Demonstration and Evaluation of Fluorescent Outdoor Lighting in the City of Austin, Texas

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Executive Summary

Can a fluorescent outdoor lighting system with lower wattage and light output replace a high-pressure sodium (HPS) outdoor lighting system and provide equal or greater perceptions of safety and security? If so, when and where should this fluorescent lighting system be used? The Lighting Research Center conducted research that investigated these questions in the context of three installations within the City of Austin, Texas: 100-watt fluorescent lighting systems that replaced a mix of 100-watt HPS and 250 watt HPS lighting systems on one block of street lighting; and 100-watt fluorescent lighting systems that replaced 250-watt HPS lighting systems in two parking lots.

The 100-watt fluorescent lighting systems consisted of two 50-watt T5 twin-tube fluorescent lamps with a correlated color temperature of 4100 K. The selection of the replacement lamps and lighting fixtures was made by Austin Energy and Magnaray® International. The use of the Lighting Research Center's Unified Photometry System* was not considered in the selection of the replacement fluorescent lamps for this project. However, the use of 4100 K CCT lamps moves in the correct direction toward optimizing lighting applications for vision at low light levels. Since the fluorescent lighting systems were already in place prior to the commencement of this research project, before and after installation surveys could not be administered to compare the two different lighting systems within the same environment. Because of this situation, HPS lighting installations similar to the fluorescent installations were found and used for comparison purposes. The street block and parking lots with HPS lighting were similar but not exactly the same as their counterpart installations utilizing the fluorescent lighting. The light levels and the spatial distribution of the light were not the same.

A phone survey of residents living on or near West Avenue between 9th and 11th Streets was conducted to collect residents' perceptions of visibility, safety, security, brightness, and color rendering regarding the fluorescent street lighting between 9th and 10th Streets and the HPS street lighting between 10th and 11th Streets. Only five completed surveys were received. This low number of responses allowed for minimum analysis to be performed. Therefore, the Lighting Research Center used results from other mesopic (low light level) street lighting research to develop recommendations for Austin Energy street lighting. Previous LRC research has shown that white lamp sources tuned to optimize mesopic vision (6500 K CCT) can provide similar or better perceptions of visibility, safety, security, and brightness with approximately 30% lower wattage than HPS lamps.

The Austin Energy use of 250 watt HPS for roadway intersections on West Avenue provides illuminance values within the intersection that far exceed Illuminating Engineering Society of North America recommendations. Because of this over lighting situation, Austin Energy has an opportunity to replace the 250 watt HPS with any of the

* The Unified Photometry System is a means of predicting visibility under low light conditions. The system considers the light level and spectral (color) range of an electric light source and how these factors assist human vision.

following options all of which will meet the IESNA illuminance recommendations or the unified photometry system for equal visual performance.

- 150 watt HPS at 2100 K CCT
- 100 watt HPS at 2100K CCT
- 2, 50 watt T5 twin tube Fluorescent at 4100K CCT
- 70 watt fluorescing light source at 6500K CCT

Parking lot lighting was evaluated using 15 subjects who visited the two fluorescent-lighted and two HPS-lighted parking lots three times each. The fluorescent lighting installation evaluations took place at Energy Control Center, which had high illuminance, and Parks and Recreation Headquarters, which had low illuminance. The HPS lighting installation evaluations took place at Gillis Park, which had high illuminance, and South Austin Community Health Center, which had low illuminance. To ensure there were actual similarities in perceptions of safety and security within the two sets of parking lots (high illuminance lots and low illuminance lots), study participants first rated their perceptions of safety and security during daylight hours and again in darkness with the parking lot lights turned off. The results of these surveys were similar in terms of people's perceptions of safety and security for each set of parking lots, without the influence of the parking lot lighting. Therefore, they could be successfully used as a comparison set.

A follow-on parking lot survey measured subjects' perceptions of brightness, safety, security, and color rendering for each of the four parking lot lighting systems and designs. By comparing the results of the surveys for each set of parking lots, the LRC could determine whether the fluorescent lighting system offered any advantages over the standard HPS lighting systems.

For the high illuminance level parking lots (Gillis and the Energy Control Center), subjects' perceptions of safety and security were found to be similar, regardless of the lamp spectral distribution. The perception of brightness also appeared to be similar according to the subjects, regardless of the light source. However, subjects' perceptions of color rendering seemed to slightly favor the fluorescent light source.

The low illuminance parking lot comparison indicated that subjects' perceptions of safety, security, and brightness were similar for both the fluorescent and HPS light sources. However, the results were essentially all negative: Both parking lots were perceived as having poor safety, security, and brightness. The spatial distribution of light within these parking lots was poor and the low illuminance levels added to the perception of poor safety. Preferences for color rendering appeared to favor the fluorescent light source.

In conclusion, a fluorescent lighting system with two 50-watt T5 twin tubes can replace a 250-watt high-pressure sodium system in parking lots while maintaining people's perceptions of safety and security. The cost effectiveness of installing the fluorescent lighting system for new parking lot lighting projects is a simple payback of 3.5 years.

Retrofitting existing high-pressure sodium systems requires a payback of 11.6 years. (please see details on page 36)

The following are recommendations for street and parking lot lighting:

- Using a fluorescing white lamp source tuned to optimize mesopic vision (6500 K CCT) offers opportunities to reduce lamp wattages by 30% from the HPS lamp it would replace without negatively impacting people's perceptions of visibility, safety, or security. Austin Energy should consider a program of replacing 100-watt HPS streetlights with a fluorescing lamp source of around 70 watts, and 70-watt HPS streetlights with a fluorescing lamp source of approximately 50 watts.
- Metal halide (even ceramic metal halide) used in street lighting has some serious shortcomings, including shorter lamp life (20,000 hours) than HPS (30,000 hours) and higher lumen depreciation over the life of the lamp. These shortcomings cause the LRC to be concerned in recommending the use of metal halide as a replacement for HPS. The added maintenance costs will more than offset any energy savings, causing higher total costs for Austin Energy.
- Parking lot lighting design should strive to provide average horizontal illuminance values greater than 10 lux, with good spatial light distribution to ensure high degrees of perceived safety and security. The use of the Illuminating Engineering Society of North America's guideline RP-20 for the design of parking lot lighting is encouraged.
- Strive to utilize lamps in outdoor lighting installations that are spectrally closer to maximizing mesopic vision within the white light range at 6500 K CCT.[1]
- Other fluorescing light sources, such as electrodeless (induction) lamps, should be explored beyond the T5 twin tubes. Electrodeless lamps provide longer lamp life, which could reduce maintenance costs. This exploration should occur prior to Austin Energy deciding to convert any outdoor lighting from HPS. An economic analysis such as presented in this report can be used to determine the cost effectiveness of all HPS replacement options.
- Based on the Unified Photometry System[3], properly designed parking lot lighting systems can reduce lamp wattage by approximately 30% while maintaining visual performance if the light source is tuned at 6500K CCT to maximize mesopic vision within the white light range.
- The use of the Unified Photometry System to determine replacement wattages of lamps with different spectral distributions that will provide similar visibility is encouraged. Austin Energy can examine replacing HPS wattages other than 250 watts for both street and parking lot lighting by using this system. Once replacement lamps are selected, an economic analysis can be performed to determine if a reasonable payback is possible.

