownership and operating cost and lifecycle cost economics show savings when using the induction lamp compared to the existing HPS.

The 70-watt ceramic metal halide is not a good substitution for 100-watt HPS street lighting systems and should not be pursued, primarily because the economics of the metal halide system provide minimum economic advantages compared to 100-watt HPS systems. Shorter lamp life and high lamp costs increase annual maintenance costs.

White light-emitting diodes (LEDs) are beginning to enter the street light market. These long lasting (approximately 50,000 hours) LEDs can be tuned to meet mesopic lighting conditions by applying phosphors to obtain a 6500 K CCT. Currently, commercially available white LEDs are approximately 50 lumens per watt including driver energy. However, their efficacy is improving every year. White LEDs should be considered for replacing HPS street lighting in about three years time when their efficacy is higher and their cost has reached reasonable levels to be economically viable. Groton Utilities may want to consider postponing decisions on street light replacements until white LEDs become economically available. Figure 16 illustrates a new LED street light.

Figure 16. LED street light

The unified photometry system should be used to determine replacement wattages of various size street lights based on lamp S/P ratio and, for new installations, IESNA recommended luminance values for the type of street being illuminated. For existing street lighting, measurements of existing luminance values can be calculated by measuring illuminance and roadway surface reflectance. The luminance values can be entered into the unified photometry system to determine appropriate replacement lighting systems that provide equal visual performance.

Any new or replaced street lighting must follow Connecticut law and meet the full cutoff classification of street light fixtures.

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Appendix A: Unified Photometry: An Energy-Efficient Street Lighting Demonstration in Easthampton, Massachusetts

Rensselaer

Progress Report: Improving Acceptance and Use of Energy-Efficient Lighting

Unified photometry: An energy-efficient street lighting demonstration in Easthampton, Massachusetts

Submitted to: The U.S. Energy Protection Agency

Prepared by: Yukio Akashi, Mark Rea, Peter Morante

Date: April 9, 2004

Sponsor: The U.S. Energy Protection Agency

Collaboration: Western Massachusetts Electric Company

Town of Easthampton, Massachusetts

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Paclantic International

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Unified photometry: An energy-efficient street lighting demonstration in Easthampton, Massachusetts

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April 9, 2004

SUMMARY: The Lighting Research Center (LRC) has developed a new, unified photometry system, covering all light levels—from photopic (e.g., lit interior and daytime) through mesopic (e.g., lit streets at night) to scotopic (e.g., unlit spaces at night) light levels (Rea et al. 2003; Rea et al., 2004). This new system is consistent with existing photometry and maintains all orthodox photometric conventions. And, it is easy to use by lighting engineers and manufacturers. However, to evaluate the suitability of the new photometry system for practical applications, it was still necessary to conduct a demonstration of its benefits. The LRC, in partnership with Western Massachusetts Electric Company (WMECO) and the Town of Easthampton, Massachusetts, conducted a demonstration study along Clark Street in Easthampton. The results of the demonstration showed that the new fluorescent lighting system can save 30% of the energy consumed by conventional HPS lighting on the street. In addition, the results of the surveys suggested, on the average, that residents evaluated the fluorescent lighting system as better than the HPS system regarding brightness perception, color appearance, and the perception of safety and security. Finally, this study supported the use of the new, unified photometry system.

1. INTRODUCTION

Human eyes have two types of visual receptors in the retina—cones and rods. The current system of photometry, based on the spectral sensitivity of foveal cones, does not function well at characterizing the visual effectiveness of electric light sources at mesopic light levels where rods are also involved. Since the peak wavelength sensitivity of rods is shorter than it is for cones, human visual sensitivity shifts toward shorter wavelengths at lower light levels. Therefore, current photometry underestimates the effectiveness of lamps with relatively more short-wavelength output at mesopic light levels. The unified photometry system can more appropriately evaluate the effectiveness of lamps with various spectral power distributions (SPD) by providing “unified” luminance according to the light levels to which human eyes adapt (Rea et al. 2003; Rea et al. 2004).

The use of unified photometry may completely change practices in outdoor lighting. Table 1 shows photopic illuminance and relative electric power required to obtain criterion levels of off-axis visual performance when illuminated by various SPDs. As the light level decreases, the performance of high-pressure sodium (HPS) lamps, relative to other sources, is reduced. Conversely, metal halide (MH) and fluorescent lamps, which have more short-wavelength components, reduce their relative power requirements to meet criterion visual performance levels.

The LRC developed the unified photometry system based on a series of recent laboratory studies (He et al. 1997; He et al. 1998). Simulated driving studies verified the validity of the fundamental findings but found a difference in off-axis detection between MH and HPS lamps to be sometimes larger than would be predicted by the unified photometry system (Bullough and Rea 2000; Lingard and Rea 2002). A recent field study to examine target detection by subjects driving along a closed track found that targets illuminated by MH lamps can be more quickly detected by the subjects than those made visible by HPS lamps (Akashi and Rea 2002). The results dramatically underscored the benefits of the unified photometry system. This demonstration study was conducted to extend the findings from those controlled studies to real street lighting contexts.

The objectives of the study were to demonstrate how much lighting power can be reduced through the use of the unified photometry system while improving subjective impressions.

Table 1. Photopic illuminance and relative power required to obtain the same brightness perception and visibility of spaces and objects illuminated by various SPD lamps

Light source	S/P ratio*	0.6 cd/m²		0.3 cd/m²		0.1 cd/m²	
		E (lx)**	Relative power***	E (lx)	Relative power	E(lx)	Relative power
400 W HPS	0.66	26.9	100%	13.5	100%	4.5	100%
1000 W incandescent	4.41	26.9	833%	10.5	648%	2.6	478%
3500 K fluorescent	1.44	26.9	130%	10.4	100%	2.5	73%
400 W MH	1.57	26.9	119%	10.0	88%	2.4	63%
5000 K fluorescent	1.97	26.9	130%	9.0	87%	1.9	57%
6500 K fluorescent	2.19	26.9	130%	8.5	82%	1.8	52%

* - S/P ratio: the ratio of scotopic lumens to photopic lumens of each lamp
** - E: illuminance measured in lux (lx)
***-Relative power (%) normalized to HPS

2. DEMONSTRATION
2.1. Location
For the demonstration site, the LRC sought a typical rural residential street where HPS lamps were installed. HPS lamps are one of the most efficacious lamps under the current photometry system. There are other lamps that are more efficacious under the new photometry system and therefore a change from HPS lamps was desirable for this demonstration. Streets in rural residential areas are typically illuminated by 70-100 W HPS lamps; the luminaires are widely spaced along the streets. The low lamp wattages and the wide luminaire spacing may reduce adaptation luminances down to light levels (e.g., 0.1 cd/m²) where the new system of photometry could demonstrate an advantage for a new lamp type.

In cooperation with WMECO, the LRC found Clark Street in Easthampton, Mass., where town officials have pursued energy-efficient street lighting technologies. Clark Street is approximately 1.2 km long and eight meters wide, located in a typical rural residential area, and illuminated by 70W HPS lamps attached to every two or three utility poles. Since it met all requirements listed above, Clark Street was suitable for this demonstration. Figure 1 shows the location of Clark Street and Figure 2 is a photo of the street.

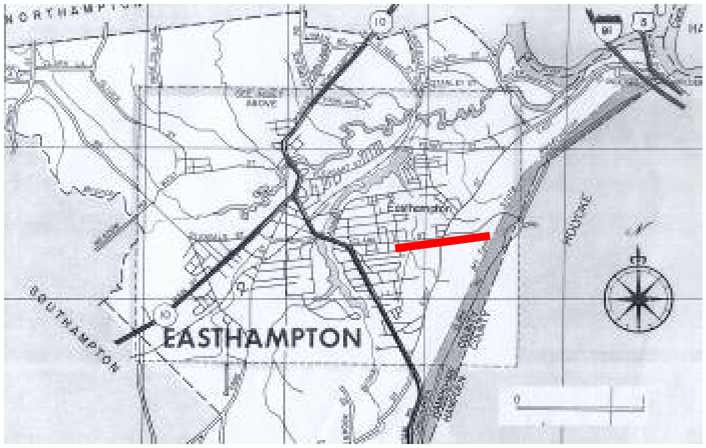

Figure 1. Demonstration site, Clark Street in Easthampton, Mass. (shown in red)

Figure 2. A view of Clark Street looking east

2.2. Existing luminaires

Clark Street was equipped with 19 HPS luminaires of the type shown in Figure 3. This study used seven of the 19 luminaires between Laura Street and Admiral Street. These luminaires were installed at a height approximately 8.2 meters (27 feet) from the road pavement and approximately 61 meters (200 feet) apart. Figure 4 shows the layout of the luminaires. Table 2 summarizes specifications for the lamp, ballast, and luminaire. As the table shows, each HPS luminaire system required 86W input power. Each luminaire has a photosensor so that it can be automatically turned on or off according to ambient illuminance.