Introduction

The Lighting Research Center (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 determining 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 ones 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 (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.[4]

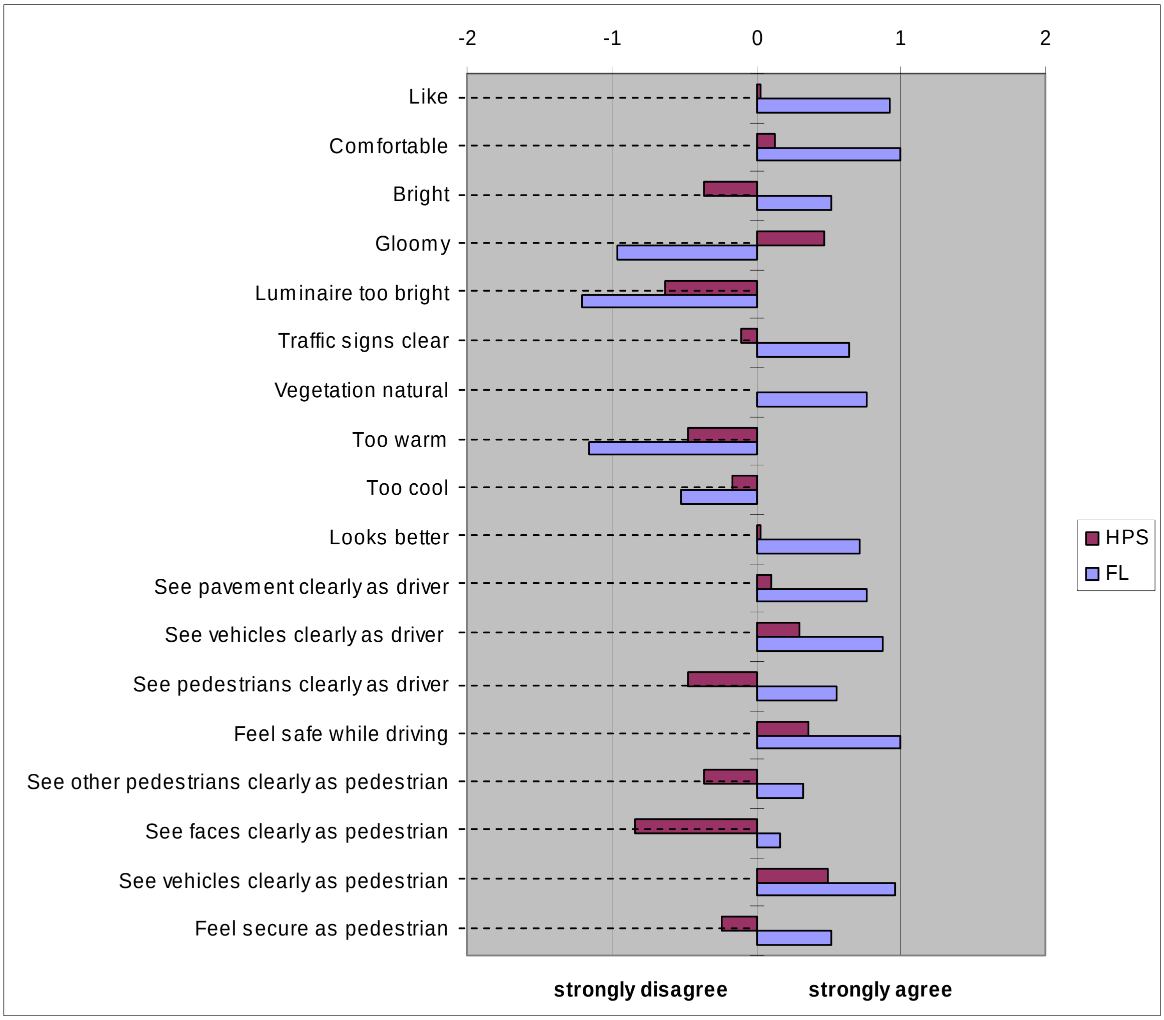
Table 1. Photopic illuminance and relative power required to obtain the same brightness perception and visibility of spaces and objects illuminated by various SPD lamps[4]

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 prove the theory that a light source tuned to how humans see under low light conditions could provide the same or better visibility with lower 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 streetlight 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 conditions), 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, indicates a strong preference toward the fluorescent lighting for both driving and walking. People said they could see better and felt safer with lighting that used 30% less energy.[4] These data provided the basis for Austin Energy to conduct a demonstration and evaluation of a fluorescent outdoor lighting system with the belief that it would have a significant opportunity for success.

Figure 1: Streetlight Comparison Results, Easthampton, Massachusetts



To identify the potential benefits of fluorescent lighting for outdoor lighting applications within the City of Austin, Texas, Austin Energy (a municipal electric utility) and Magnaray® International (a lighting manufacturer) replaced conventional high-pressure sodium (HPS) luminaires (250 watts and 100 watts) on one street and in two parking lots in the City of Austin with luminaires consisting of two 50-watt, twin-tube, 4100 K CCT fluorescent lamps plus ballasts. Total wattage including the electronic ballast was 106 watts.[5] Input power was reduced 10% as compared to the 100 watt HPS and 65% when compared to the 250 watt HPS for streetlights and 65% for parking lots using the fluorescent lighting rather than HPS lighting. The selection of the replacement lamps and lighting fixtures was made by Austin Energy and Magnaray®. The use of the LRC's Unified Photometry System was not considered in the selection of the fluorescent replacement lamps for this project. However, the use of the 4100 K CCT lamps moves in the correct direction toward optimizing the lighting applications for mesopic vision.

Before proceeding with additional conversions of HPS outdoor lighting to fluorescent, Austin Energy wanted to ensure that true energy savings could be achieved while maintaining or improving public perception of brightness and the sense of security and safety. Therefore, this demonstration and evaluation of fluorescent outdoor lighting in the City of Austin was undertaken to compare the new fluorescent lighting installation to HPS lighting in order to develop guidelines of whether, where, and how fluorescent lighting can be implemented in the City of Austin. The LRC was contracted to conduct the evaluation and develop recommendations on the use of fluorescent outdoor lighting systems.

Project Goals

The goals of the "Demonstration and Evaluation of Fluorescent Outdoor Lighting in the City of Austin" project were to determine whether, where, and how fluorescent outdoor lighting could be implemented for the City of Austin while reducing energy needs by examining the current City of Austin fluorescent lighting installations and comparing results with other LRC outdoor lighting research and knowledge.

Research Methodology

Selection of Comparison Lighting Installations

The fluorescent street and parking lot lighting were installed prior to Austin Energy requesting an evaluation by the LRC of these sites. Therefore, conducting a before-installation survey of the original HPS outdoor lighting system to determine residents' and parking lot users' perceptions of brightness, safety, and security was not possible. The method chosen to compare the new fluorescent lighting systems to the original HPS systems was to select HPS outdoor lighting locations similar to those that were converted to the fluorescent systems. The location similarities most important were:

- uniformity or lack of uniformity of illuminance throughout the street or parking lot
- a perception of similar brightness
- illuminance levels that would be higher for the HPS lighting than the comparison fluorescent sites, but within the predictable range for mesopic lighting.

With assistance from Dennis Lilley of Austin Energy, who developed a list of potential comparison HPS lighting sites, personnel from the LRC visited each site, took illuminance measurements, and selected two parking lots and an adjacent block on the same street as the fluorescent street lighting for the comparison HPS sites. These HPS sites were deemed similar enough to the sites of the three fluorescent installations, based on the criteria above.

Street lighting comparison sites

The fluorescent streetlights were located on West Avenue on the block between 9th and 10th Streets. A similar block (approximately the same length, same number of streetlights, similar uniformity illuminance, and similar perception of brightness) with HPS street lighting was found on West Avenue between 10th and 11th Streets. This block was chosen as the comparison site. Illuminance measurements of both blocks confirmed their similar illuminance uniformity and levels.

Lamp and light fixture information for the street lighting is listed in Table 2 below. Photographs of each of the streetlight installations are shown in Figures 2 and 3.