Figure 3. Existing HPS luminaire

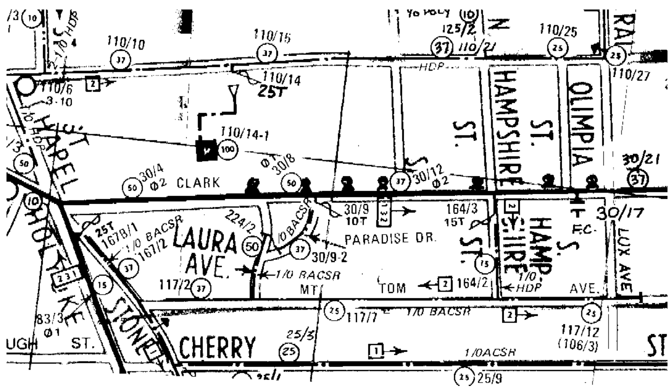

Figure 4. Luminaire layout along Clark Street

Table 2. Specification of existing HPS luminaires

Item	Description	Product #	Manufacturer
Lamp	HPS, 70 W, 6300 lm	LU70/MED	GE Lighting Systems
Ballast	Magnetic ballast, 120 V, 60 Hz, input power: 86 W	S0070-02C-511	Howard Industries
Luminaire	Semi-cutoff, cobrahead luminaire	M2RR07S1N2AMS2	GE Lighting Systems

2.3. Selection of luminaire and lamps

As the unified photometry system suggests, lamps with relatively more short-wavelength output perform better at mesopic light levels than current photometry estimates. For nominally white light sources, higher correlated color temperature (CCT) lamps usually have more short-wavelength output than those with lower CCT. Therefore, it is believed that higher CCT lamps perform better than current illuminance or luminance meters indicate. However, to estimate the performance of a given lamp at mesopic light levels compared to their photopic performance, the ratio of scotopic luminance to photopic luminance (S/P ratio) is more accurate than CCT. As the S/P ratio of lamps increases, the mesopic efficacy of the lamps improves.

Using the S/P ratio as an input variable for calculating mesopic efficacy, LRC researchers sought an efficacious lamp at mesopic light levels among fluorescent lamps because it is easy to control their S/P ratios without impairing color rendering properties. In addition, fluorescent lamps have less initial cost than HPS lamps. A potential downside of fluorescent lamps is reduced output at lower temperatures. It was not yet clear how well fluorescent lamps would perform in closed luminaires at cold temperatures. To examine lamp performance in cold weather, the researchers planned to measure illuminances when the temperature was below the freezing point.

The fluorescent lamps for this study had to meet two requirements—the lamps should have (1) a high S/P ratio and (2) a "unified" luminous flux equivalent to HPS lamps. To achieve the high S/P ratio, a 6500 K fluorescent product line (Paclantic International) was chosen with an S/P ratio of 2.88 (compared to 0.65 for the existing HPS lamps). Figure 5 shows the SPD of the fluorescent product line. To calculate "unified" luminous flux, however, it is important to know the ambient luminance to which human eyes adapt at the demonstration site.

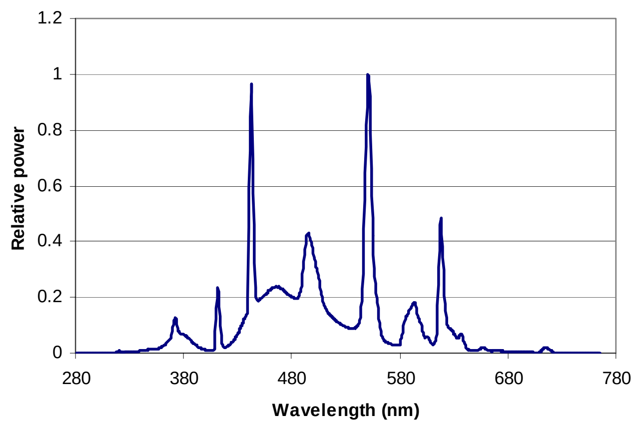

Figure 5. Spectral power distribution of fluorescent lamp

Horizontal photopic illuminance levels were measured across Clark Street every 3.6 meters (12 feet) and every 3 meters (10 feet) along the street between two luminaires, creating a grid 7.2 meters (24 feet) wide by 61 meters (200 feet) long between Laura Avenue and Paradise Drive. Table 3 shows the results of the illuminance measurements. The average illuminance of the measured area was approximately 3.4 lx. The average luminance of the roadway surface is approximately 0.08 cd/m^2, assuming the typical reflectance of asphalt is 7% (Gillet and Rombauts 2001). If the value of 0.08 cd/m^2 is used for the average luminance, the calculation result suggests a very large potential for energy savings by using this fluorescent technology. However, it was unknown how well the average luminance on the pavement could represent the overall brightness perception on the street. Therefore, this study used a higher and more conservative photopic luminance value for the calculation of power and control luminance: 0.3 cd/m^2. The 0.3

cd/m² luminance is also recommended by the IESNA as a maintained luminance for local residential streets (Rea 2000).

Table 3 Photopic illuminance distribution of HPS lighting (lx)

Distance Foot (m)	Edge 0' (0.0)	Center 12' (3.6)	Edge 24' (7.2)
0 (0.0)	10.00*	14.80	7.50
10 (3.0)	7.30	11.00	5.20
20 (6.1)	6.10	10.50	3.20
30 (9.1)	3.00	5.90	4.30
40 (12.2)	3.20	4.00	3.60
50 (15.2)	1.00	2.90	3.20
60 (18.3)	0.60	2.30	2.80
70 (21.3)	0.50	1.50	2.00
80 (24.4)	0.40	0.80	1.00
90 (27.4)	0.20	0.50	0.60
100 (30.5)	0.20	0.50	0.60
110 (33.5)	0.30	1.00	1.10
120 (36.6)	0.40	1.30	1.50
130 (39.6)	0.60	1.40	1.50
140 (42.7)	0.90	1.80	1.70
150 (45.7)	1.20	2.20	2.50
160 (48.8)	1.50	2.80	3.50
170 (51.8)	2.80	4.80	3.00
180 (54.9)	5.30	7.20	3.30
190 (57.9)	5.10	8.60	4.40
200 (61.0)	6.70*	9.50	6.00

* Illuminances measured directly below luminaire

The results of the power and luminance calculations are shown in Table 4. When the photopic luminance of the roadway pavement under HPS lighting (S/P = 0.65) is 0.3 cd/m², the equivalent mesopic luminance under the same lighting condition is 0.22 cd/m². Conversely, when the equivalent mesopic luminance of the pavement under fluorescent lighting (S/P = 2.88) is 0.22 cd/m², the photopic luminance is 0.18 cd/m². Hence, only 3900 photopic lumens are required for each new fluorescent luminaire to create a mesopic luminance of 0.22 cd/m², while an HPS luminaire needs 6300 photopic lumens to create the same mesopic luminance.

Table 4 Comparison between HPS and fluorescent systems in photopic and mesopic luminances

	Mesopic luminance (cd/m²)	S/P ratio	Photopic luminance (cd/m²)	Luminous flux (lm)	Lamp input power (W)
HPS	0.22	0.65	0.30	6300	70
Fluorescent	0.22	2.88	0.18	3900	49

Among the lamps in the 6500 K fluorescent product line described above, a 55W, T5 biaxial fluorescent lamp could achieve the lumens of 3900 lm (the actual light output of the lamp was measured at 4000 lm). The input power to the fluorescent lamp-ballast system was 60W compared to 85W with the HPS lamp-ballast system, resulting in a 30%

power reduction. Based on the calculation, the LRC chose this fluorescent lamp for the replacement of the existing HPS lamps. In addition to energy conservation, the fluorescent system has additional expectable advantages over HPS lamps. The fluorescent luminaires have a sharper cutoff angle resulting in less glare. The color rendering index (CRI) of the fluorescent lamps was 78 compared to 22 for the HPS lamps. It was expected that color appearance of traffic signs, vegetation, and vehicles would be improved by the lamp replacement. Additionally, the good color rendering property of the fluorescent lamps would enhance the perception of brightness, safety, and security in the street.

The LRC chose fluorescent luminaire equipped with a parabolic high-reflectance aluminum reflector and a full-cutoff flat lens (Table 5). The luminaire is shown in Figure 6. Subsequently, the flat lens was changed to a drop lens (Figure 7) for a reason described later. Each luminaire was equipped with a photosensor identical to the one used with the existing HPS luminaire (Figure 3).