Table 2: Streetlight Fixture Information

	West Avenue Between 9th and 10th Streets	West Avenue Between 10th and 11h Streets
Lamp Type	Fluorescent	HPS
Lamp Wattage[5,6]	2 lamps - 50 watts each	250 watts at intersections and 100 watts between intersections
CCT[5,6]	4100 K	2100 K
Fixture Type	Twin Magnaray® W Series[5]	Cobra Head
Number of Fixtures	4	4
Lighting Control	Photo cell	Photo cell
Mounting Height	25 feet	25 feet
Avg. Illuminance (lux)	8.94 lux	12.22 lux

Figure 2: West Avenue Between 9th and 10th Streets (Fluorescent lighting)

Figure 3: West Avenue Between 10th and 11th Streets (HPS lighting)

Parking lot lighting comparison sites

Gillis Park's HPS-lighted parking lot was chosen because it has high illuminance levels, is relatively uniform in its illuminance, and gives a perception of high brightness, as does its comparison fluorescent lighting site, the Energy Control Center parking lot. The South Austin Community Health Center's HPS-lighted parking lot was chosen because it has low average illuminance levels, is not uniform in its illuminance, and gives little perception of brightness. These conditions were also found at the selected comparison fluorescent lighting site, the Parks and Recreation Headquarters parking lot. Overall, the comparison parking lots were similar, but they did vary in spatial light distribution and illuminance.

Lamp and light fixture information is listed in Table 3 below for the four parking lots. Photographs of each of the parking lots are shown in Figures 4, 5, 6 and 7.

Table 3: Parking Lot Fixture Information

	Comparison 1		Comparison 2	
	Gillis Park	Energy Control Center	Parks and Rec Headquarters	South Austin Health Center
Lamp Type	HPS	Fluorescent	Fluorescent	HPS
Lamp Wattage[5,6]	250 watts	2 lamps - 50 watts each	2 lamps - 50 watts each	250 watts
CCT[5,6]	2100 K	4100 K	4100 K	2100 K
Fixture Type	Cobra Head	Twin Magnaray® W Series[5]	Twin Magnaray® W Series[5]	Shoebox
Number of Fixtures	5	8	2	2
Lighting Control	Photo Cell	Photo Cell	Photo Cell	Time Clock
Mounting Height	25 feet	25 feet	25 feet	20 feet
Avg. Illuminance (lux)	19.32 lux	11.36 lux	2.69 lux	5.36 lux

Figure 4: Gillis Park (HPS lighting)

Figure 5: Energy Control Center (Fluorescent lighting)

Figure 6: South Austin Health Clinic (HPS lighting)

Figure 7: Parks and Recreation Headquarters (Fluorescent lighting)

Light Illuminance Measurements

Illuminance measurements were taken by LRC personnel using a Hagner, model E2, illuminance meter calibrated against the LRC standard. For the street lighting on West Avenue, horizontal illuminance measurements were taken every 20 feet along the length and width of the road for the blocks between 9th and 10th Streets (fluorescent lighting) and 10th and 11th Streets (HPS lighting). For the parking lot lighting, horizontal illuminance measurements were taken every 30 feet along both the width and length of the Gillis Park and Parks and Recreation parking lots. Measurements were taken every 20 feet at the Energy Control Center and South Austin Community Health Center parking lots.

Figures 8 and 9 illustrate the illuminance levels and lighting uniformity of the two sections of street lighting on West Avenue.

Figure 8: West Avenue Between 9th and 10th Streets, Fluorescent Streetlights

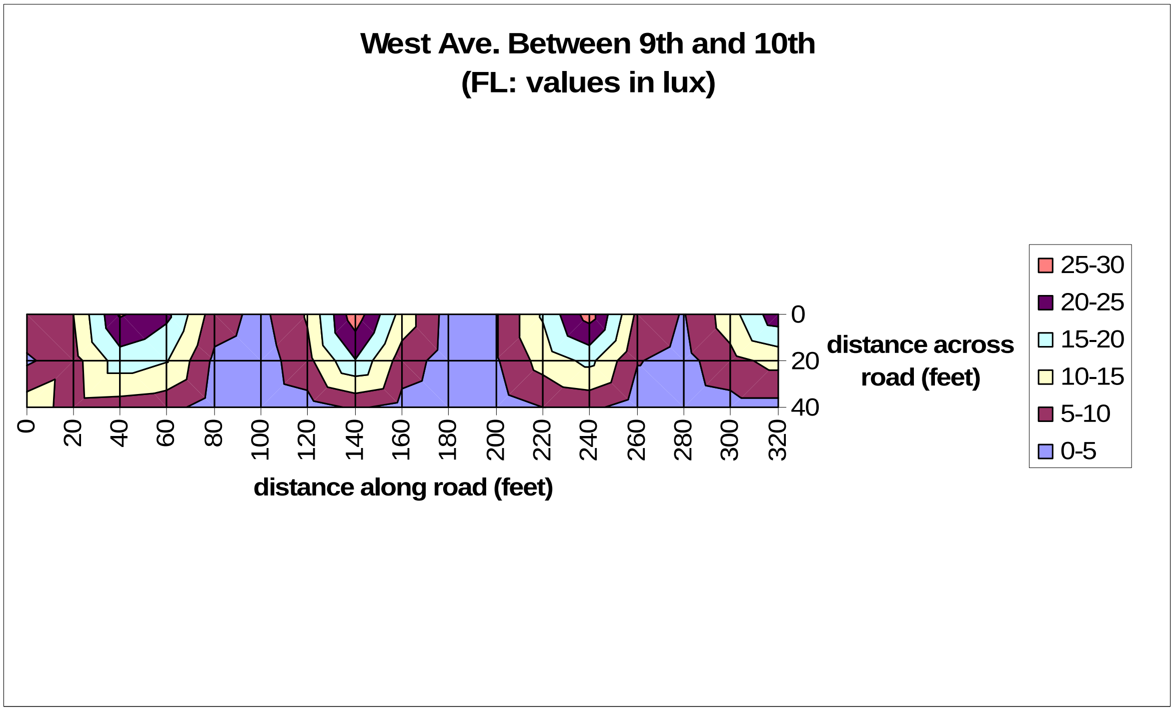
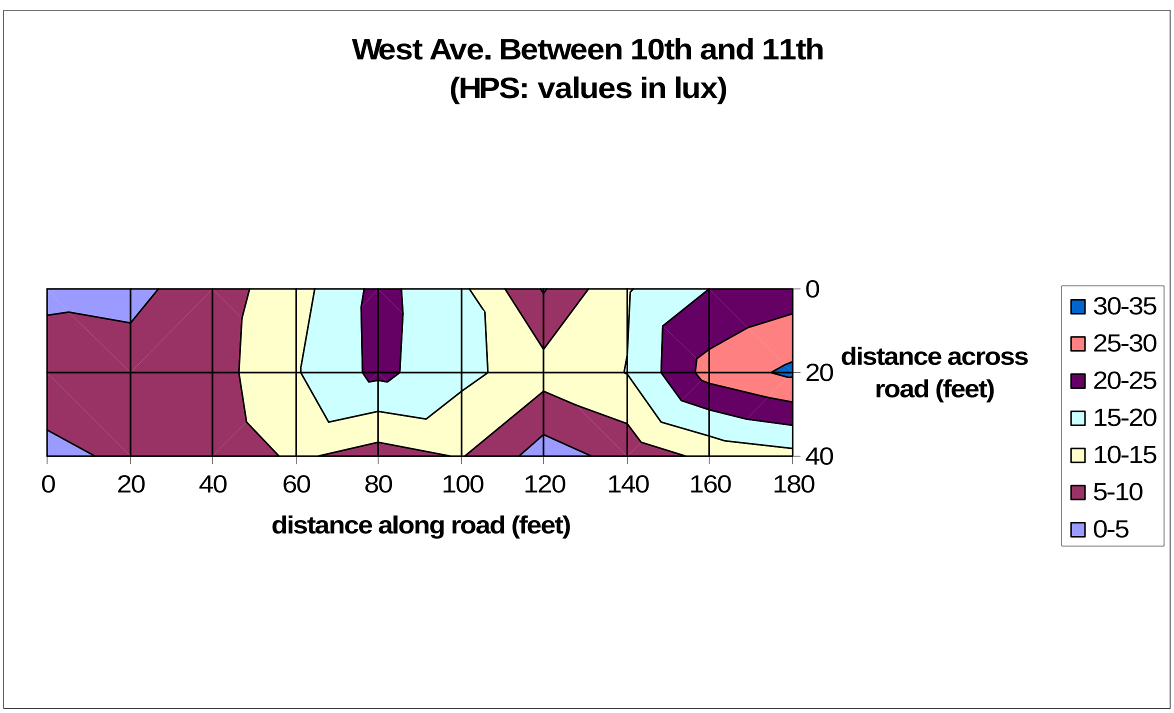


Figure 9: West Avenue Between 10th and 11th Streets, HPS Streetlights



Figures 10, 11, 12, and 13 illustrate the illuminance levels and lighting uniformity of each parking lot.