Table 5. Fluorescent system details

	Description	Product #	Manufacturer
Lamp	55W 6500K T5 biax fluorescent lamp, 4000 lm	Prototype	Paclantic International
Ballast	Electronic ballast for FT55W/2G11 (input power: 59 W)	B254PUNV-D	Universal Lighting Technologies
Luminaire	Flat lens luminaire (changed into drop lens before the second questionnaire evaluation)	W4T55496EB	Magnaray International

Figure 6. Fluorescent luminaire with flat lens

Figure 7. Fluorescent luminaire with drop lens

2.4. Evaluation method

To compare the HPS and fluorescent lamps, the LRC issued questionnaires before and after the installation to residents who lived along and near the street. Each of the first and the second questionnaire sheets contained 18 questions. The questions in both sets were nearly identical to each other to allow for a comparison of the before- and after-replacement responses. Appendices 1 and 2 show the first and second questionnaire sheets respectively. Both questionnaires sheets were sent by mail. A self-addressed envelope was enclosed in each mailing so that the residents could easily send their responses back to the LRC. To further encourage residents' participation, WMECO offered a $25 gift certificate to each participant responding to both surveys.

2.5. Procedure

The schedule of this study is listed below:

Jul. 30	Representatives of the town of Easthampton, WMECO, and the LRC had a meeting and chose Clark Street as a demonstration site.
Sep. 17	WMECO, the town of Easthampton, and the LRC held a meeting with residents. The LRC measured illuminance distribution on Clark Street. WMECO and the LRC sent questionnaire sheets to approximately 70 nearby residents.
Oct. 8	The LRC received 30 responses out of the 70 residents and analyzed the data. The LRC prepared the luminaires (wiring and attaching sensors).
Oct. 10	WMECO replaced the HPS luminaires with fluorescent luminaires.
Nov. 18	The LRC sent postcards to let participants know the delay caused by lens replacement.
Dec. 17	WMECO replaced flat lenses with drop lenses.
Dec. 19	The LRC measured illuminance distribution on Clark Street.
Jan. 9	The LRC sent the second questionnaire sheets to the 30 participants.
Feb. 2	The LRC measured illuminance distribution at a temperature of 15°F and took pictures.
Feb. 10	The LRC received 25 responses out of the 30 first-respondents. WMECO provided gift certificates to the 25 participants.
Feb. 15	WMECO restored HPS luminaires. The LRC analyzed the data.

Prior to the replacement of the HPS lighting, the LRC first conducted a field survey, measured illuminance distribution and took photographs along the street. The illuminance measurements were conducted between the two luminaires as described previously. In addition, to evaluate luminaire luminous intensity distribution around a luminaire located at the intersection of Paradise Drive and Clark Street, illuminance levels were also measured every 1.8 meters (6 feet) across the street and 1.5 meters (5 feet) along the street covering a grid 10.2 meters (36 feet) wide and 12 meters (40 feet) long.

On September 17, 2004, WMECO called a meeting with nearby residents at the community center on Clark Street. Approximately 15 residents attended the meeting (Appendix 3). At the meeting, Mayor Michael Tautznik of Easthampton spoke to the attendees and encouraged their participation in the demonstration. Then the representatives from the LRC explained the replacement procedure and the demonstration schedule and provided the first questionnaires to the attendees. On the next day following the meeting, WMECO sent the first questionnaires to the remainder of the residents for the LRC. In total, 70 residents received the initial surveys. By October 8, the LRC had received 30 responses from the 70 recipients.

On October 10, 2003, WMECO replaced the existing HPS luminaires with the above described fluorescent luminaires. However, LRC researchers observed the street and found that the area illuminated by the flat lens fluorescent luminaires appeared dark due to their low luminaire brightness (Akashi 2003b). Contrarily, the semi-cutoff beam distribution of the initial HPS cobrahead luminaires, emitting light sideward, increased the brightness perception of the street. To make a fair comparison between HPS and fluorescent systems, researchers decided to replace the flat lens with a drop lens having a semi-cutoff luminous intensity distribution. The LRC sent postcards to the participants notifying them of potential delay caused by the lens replacement. Magnaray International prepared seven drop lenses for replacement. On December 17, 2003, WMECO completed the replacement. Once again, LRC researchers measured illuminance distribution in the same manner as done for the HPS lighting on September 17, 2003. The temperature was near the freezing point (0°C/32°F) when the measurements were made.

After several weeks, the LRC sent a second questionnaire to the 30 participants on January 9, 2004. By the middle of the February, the LRC received 25 responses out of the 30 participants. WMECO provided $25 gift certificates to each of the 25 participants. To examine the performance of the fluorescent system, the LRC chose a colder day at a temperature of approximately 15°F and measured illuminance distribution around a luminaire on Paradise Drive. Finally, WMECO restored the HPS lamps on February 15, 2004.

In Appendix 4, Figures A4-1, A4-2, and A4-3 show views of the initial HPS lighting, the fluorescent lighting with flat lenses, and the fluorescent lighting with drop lenses.

2.6. Results of illuminance measurements

Table 3 and Figure A5-1 (Appendix 5) show the photopic illuminance distribution between the two luminaires in the initial HPS condition. Figure A6-1 (Appendix 6) shows the results of the photopic illuminance measurements near the luminaire on the Paradise Drive. For the new fluorescent systems with drop lenses, Table 6, Figure A5-2 (Appendix 5), and Figure A6-2 (Appendix 6) show the results of the illuminance measurements.

A comparison in illuminance distributions between the two luminaires suggests that the average illuminance was 2.8 lx compared to 3.4 lx for the HPS lamps, meaning that the average illuminance of the fluorescent system was approximately 20% lower than the average illuminance of the HPS lighting. On Paradise Drive, Figures A6-1 and A6-2 demonstrate that the fluorescent system had much narrower illuminance distribution and higher illuminance levels just below the luminaire than those of the HPS system.

Illuminance measurement results under a colder temperature condition (15°F, or -9.40°C) on February 2, 2004 are shown in Figure A6-3 (Appendix 6). As the figure suggests, the average illuminance was 35% lower than the previous measurements (at 32°F). Therefore, the average illuminance between the two poles could be around 1.8 lx, or approximately 45% lower than the HPS lighting (3.4 lx) under the low temperature condition. Since it was very cold while the fluorescent systems were installed, the average illuminance may have been lower than the initial photopic illuminance measurement of 2.8 lx. However, the input power of fluorescent lamps may have also been decreased in proportion to the reduction in output as described later.

Table 6. Illuminance distribution of fluorescent system (lx)

Distance Foot	(m)	Edge 0' (0.0)	Center 12' (3.6)	Edge 24' (7.2)
0	(0.0)	25.00*	20.10	6.60
10	(3.0)	14.30	10.50	3.70
20	(6.1)	5.20	4.10	2.10
30	(9.1)	2.04	1.80	1.05
40	(12.2)	0.82	0.68	0.68
50	(15.2)	0.75	0.33	0.45
60	(18.3)	0.19	0.17	0.16
70	(21.3)	0.12	0.10	0.08
80	(24.4)	0.09	0.08	0.10
90	(27.4)	0.15	0.08	0.08
100	(30.5)	0.08	0.06	0.09
110	(33.5)	0.12	0.07	0.06
120	(36.6)	0.09	0.08	0.03
130	(39.6)	0.10	0.08	0.10
140	(42.7)	0.17	0.15	0.16
150	(45.7)	0.37	0.37	0.33
160	(48.8)	0.71	0.60	0.65
170	(51.8)	1.56	1.62	1.29
180	(54.9)	3.62	3.56	2.29
190	(57.9)	8.55	8.40	4.56
200	(61.0)	17.60*	13.50	6.10

* Illuminances measured directly below luminaires

2.7. Results of evaluation

The analysis of the evaluation data took the mean and median of five-point rating data over the 30 responses for the HPS and 25 responses for the fluorescent lighting. Figures 8 and 9 show the evaluation data for the 18 questions. A comparison of the before- and after-replacement evaluations suggests, on the average, that the fluorescent system was evaluated as better than the HPS lighting on all questions. The results of the medians also suggest that the fluorescent system was better than (on 13 questions) or the same as (on 5 questions) the HPS lighting.

To examine statistically significant differences between the two lighting conditions, a paired t-test was applied to each of the 18 questions by using the 25 response data. Table 7 shows the results of the statistical analysis as well as the mean and standard deviations of the evaluations of the 25 participants for the 18 questions. Appendix 7 details the results of the t-tests. From Table 7, the data again shows that the mean of the 25 responses for the fluorescent system were better than those for the HPS lighting. The results of the t-tests suggests that the difference in evaluation between the HPS lighting and the fluorescent system was statistically significant in terms of questions 2: comfort, 3: brightness, 4: gloom, 5: luminaire glare, 6: color appearance of traffic signs, 7: color appearance of vegetation, 8: too warm light color, 11: pavement visibility from drivers, 13: pedestrian visibility from drivers, 14: safe feeling while driving, 15: pedestrian visibility from pedestrians, 16: face visibility from pedestrians, and 18: secure feeling while walking. Regarding preference (question 1) and comprehensive evaluation (question 20), no significant difference was found between the HPS and the fluorescent lighting although, on average, the fluorescent lighting was better than the HPS lighting.

Consequently, the results of the evaluations suggested under the fluorescent lighting condition:

- The street appeared brighter and more comfortable;
- The luminaires caused less glare;
- Colors of traffic signs appeared more clearly;
- Vegetation colors looked more natural;
- Pavement visibility, pedestrian visibility, and perception of safety while driving were improved;
- Pedestrian visibility, facial recognition, and perception of security while walking were improved

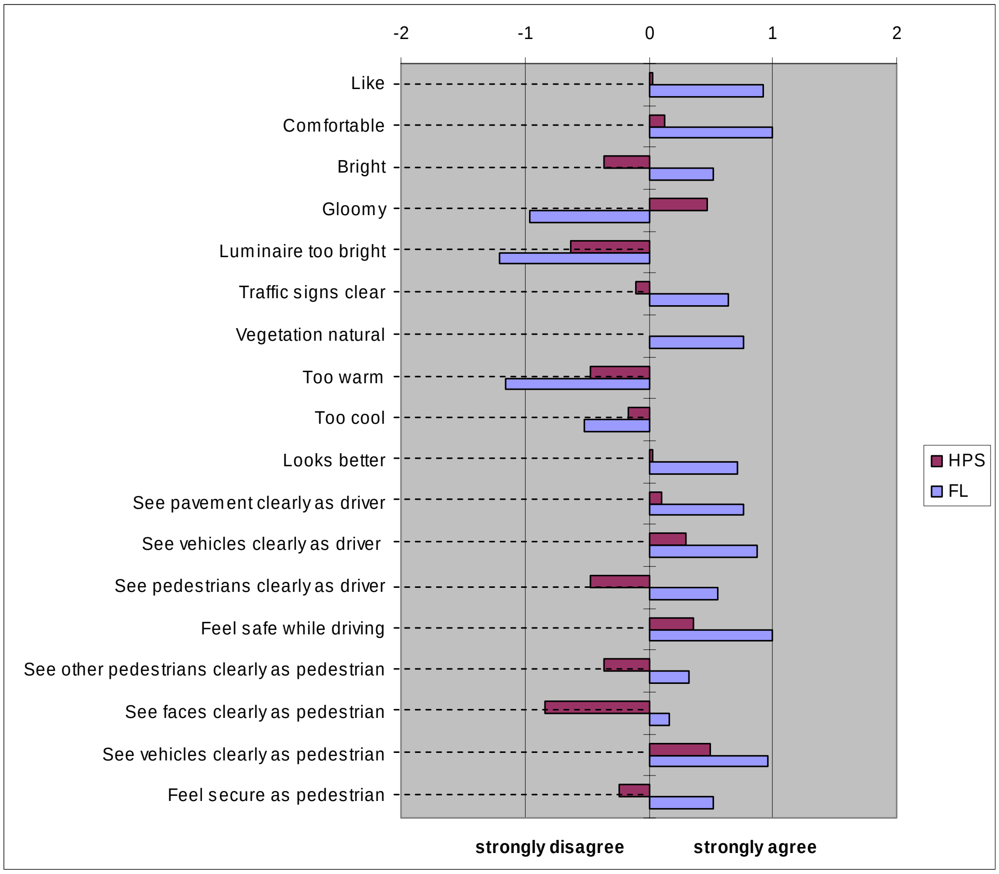

Figure 8. Mean evaluation results (30 responses for HPS and 25 responses for fluorescent lighting)

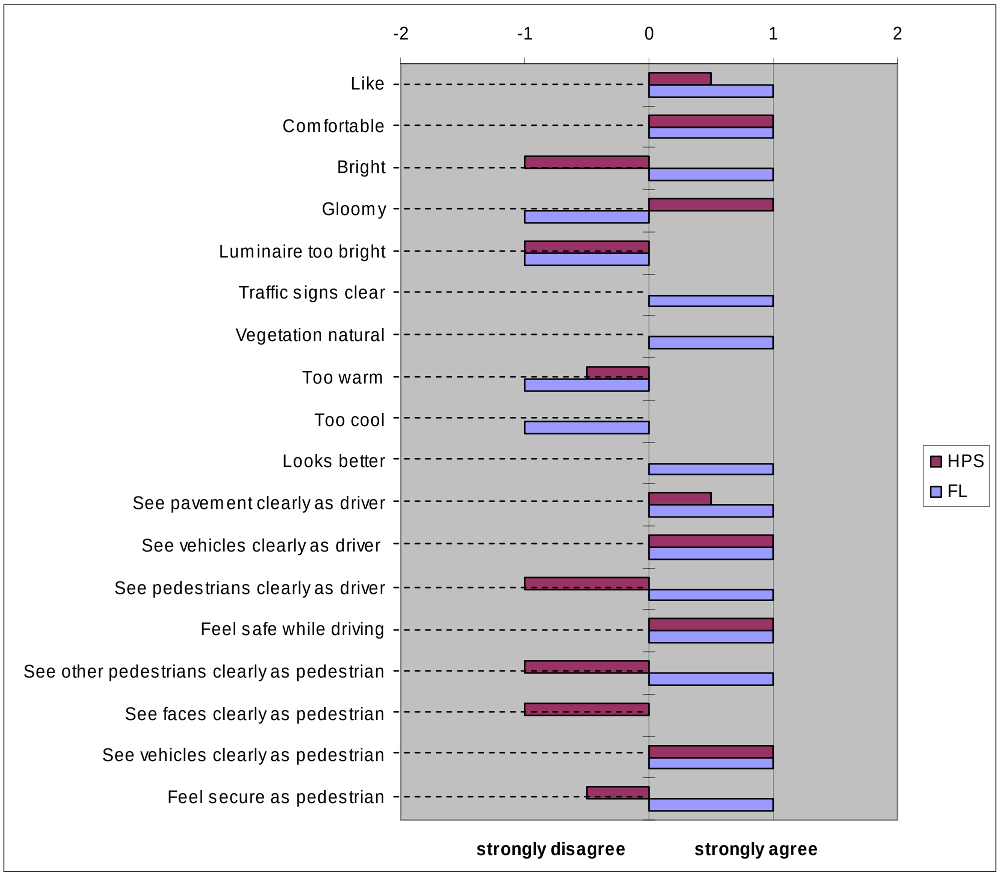

Figure 9. Median evaluation results (30 responses for HPS and 25 responses for fluorescent lighting)

Table 7. Results of evaluations: mean, standard deviation, and results of paired t-tests (25 responses for both HPS and fluorescent lighting conditions)

#	Questions	HPS		FL		p-value
		Mean	SD	Mean	SD	
1	Like	0.08	1.222	0.92	1.288	0.054
2	Comfortable	0.2	1.118	1	1.08	0.020 *
3	Bright	-0.4	1.118	0.52	1.262	0.015 *
4	Gloomy	0.48	1.262	-0.96	1.172	0.000 **
5	Luminaire too bright	-0.6	1.041	-1.2	0.957	0.040 *
6	Traffic signs clear	-0.04	1.136	0.64	0.995	0.038 *
7	Vegetation natural	-0.08	1.152	0.76	0.831	0.018 *
8	Too warm	-0.32	0.9	-1.16	1.028	0.002 **
9	Too cool	-0.16	0.943	-0.52	1.358	0.280
10	Looks better	0.08	1.038	0.72	1.37	0.111
11	See pavement clearly as driver	0.16	1.143	0.76	0.831	0.049 *
12	See vehicles clearly as driver	-0.56	1.158	0.56	0.87	0.067
13	See pedestrians clearly as driver	0.44	0.917	1	0.764	0.000 **
14	Feel safe while driving	-0.36	1.15	0.32	1.03	0.010 *
15	See other pedestrians clearly as pedestrian	-0.92	0.997	0.16	1.179	0.047 *
16	See faces clearly as pedestrian	0.64	0.907	0.96	0.676	0.001 **
17	See vehicles clearly as pedestrian	-0.2	1.118	0.52	0.872	0.175
18	Feel secure as pedestrian	0.08	1.222	0.92	1.288	0.005 **

*p<0.05, **p<0.01

3. DISCUSSION

3.1. Calculation of mesopic luminance

As previously described, this study measured photopic illuminance distributions for the HPS and fluorescent lighting. By using those measurements, this study tried to calculate the "unified" luminance to which human eyes actually adapted. However, it is unknown to what luminance human eyes adapt while driving and walking along streets which have non-uniform, complex luminance distributions. This study assumed that human eyes would adapt to the average luminance of each unit area (3.2 meters by 3.0 meters) corresponding to the measurement grid of the study. Another assumption made in this calculation was that the asphalt surface has the perfect diffuse reflection characteristics with a reflectance of 7% (Gillet and Rombauts 2001). Based on those assumptions, this calculation first obtained photopic luminance distributions on the pavement. Table 8 shows the photopic luminances for the HPS and the fluorescent lighting.