Figure 10: Gillis Park Illuminance Distribution (HPS lighting)

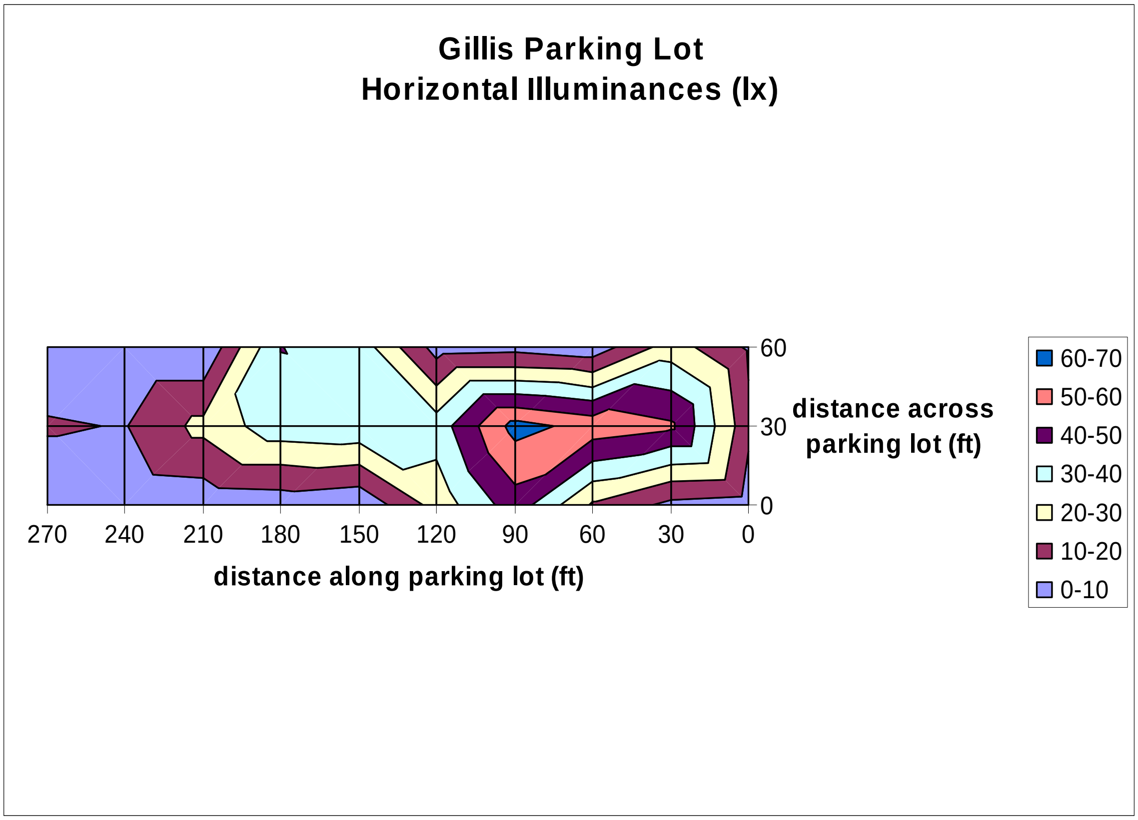
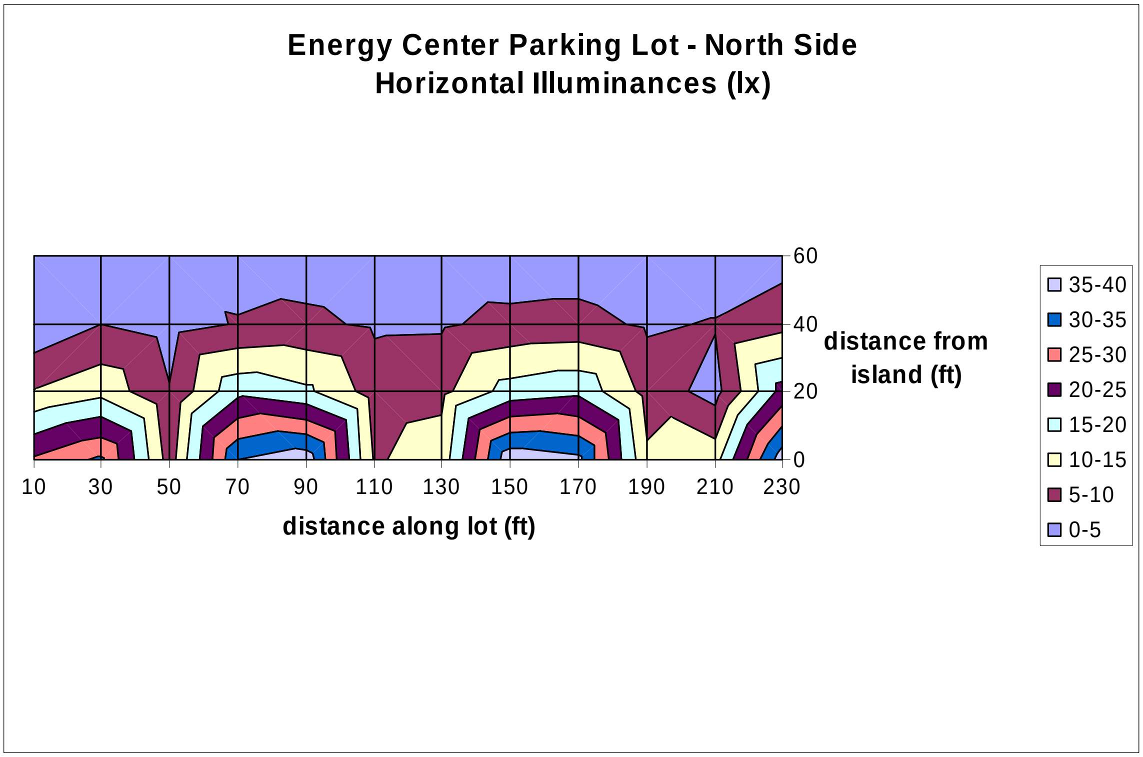


Figure 11a and 11b: Energy Control Center Illuminance Distribution (Fluorescent Lighting)