Table 8. Photopic luminance distribution of HPS and fluorescent systems (cd/m^2)

Distance		Edge 0' (0.0)		Center 12' (3.6)		Edge 24' (7.2)	
Foot	(m)	**HPS**	**FL**	**HPS**	**FL**	**HPS**	**FL**
0	(0.0)	0.223*	0.577*	0.330	0.508	0.167	0.249
10	(3.0)	0.163	0.413	0.245	0.340	0.116	0.164
20	(6.1)	0.136	0.210	0.234	0.177	0.071	0.105
30	(9.1)	0.067	0.103	0.131	0.093	0.096	0.058
40	(12.2)	0.071	0.047	0.089	0.040	0.080	0.040
50	(15.2)	0.022	0.043	0.065	0.020	0.071	0.027
60	(18.3)	0.013	0.012	0.051	0.011	0.062	0.010
70	(21.3)	0.011	0.008	0.033	0.006	0.045	0.005
80	(24.4)	0.009	0.006	0.018	0.005	0.022	0.006
90	(27.4)	0.004	0.009	0.011	0.005	0.013	0.005
100	(30.5)	0.004	0.005	0.011	0.004	0.013	0.006
110	(33.5)	0.007	0.008	0.022	0.004	0.025	0.004
120	(36.6)	0.009	0.006	0.029	0.005	0.033	0.002
130	(39.6)	0.013	0.006	0.031	0.005	0.033	0.006
140	(42.7)	0.020	0.011	0.040	0.010	0.038	0.010
150	(45.7)	0.027	0.022	0.049	0.022	0.056	0.020
160	(48.8)	0.033	0.041	0.062	0.035	0.078	0.038
170	(51.8)	0.062	0.082	0.107	0.085	0.067	0.070
180	(54.9)	0.118	0.161	0.160	0.159	0.074	0.113
190	(57.9)	0.114	0.297	0.192	0.293	0.098	0.191
200	(61.0)	0.149*	0.469*	0.212	0.399	0.134	0.235

*Illuminances measured directly below luminaires

Using the unified photometry system, the photopic luminances in Table 8 were converted into "unified" luminances in Table 9. The averaged "unified" luminance of the fluorescent system was 0.097 cd/m^2 compared to 0.059 cd/m^2 for the HPS system. Those values suggest that luminance to which human eyes might adapt to under the fluorescent lighting condition was approximately 40% higher than adaptation luminance under the HPS lighting. A recent study suggested that an illuminance change of over 20% is noticeable by 50% of the people (Akashi and Neches 2004).

Table 9. Unified luminance distribution of HPS and fluorescent systems (cd/m^2)

Distance		Edge 0' (0.0)		Center 12' (3.6)		Edge 24' (7.2)	
Foot	(m)	HPS	FL	HPS	FL	HPS	FL
0	(0.0)	0.187*	0.577*	0.297	0.508	0.134	0.249
10	(3.0)	0.130	0.413	0.209	0.340	0.088	0.164
20	(6.1)	0.106	0.210	0.198	0.177	0.051	0.105
30	(9.1)	0.048	0.103	0.102	0.093	0.071	0.058
40	(12.2)	0.051	0.047	0.066	0.040	0.059	0.040
50	(15.2)	0.015	0.043	0.046	0.020	0.051	0.027
60	(18.3)	0.009	0.012	0.036	0.011	0.045	0.010
70	(21.3)	0.007	0.008	0.023	0.006	0.031	0.005
80	(24.4)	0.006	0.006	0.012	0.005	0.015	0.006
90	(27.4)	0.003	0.009	0.007	0.005	0.009	0.005
100	(30.5)	0.003	0.005	0.007	0.004	0.009	0.006
110	(33.5)	0.004	0.008	0.015	0.004	0.017	0.004
120	(36.6)	0.006	0.006	0.020	0.005	0.023	0.002
130	(39.6)	0.009	0.006	0.021	0.005	0.023	0.006
140	(42.7)	0.014	0.011	0.028	0.010	0.026	0.010
150	(45.7)	0.018	0.022	0.034	0.022	0.039	0.020
160	(48.8)	0.023	0.041	0.045	0.035	0.057	0.038
170	(51.8)	0.045	0.082	0.081	0.085	0.048	0.070
180	(54.9)	0.090	0.161	0.128	0.159	0.053	0.113
190	(57.9)	0.086	0.297	0.157	0.293	0.073	0.191
200	(61.0)	0.118*	0.469*	0.176	0.399	0.104	0.235

* Illuminances measured directly below luminaires

The unified photometry system may also allow us to more appropriately evaluate luminance uniformity on the pavement. Using current photopic photometry, the luminance uniformity (L_{ave}/L_{min}) of the HPS lighting had a ratio of 17 and the fluorescent lighting 86. Using unified photometry, the luminance uniformity (L_{ave}/L_{min}) of the HPS lighting had a ratio of 20 and the fluorescent lighting 46. This suggests that the use of lamps with higher S/P ratios can improve the "unified" luminance uniformity on the pavement. This may overcome a disadvantage of fluorescent lamps that their larger lamp sizes make their optical control more difficult than HPS lamps.

3.2. Limitations of this demonstration

The results of this demonstration study indicated that the unified photometry functioned well in a real street context. However, there were several factors that could not be controlled during the experiment. One of the issues was that the fluorescent system provided less uniform light distribution than the HPS system. This was because the fluorescent luminaire was designed for fence lighting and not optimized for street lighting. The luminous intensity distribution of the luminaire was too narrow for the mounting height of 8.2 meters (27 feet), although it is unclear how the non-uniform luminance distribution influenced the evaluation. To better assess the fluorescent luminaire system, a different angular distribution should be demonstrated.

Second, as the measurements suggested, low temperatures (0°F to 32°F) reduced the output of the fluorescent lamps. Illuminance reduction caused by the low temperature might have affected the evaluations. Nonetheless, the results of the evaluations proved that most participants felt that the fluorescent lighting condition was brighter. Also, during the demonstration, there were no complaints from residents or town officials. Figure 10 shows the relative output of T8 and T5 linear fluorescent lamps as a function of ambient temperature (Akashi 2003a). As the figure suggests, T8 and T5 lamps are optimized at temperatures of 25°C and 35°C. If the ambient temperature is higher or lower than the optimal temperature, the output of those lamps is decreased. The input power is also reduced in proportion to the decrease of the output. For a more accurate energy-efficiency evaluation of fluorescent lighting systems, it is necessary to examine the profile of output and input power of fluorescent lamps in closed fixtures at both high and low temperatures.

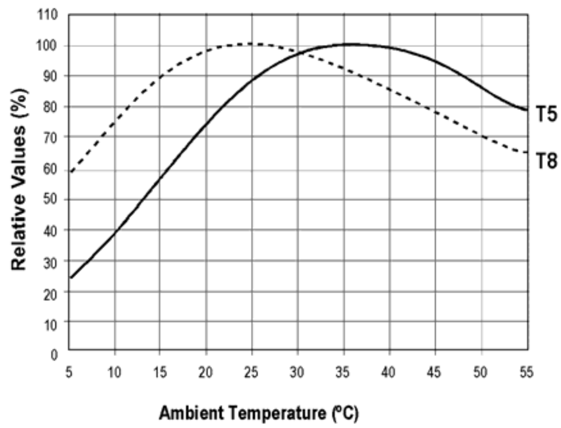

Figure 10. Relative light output variation as a function of ambient temperature for T5 and T8 fluorescent lamps.

(This diagram is based on SILHOUETTE T5, T5HO & T5 Circular Fluorescent Lamp Technology Guide, Philips Lighting)

The influence of seasonal factors such as color of leaves, fallen leaves, and fallen snow pose potential problems. These factors were uncontrollable and their influence on the evaluations is unknown. To avoid these problems in future studies, it is important to compare both lighting conditions simultaneously throughout the year.

This study used fluorescent lamps because they are relatively easy to change their SPD by selecting phosphors and their proportions. However, high intensity discharge lamps such as metal halide lamps with a high S/P ratio can also replace HPS lamps in the same contexts.