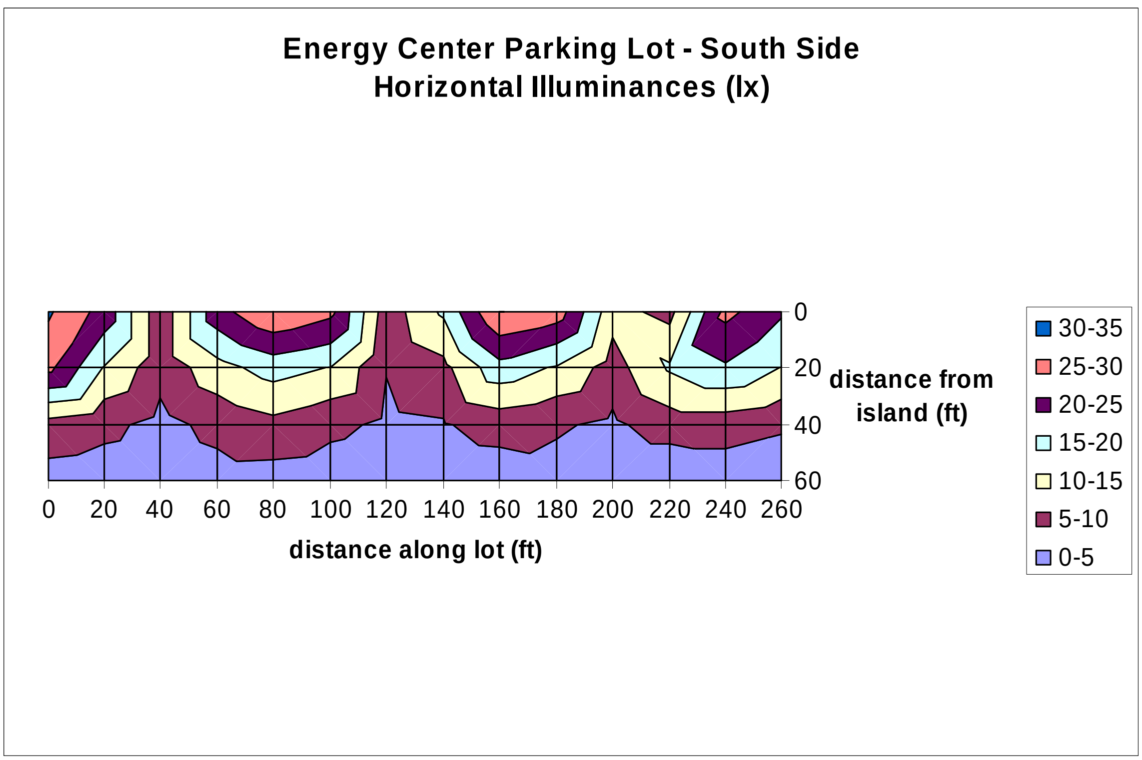
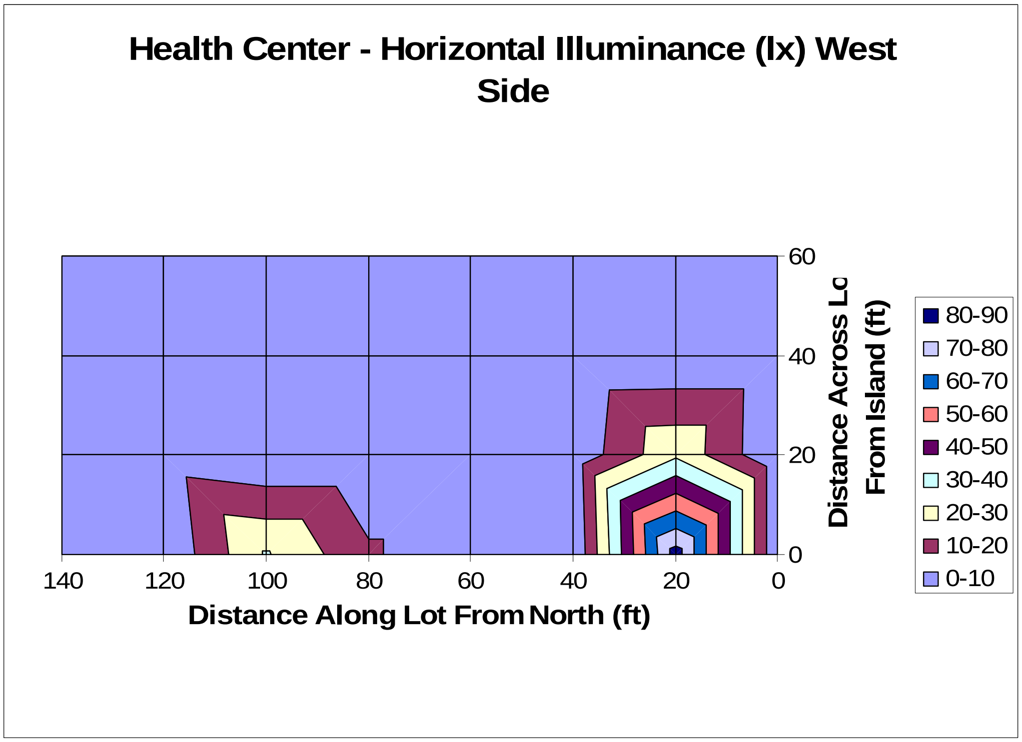


Figure 12a and 12b: South Austin Community Health Center Illuminance Distribution (HPS Lighting)



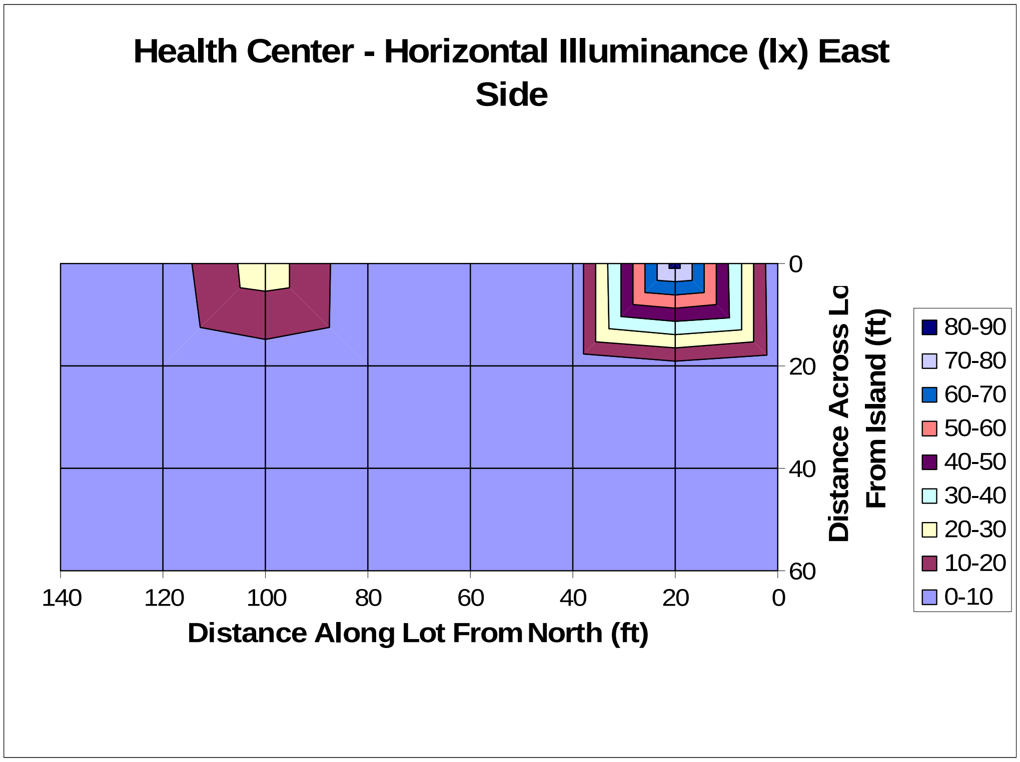
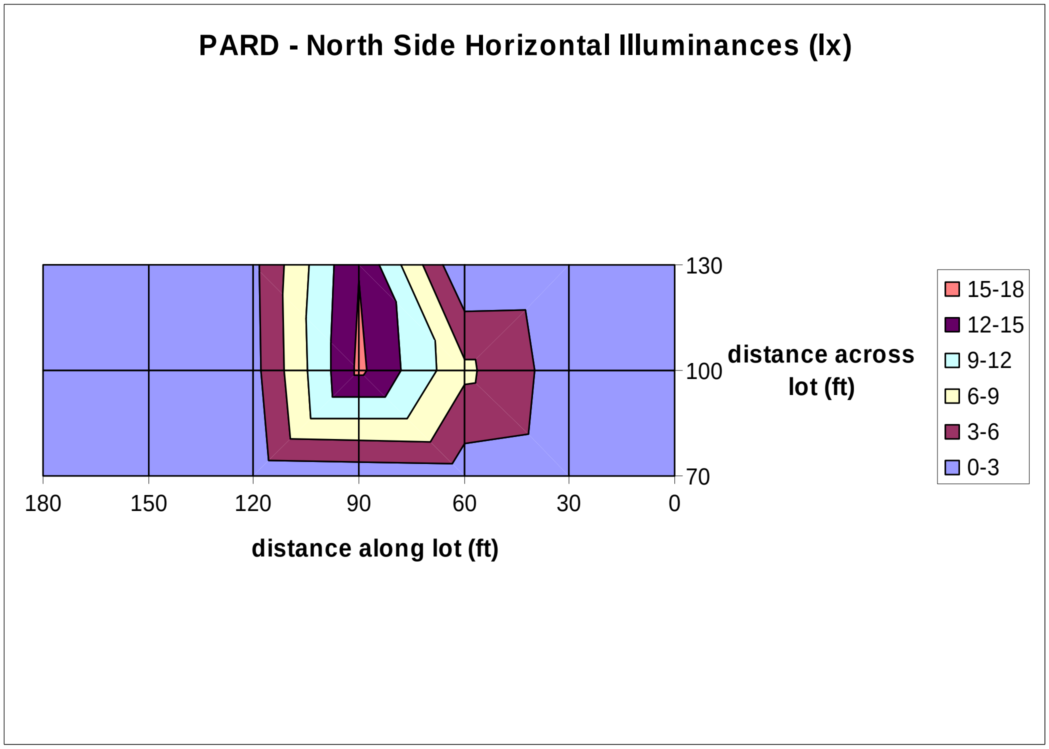
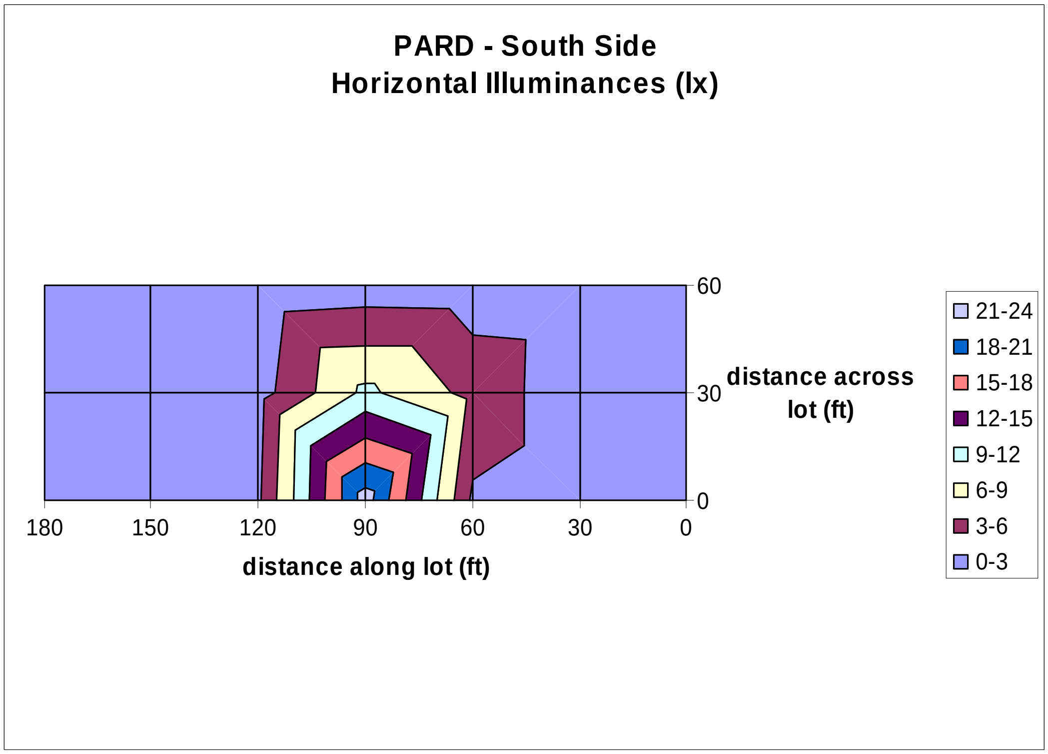


Figure 13a and 13b: Parks and Recreation Illuminance Distribution (Fluorescent lighting)





Street Lighting Evaluation Methodology

A phone survey of residents living on or near West Avenue between 9th and 11th Streets was conducted between September 24 and October 23, 2007, by Creative Consumer Research, a company hired by Austin Energy. Residents were first contacted to determine their acceptance to participating in the study. They were asked to observe the street lighting between 9th and 10th Streets and 10th and 11th Streets at night as both a driver and as a pedestrian for several days. Creative Consumer Research established a date and time to call back each participating resident to complete the survey questionnaire. Each resident who completed the survey was given a $10 gift certificate to a local supermarket. The questionnaire was developed by the LRC and reviewed and modified by Austin Energy and Creative Consumer Research to put it into a format that would be conducive to a phone survey. A copy of the questionnaire is included in Appendix A. Creative Consumer Research called participating residents back at the appointed time and obtained responses to each question. The questions were designed to ascertain residents' opinions of the two different streetlight systems, fluorescent and HPS, as it pertained to perceptions of visibility, brightness, safety, security, and color rendition.

Parking Lot Lighting Evaluation Methodology

A within-subject survey methodology was applied to compare the two sets of parking lots each having one HPS system and one fluorescent system. A group of 15 subjects was recruited through a market research company to participate in the survey. Each subject was paid a stipend of $125 if they completed all three surveys. The group consisted of eight males and seven females of varying ages and education. All resided within the Austin, Texas, metropolitan area. The subjects were driven to each site three times in the following order: during daylight hours, after darkness with the parking lot lights turned off, and after darkness with the parking lot lights on.

To ensure there were actual similarities in perceptions of safety and security within the two sets of parking lots (high illuminance and low illuminance), study participants first rated their perceptions of safety and security during daylight hours and then again in darkness with the parking lot lights turned off. The same survey was used for all parking lots during both the daylight and darkness-with-no-lights scenarios. A copy of the survey, which was developed by the LRC and reviewed by Austin Energy, is attached in Appendix B. If the results of these surveys were similar in their perceptions of safety and security for each set of parking lots without the influence of the parking lot lighting, then it could be said that the parking lots demonstrated similar characteristics and could be successfully used as a comparison set.

A follow-on survey developed by the LRC and reviewed by Austin Energy, which is included in Appendix C, measured the brightness, safety, security, and color rendering perceptions of the subjects for each of the four parking lot lighting systems and designs. By comparing the results of the surveys for each of the sets of parking lots (Gillis Park and the Energy Control Center, and the South Austin Community Health Center and the Parks and Recreation Headquarters), the LRC could determine whether the fluorescent lighting system offered any advantages over the standard HPS lighting systems.