4. CONCLUSIONS

This study successfully demonstrated how the use of a unified photometry system can conserve street lighting energy in rural areas. Fluorescent lamps with a high S/P ratio (2.88) reduced power by at least 30% relative to conventional HPS street lighting. The results of the evaluations suggested, on the average, that the fluorescent lighting system was evaluated as better than the HPS lighting for all 18 questions and that, on 13 of the 18 questions, the difference in evaluation between the fluorescent lighting and HPS lighting was statistically significant. Consequently, the results of the evaluations suggested under the fluorescent lighting condition: the street appeared brighter and more comfortable; the luminaires caused less glare; colors of traffic signs appeared more clearly; vegetation colors looked more natural; pavement visibility, pedestrian visibility, and perception of safety while driving were improved; pedestrian visibility, facial recognition, and perception of security while walking were improved. Therefore, this demonstration supported the used of the unified photometry in a street lighting context.

ACKNOWLEDGEMENTS

This demonstration study was supported by the United States Environmental Protection Agency. The authors would like to acknowledge Easthampton Mayor Michael Tautznik; Paul P. Tangredi, John E. Scanlon, and Elizabeth of Western Massachusetts Electric Company for their collaboration. The authors would like to thank Larry Leetzow of Magnaray International, Inc. and Jack Johng of Paclantic International, Inc. for their donation of prototype luminaires and lamps respectively. Mariana Figueiro, Martin Overington, Dennis Guyon, and Jennifer Taylor of the Lighting Research Center made valuable contributions to this demonstration study.

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Appendix 1: First questionnaire sent September 18, 2003

**Questionnaire on Lighting of Clark Street in Easthampton, Massachusetts:
A demonstration project sponsored by the U.S. Environmental Protection Agency**

Yukio Akashi, Mark Rea, Peter Morante
Lighting Research Center, Rensselaer Polytechnic Institute, 21 Union Street, Troy, NY 12180

The Lighting Research Center (LRC), in partnership with the Western Massachusetts Electric Company (WMECO) and the Town of Easthampton, will conduct an energy efficient lighting demonstration. The LRC and WMECO will temporally replace existing high pressure sodium lamps with fluorescent lamps for the seven of the 19 poles along Clark Street (between Laura St. and Admiral St.) Before replacing the lighting, we would like to know your opinions on the street. Please observe the street and the lighting at night, then, circle the number which most closely describes the degree of your agreement with each statement— -2: strongly disagree, -1: disagree, 0: neutral, +1: agree, +2: strongly agree. Then, please return this sheet to us by September 26th, 2003.

Overall

1. I like the lighting on Clark Street.	(-2 -1 0 +1 +2)
2. The lighting on Clark Street is comfortable.	(-2 -1 0 +1 +2)
3. Clark Street looks bright.	(-2 -1 0 +1 +2)
4. Clark Street looks gloomy.	(-2 -1 0 +1 +2)
5. The light fixtures on the poles in Clark Street are too bright.	(-2 -1 0 +1 +2)
6. Colors of traffic signs along Clark Street appear clear.	(-2 -1 0 +1 +2)
7. Colors of vegetation along Clark Street look natural.	(-2 -1 0 +1 +2)
8. The lighting on Clark Street is too warm in color for a street.	(-2 -1 0 +1 +2)
9. The lighting on Clark Street is too cool in color for a street.	(-2 -1 0 +1 +2)
10. The lighting of the street looks better than others.	(-2 -1 0 +1 +2)

As a driver, with this lighting,

11. I can see the roadway pavement on Clark Street clearly.	(-2 -1 0 +1 +2)
12. I can see other vehicles approaching on Clark Street clearly.	(-2 -1 0 +1 +2)
13. I can see pedestrians approaching on Clark Street clearly.	(-2 -1 0 +1 +2)
14. I feel safe while driving along Clark Street.	(-2 -1 0 +1 +2)

As a pedestrian, with this lighting,

15. I can see other pedestrians approaching on Clark Street clearly.	(-2 -1 0 +1 +2)
16. I can see faces of pedestrians on Clark Street clearly.	(-2 -1 0 +1 +2)
17. I can see vehicles approaching on Clark Street clearly.	(-2 -1 0 +1 +2)
18. I feel secure while walking on the sidewalk of Clark Street.	(-2 -1 0 +1 +2)

If you have any questions and comments, please feel free to contact Yukio Akashi at 518-687-7126 (akashy@rpi.edu). Thank you for your time and cooperation.

Appendix 2: Second questionnaire sent January 9, 2004

Lighting Questionnaire for Clark Street, Easthampton, Massachusetts
A demonstration project sponsored by the U.S. Environmental Protection Agency
Lighting Research Center, Rensselaer Polytechnic Institute, 21 Union Street, Troy, NY 12180

Thank you for your participation in the energy efficient lighting demonstration that the Lighting Research Center (LRC) is conducting with the Western Massachusetts Electric Company (WMECO) and the Town of Easthampton. The LRC and WMECO temporarily replaced the original orange-colored light bulbs with white light bulbs for the seven of the 19 poles along Clark Street (between Laura Avenue and Admiral Street) in October 2003. Then, we slightly modified the lenses of the white light fixtures in December 2003. Now, we would like to know your opinions of the current white street lighting. Please observe the street and the lighting at night, then, circle the number which most closely describes the degree of your agreement with each statement:

-2: strongly disagree, -1: disagree, 0: neutral, 1: agree, 2: strongly agree.

Then, please return this sheet with the enclosed envelope to us by January 31st, 2004.

Overall for the new white lighting,

11. I like the new white lighting on Clark Street.	-2	-1	0	1	2
12. The lighting on Clark Street is comfortable.	-2	-1	0	1	2
13. Clark Street looks bright.	-2	-1	0	1	2
14. Clark Street looks gloomy.	-2	-1	0	1	2
15. The light fixtures on the poles in Clark Street are too bright.	-2	-1	0	1	2
16. The colors of traffic signs along Clark Street appear clear.	-2	-1	0	1	2
17. The colors of vegetation along Clark Street look natural.	-2	-1	0	1	2
18. The lighting on Clark Street is too warm (orange) in color for a street.	-2	-1	0	1	2
19. The lighting on Clark Street is too cool (blue) in color for a street.	-2	-1	0	1	2
20. The new lighting of the street looks better than the old lighting (you may also compare the new lighting with the orange-colored lighting along Clark Street between Charles St. and East St.).	-2	-1	0	1	2

As a driver, with this white lighting,

11. I can see the roadway pavement on Clark Street clearly.	-2	-1	0	1	2
12. I can see other vehicles approaching on Clark Street clearly.	-2	-1	0	1	2
13. I can see pedestrians approaching on Clark Street clearly.	-2	-1	0	1	2
14. I feel safe while driving along Clark Street.	-2	-1	0	1	2

As a pedestrian, with this white lighting,

15. I can see other pedestrians approaching on Clark Street clearly.	-2	-1	0	1	2
16. I can see faces of pedestrians on Clark Street clearly.	-2	-1	0	1	2
17. I can see vehicles approaching on Clark Street clearly.	-2	-1	0	1	2
18. I feel secure while walking on the sidewalk of Clark Street.	-2	-1	0	1	2

If you have any questions and comments, please feel free to contact Yukio Akashi at 518-687-7126 (akashy@rpi.edu). Thank you for your time and contribution.

Appendix 3: Meeting with nearby residents at Clark Street Community Center

Figure A3-1. Easthampton Mayor Michael Tautznik speaks at the meeting at the Clark street community center

Figure A3-2. Yukio Akashi of the LRC explains the demonstration procedure

Appendix 4: Views of lighting conditions

Figure A4-1. HPS lighting

Figure A4-2. Fluorescent lighting with flat lens

Figure A4-3. Fluorescent lighting with drop lens

Appendix 5: Photopic illuminance measurements between two luminaires

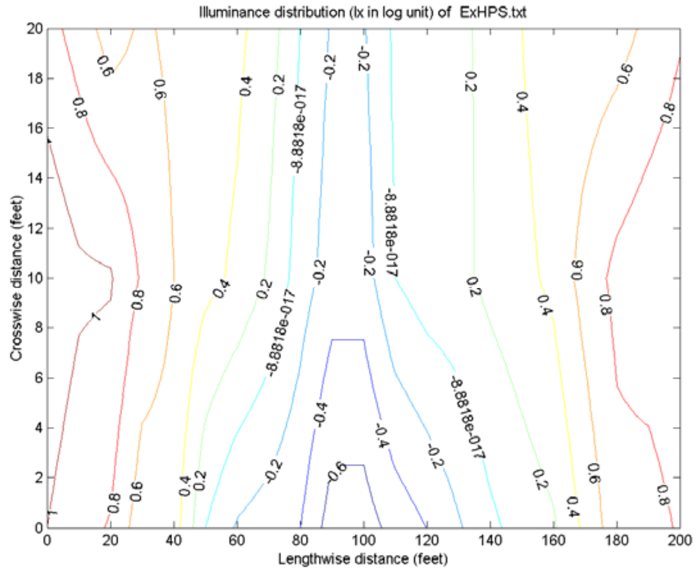

Figure A5-1. Illuminance distribution between two poles for HPS lighting (log lx)

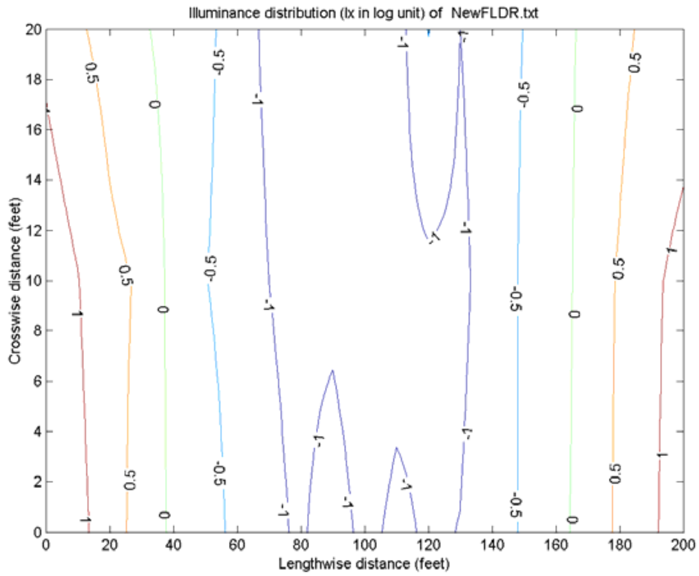

Figure A5-2. Illuminance distribution between two poles for fluorescent lighting (log lx)

Appendix 6: Photopic illuminance distribution near the luminaire at the intersection of Paradise Drive and Clark Street.

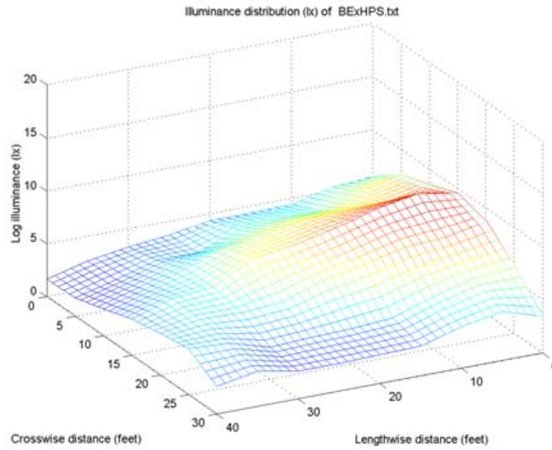

Figure A6-1. Illuminance distribution around a pole for the existing HPS lighting (log lx)

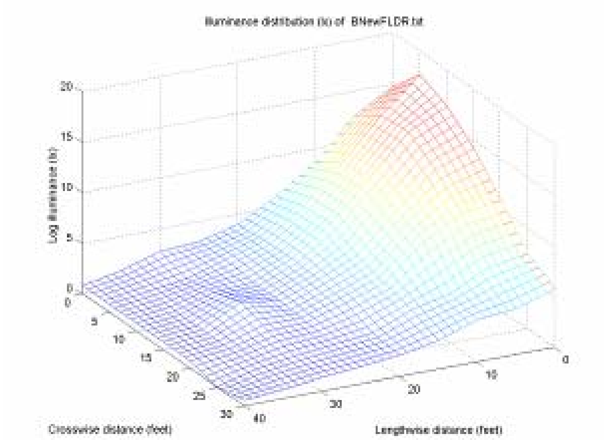

Figure A6-2. Illuminance distribution around a pole for the fluorescent lighting (log lx) (data measured at 32°F)

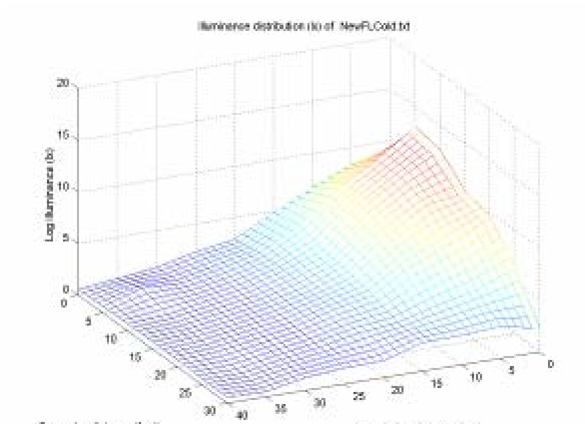

Figure A6-3. Illuminance distribution around a pole for the fluorescent lighting (log lx) (data measured at 15°F)

Appendix 7: Results of paired T-test and confidence interval

1. I like the lighting on Clark Street

	N	Mean	StDev	SE Mean
HPS	25	0.080	1.222	0.244
FL	25	0.920	1.288	0.258
Difference	25	-0.840	2.075	0.415

95% CI for mean difference: (-1.697, 0.017)
T-Test of mean difference = 0 (vs not = 0): T-Value = -2.02, P-Value = 0.054

2. The lighting on Clark Street is comfortable.

	N	Mean	StDev	SE Mean
HPS	25	0.200	1.118	0.224
FL	25	1.000	1.080	0.216
Difference	25	-0.800	1.607	0.321

95% CI for mean difference: (-1.463, -0.137)
T-Test of mean difference = 0 (vs not = 0): T-Value = -2.49, P-Value = 0.020*

3. Clark Street looks bright.

	N	Mean	StDev	SE Mean
HPS	25	-0.400	1.118	0.224
FL	25	0.520	1.262	0.252
Difference	25	-0.920	1.754	0.351

95% CI for mean difference: (-1.644, -0.196)
T-Test of mean difference = 0 (vs not = 0): T-Value = -2.62, P-Value = 0.015*

4. Clark Street looks gloomy.

	N	Mean	StDev	SE Mean
HPS	25	0.480	1.262	0.252
FL	25	-0.960	1.172	0.234
Difference	25	1.440	1.502	0.300

95% CI for mean difference: (0.820, 2.060)
T-Test of mean difference = 0 (vs not = 0): T-Value = 4.79, P-Value = 0.000**

5. The light fixtures on the poles in Clark Street are too bright.

	N	Mean	StDev	SE Mean
HPS	25	-0.600	1.041	0.208
FL	25	-1.200	0.957	0.191
Difference	25	0.600	1.384	0.277

95% CI for mean difference: (0.029, 1.171)
T-Test of mean difference = 0 (vs not = 0): T-Value = 2.17, P-Value = 0.040*

6. Colors of traffic signs along Clark Street appear clear.

	N	Mean	StDev	SE Mean
HPS	25	-0.040	1.136	0.227
FL	25	0.640	0.995	0.199
Difference	25	-0.680	1.547	0.309

95% CI for mean difference: (-1.319, -0.041)
T-Test of mean difference = 0 (vs not = 0): T-Value = -2.20, P-Value = 0.038*

7. Colors of vegetation along Clark Street look natural.

	N	Mean	StDev	SE Mean
HPS	25	-0.080	1.152	0.230
FL	25	0.760	0.831	0.166
Difference	25	-0.840	1.650	0.330

95% CI for mean difference: (-1.521, -0.159)
T-Test of mean difference = 0 (vs not = 0): T-Value = -2.55, P-Value = 0.018*

8. The lighting on Clark Street is too warm in color for a street.

	N	Mean	StDev	SE Mean
HPS	25	-0.320	0.900	0.180
FL	25	-1.160	1.028	0.206
Difference	25	0.840	1.214	0.243

95% CI for mean difference: (0.339, 1.341)
T-Test of mean difference = 0 (vs not = 0): T-Value = 3.46, P-Value = 0.002**

9. The lighting on Clark Street is too cool in color for a street.

	N	Mean	StDev	SE Mean
HPS	25	-0.160	0.943	0.189
FL	25	-0.520	1.358	0.272
Difference	25	0.360	1.630	0.326

95% CI for mean difference: (-0.313, 1.033)
T-Test of mean difference = 0 (vs not = 0): T-Value = 1.10, P-Value = 0.280

10. The lighting of the street looks better than others.

	N	Mean	StDev	SE Mean
HPS	25	0.080	1.038	0.208
FL	25	0.720	1.370	0.274
Difference	25	-0.640	1.934	0.387

95% CI for mean difference: (-1.438, 0.158)
T-Test of mean difference = 0 (vs not = 0): T-Value = -1.65, P-Value = 0.111