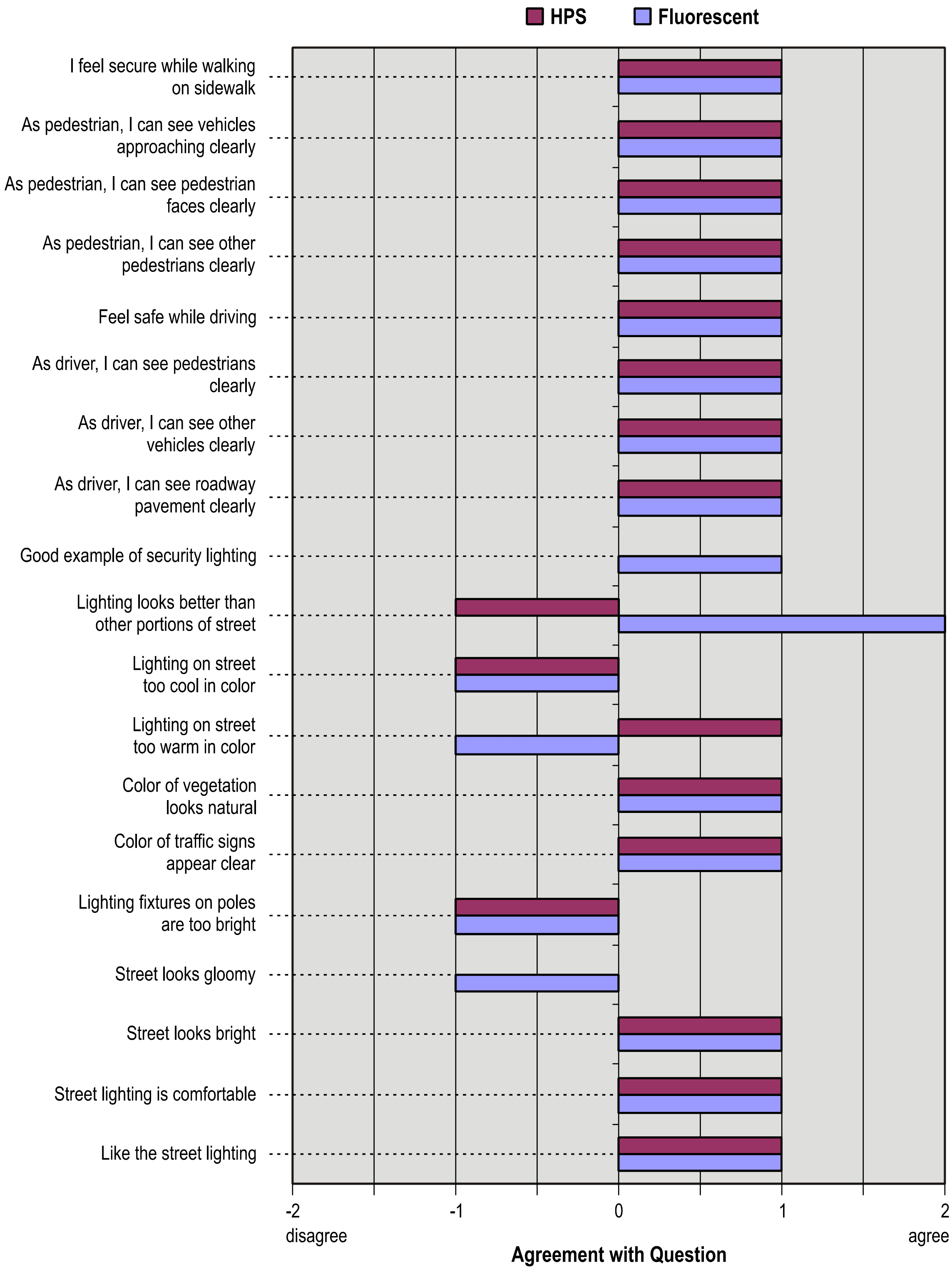
Research Results

Street Lighting Results

With only five completed surveys of perceptions of visibility, safety, security, brightness, and color rendering regarding the fluorescent and HPS street lighting on West Avenue, it is impossible to reach any statistically based conclusions. Therefore, the LRC will present the results of the five completed surveys with minimal analysis and will not draw any conclusions based on these data. However, the LRC has previously conducted street lighting research at three locations in the northeastern United States where fluorescing light sources or metal halide were utilized to replace HPS. The results of these research projects where sufficient data was received are presented below and conclusions and recommendations based on this research are made. The LRC believes the results of these research projects are applicable to Austin Energy.

Figure 14 below illustrates the results of comparing the fluorescent and HPS street lighting on West Avenue. Median (rather than average) values were used because of the limited responses. Average values could be skewed if question responses for only five participants are not clustered together. 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 14: Street Lighting Systems Comparisons of Different Light Sources

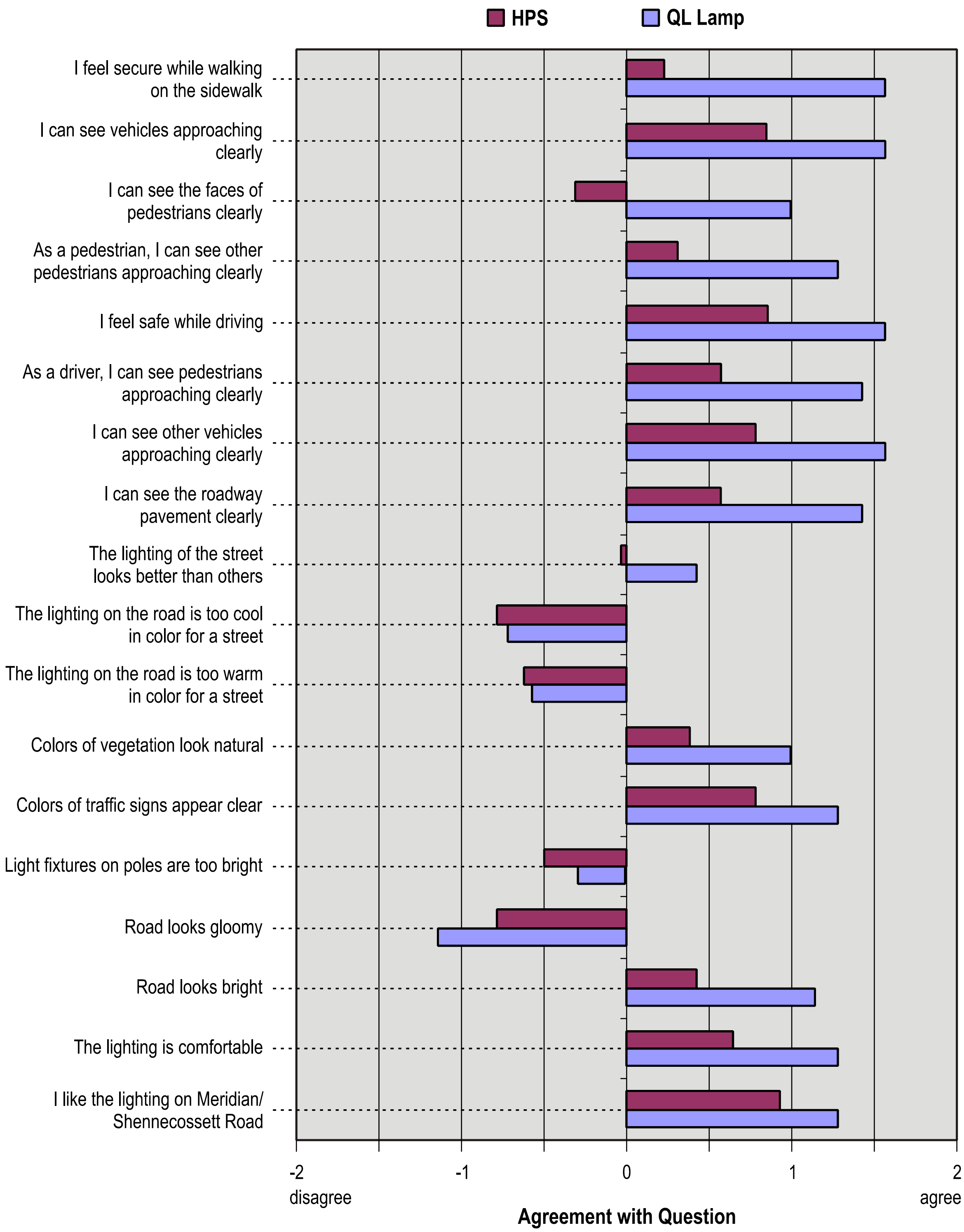


Based on the survey results, both the fluorescent and HPS street lighting on West Avenue had the same positive results for visibility, safety, and security. The greatest difference between the two light sources was found in responses to how the lighting looked. Subjects indicated that they believed the fluorescent streetlights looked better than the rest of the HPS street lighting on West Avenue.