11. I can see the roadway pavement on Clark Street clearly while driving.

	N	Mean	StDev	SE Mean
HPS	25	0.160	1.143	0.229
FL	25	0.760	0.831	0.166
Difference	25	-0.600	1.443	0.289

95% CI for mean difference: (-1.196, -0.004)
T-Test of mean difference = 0 (vs not = 0): T-Value = -2.08, P-Value = 0.049*

12. I can see other vehicles approaching on Clark Street clearly.

	N	Mean	StDev	SE Mean
HPS	25	0.360	1.075	0.215
FL	25	0.880	0.726	0.145
Difference	25	-0.520	1.358	0.272

95% CI for mean difference: (-1.080, 0.040)
T-Test of mean difference = 0 (vs not = 0): T-Value = -1.92, P-Value = 0.067

13. I can see pedestrians approaching on Clark Street clearly while driving.

	N	Mean	StDev	SE Mean
HPS	25	-0.560	1.158	0.232
FL	25	0.560	0.870	0.174
Difference	25	-1.120	1.333	0.267

95% CI for mean difference: (-1.670, -0.570)
T-Test of mean difference = 0 (vs not = 0): T-Value = -4.20, P-Value = 0.000**

14. I feel safe while driving along Clark Street.

	N	Mean	StDev	SE Mean
HPS	25	0.440	0.917	0.183
FL	25	1.000	0.764	0.153
Difference	25	-0.560	1.003	0.201

95% CI for mean difference: (-0.974, -0.146)
T-Test of mean difference = 0 (vs not = 0): T-Value = -2.79, P-Value = 0.010*

15. I can see other pedestrians approaching on Clark Street clearly.

	N	Mean	StDev	SE Mean
HPS	25	-0.360	1.150	0.230
FL	25	0.320	1.030	0.206
Difference	25	-0.680	1.626	0.325

95% CI for mean difference: (-1.351, -0.009)
T-Test of mean difference = 0 (vs not = 0): T-Value = -2.09, P-Value = 0.047*

16. I can see faces of pedestrians on Clark Street clearly

	N	Mean	StDev	SE Mean
HPS	25	-0.920	0.997	0.199
FL	25	0.160	1.179	0.236
Difference	25	-1.080	1.412	0.282

95% CI for mean difference: (-1.663, -0.497)
T-Test of mean difference = 0 (vs not = 0): T-Value = -3.82, P-Value = 0.001**

17. I can see vehicles approaching on Clark Street clearly.

	N	Mean	StDev	SE Mean
HPS	25	0.640	0.907	0.181
FL	25	0.960	0.676	0.135
Difference	25	-0.320	1.145	0.229

95% CI for mean difference: (-0.792, 0.152)
T-Test of mean difference = 0 (vs not = 0): T-Value = -1.40, P-Value = 0.175

18. I feel secure while walking on the sidewalk of Clark Street.

	N	Mean	StDev	SE Mean
HPS	25	-0.200	1.118	0.224
FL	25	0.520	0.872	0.174
Difference	25	-0.720	1.173	0.235

95% CI for mean difference: (-1.204, -0.236)
T-Test of mean difference = 0 (vs not = 0): T-Value = -3.07, P-Value = 0.005**

Appendix B: Baseline Resident Street light Survey Questionnaire

The Lighting Research Center (LRC), in partnership with Groton Utilities, will conduct a street lighting demonstration. The LRC and Groton Utilities will replace existing high pressure sodium street lights with a fluorescent lighting source on twelve poles along Meridian Street (between Park Ave. and Mitchell St.). Before replacing the lighting, we would like to know your opinions of the current street lighting. The completion of this survey is completely voluntary. Please observe the street and the lighting at night, then, circle the number which most closely describes the degree of your agreement with each statement:

-2: strongly disagree, -1: disagree, 0: neutral, +1: agree, +2: strongly agree.

Then, please return this sheet in the enclosed self addressed stamped envelope by April 20, 2007.

Overall

21. I like the lighting on Meridian Street. (-2 -1 0 +1 +2)
22. The lighting on Meridian Street is comfortable. (-2 -1 0 +1 +2)
23. Meridian Street looks bright. (-2 -1 0 +1 +2)
24. Meridian Street looks gloomy. (-2 -1 0 +1 +2)
25. The light fixtures on the poles on Meridian Street are too bright (-2 -1 0 +1 +2)
26. Colors of traffic signs along Meridian Street appear clear. (-2 -1 0 +1 +2)
27. Colors of vegetation along Meridian Street look natural. (-2 -1 0 +1 +2)
28. The lighting on Meridian Street is too warm in color for a street(-2 -1 0 +1 +2)
29. The lighting on Meridian Street is too cool in color for a street. (-2 -1 0 +1 +2)
30. The lighting of the street looks better than others. (-2 -1 0 +1 +2)

As a driver, with this lighting,

15. I can see the roadway pavement on Meridian Street clearly. (-2 -1 0 +1 +2)
16. I can see other vehicles approaching on Meridian Street clearly.(-2 -1 0 +1 +2)
17. I can see pedestrians approaching on Meridian Street clearly. (-2 -1 0 +1 +2)
18. I feel safe while driving along Meridian Street. (-2 -1 0 +1 +2)

As a pedestrian, with this lighting,

19. I can see other pedestrians approaching on Meridian Street clearly.
(-2 -1 0 +1 +2)
20. I can see faces of pedestrians on Meridian Street clearly. (-2 -1 0 +1 +2)
21. I can see vehicles approaching on Meridian Street clearly. (-2 -1 0 +1 +2)
22. I feel secure while walking on the sidewalk of Meridian Street. (-2 -1 0 +1 +2)

If you have any questions and comments, please feel free to contact Peter Morante at 518-687-7173 (moranp@rpi.edu) or the Institute Review Board; Rensselaer Polytechnic Institute; CII 7015; 110 8th Street; Troy, NY 12180. Thank you for your time and cooperation.

Name: ______________________________

Appendix C: Post-Installation Resident Street light Survey Questionnaire

The Lighting Research Center (LRC), in partnership with Groton Utilities, is conducting a street lighting demonstration. The LRC and Groton Utilities have replaced some high pressure sodium street lights (the yellowish/orangish lights) with a fluorescent lighting source on twelve poles along Meridian Street (between Park Ave. and Mitchell St.). We would like to know your opinions of these new street lights. The completion of this survey is completely voluntary. Please observe the street and the lighting at night, then, circle the number which most closely describes the degree of your agreement with each statement:

-2: strongly disagree, -1: disagree, 0: neutral, +1: agree, +2: strongly agree.

Then, please return this sheet in the enclosed self addressed stamped envelope by August 24, 2007.

Overall

31. I like the lighting on Meridian Street. (-2 -1 0 +1 +2)
32. The lighting on Meridian Street is comfortable. (-2 -1 0 +1 +2)
33. Meridian Street looks bright. (-2 -1 0 +1 +2)
34. Meridian Street looks gloomy. (-2 -1 0 +1 +2)
35. The light fixtures on the poles on Meridian Street are too bright (-2 -1 0 +1 +2)
36. Colors of traffic signs along Meridian Street appear clear. (-2 -1 0 +1 +2)
37. Colors of vegetation along Meridian Street look natural. (-2 -1 0 +1 +2)
38. The lighting on Meridian Street is too warm in color for a street(-2 -1 0 +1 +2)
39. The lighting on Meridian Street is too cool in color for a street. (-2 -1 0 +1 +2)
40. The lighting of the street looks better than others. (-2 -1 0 +1 +2)

As a driver, with this lighting,

19. I can see the roadway pavement on Meridian Street clearly. (-2 -1 0 +1 +2)
20. I can see other vehicles approaching on Meridian Street clearly.(-2 -1 0 +1 +2)
21. I can see pedestrians approaching on Meridian Street clearly. (-2 -1 0 +1 +2)
22. I feel safe while driving along Meridian Street. (-2 -1 0 +1 +2)

As a pedestrian, with this lighting,

23. I can see other pedestrians approaching on Meridian Street clearly.
(-2 -1 0 +1 +2)
24. I can see faces of pedestrians on Meridian Street clearly. (-2 -1 0 +1 +2)
25. I can see vehicles approaching on Meridian Street clearly. (-2 -1 0 +1 +2)
26. I feel secure while walking on the sidewalk of Meridian Street. (-2 -1 0 +1 +2)

If you have any questions and comments, please feel free to contact Peter Morante at 518-687-7173 (moranp@rpi.edu) or the Institute Review Board; Rensselaer Polytechnic Institute; CII 7015; 110 8th Street; Troy, NY 12180. Thank you for your time and cooperation.

Name: ______________________________