Previous to the Austin street lighting study, the LRC conducted streetlight research into visibility, safety, security, brightness, and color rendering perceptions using different light sources with differing spectral distributions. One study was of street lighting in a residential neighborhood of Easthampton, Massachusetts. Residents were asked to rate the visibility, safety, security, brightness, and color rendering of the existing 70-watt HPS streetlights and then after the installation of 50-watt twin-tube fluorescent lamps and fixtures with a CCT of 6500 K. The 50-watt, 6500 K lamps were chosen based on equal visible performance, as predicted by the Unified Photometry System. As shown in Figure 1 above, the results indicated a strong preference as both a driver and pedestrian toward the fluorescent lighting. People said they could see better and felt safer with lighting that used 30% less energy.[4] The full study results are included in Appendix D.

A second study was conducted in Groton, Connecticut, where the existing 100-watt HPS streetlights were replaced with 55-watt induction lamps, 6500 K CCT, in a modified cobra head fixture along a street that could be considered a collector road under Illuminating Engineering Society of North America (IESNA) standards. These study results have not yet been published. However, the analysis of the survey results of residents’ perceptions of visibility, safety, security, brightness, and color rendering is complete. Figure 15 presents the results of the comparison of the HPS and induction (QL Lamp) street lighting.

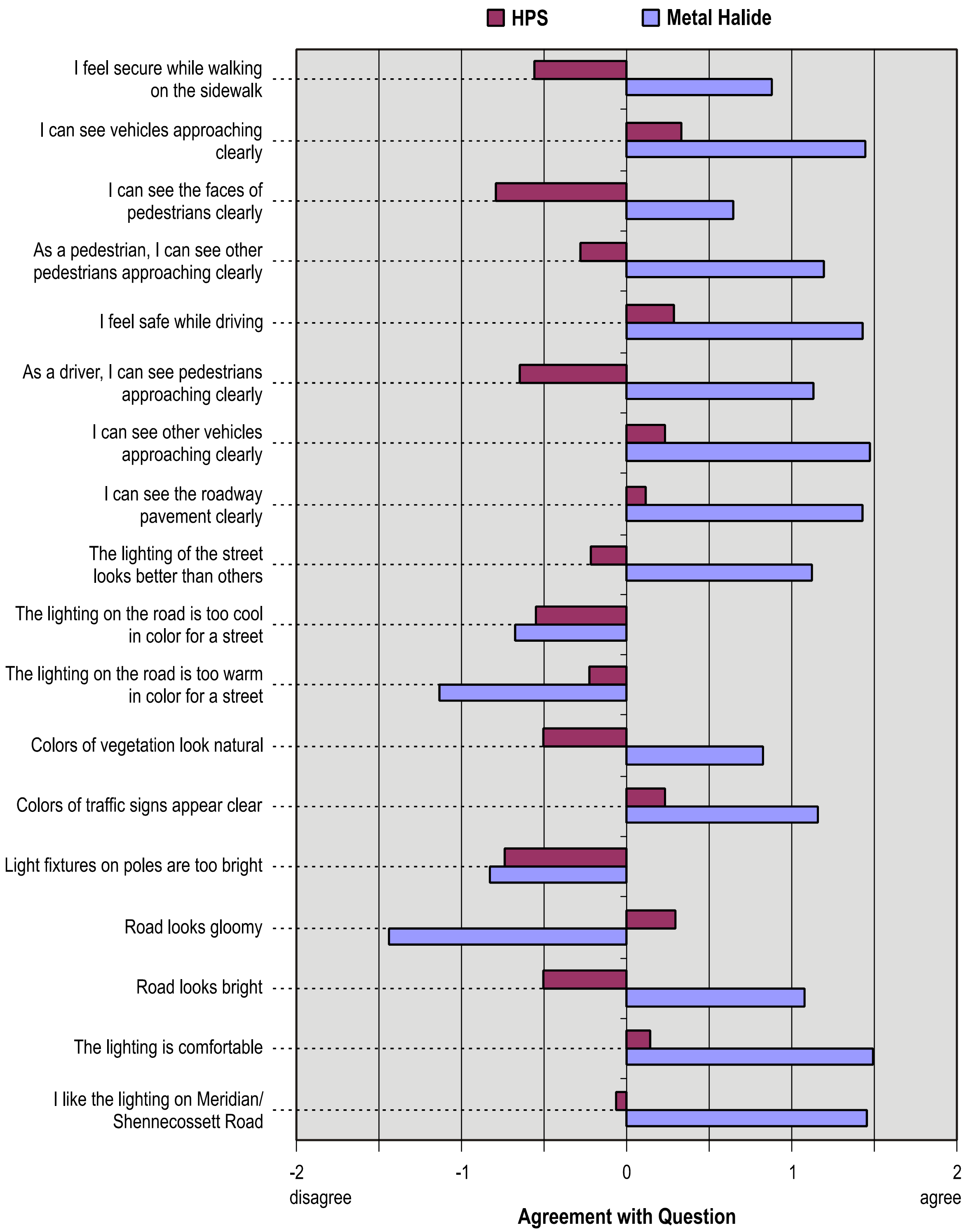
Figure 15: Streetlight Comparison Groton, CT: HPS and Induction



The results depicted in Figure 15 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. The 6500 K CCT was chosen because it matches optimum mesopic vision conditions.

A third street lighting research project, also located in Groton, Connecticut, compared the existing 100-watt HPS street lighting with 70-watt ceramic metal halide lighting at 4000 K CCT along another collector-type roadway. Figure 16 shows the results of residents' perceptions of visibility, safety, security, brightness, and color rendering when comparing the HPS system to the metal halide light sources. Again, the results from this study have not yet been published.

Figure 16: Streetlight Comparison Groton, CT: HPS and Metal Halide



These perception results are similar to those found in the Easthampton study with the 50-watt, 6500 K CCT fluorescent lighting, and the Groton study with the 55-watt, 6500 K CCT induction lamps. Residents favored the metal halide light source over the HPS.

As observed on West Avenue, Austin Energy uses 250 watt HPS streetlights at roadway intersections. There is also a second streetlight on the intersecting streets of West Avenue that is believed to be 100 watt HPS. These streetlights provide an average illuminance within the intersection of approximately 34 lux as determined through AGI 32 computer modeling of the intersection and its street lighting. IESNA, RP-8, Guide to Roadway Lighting, recommends an average illuminance value for intersections where a collector type road intersects with a local road and the pedestrian conflict is medium to be 16 lux. West Avenue is viewed as a collector road and the intersecting streets are considered local roads.

Currently, Austin Energy is over lighting these intersections by more than double the IESNA recommended illuminance levels. The recommended potential replacements for the 250 watt HPS at the intersections are based on providing sufficient lighting to meet the IESNA recommended practices or to meet the unified photometry system recommendations for mesopic street lighting to match or exceed the visual performance provided by 100 watt HPS lighting. The following are the recommended replacements for the 250 watt HPS intersection lighting.

- 150 watt HPS at 2100K CCT. This light source will still provide average illuminance values (24.6 lux) that exceed IESNA recommended levels.
- 100 watt HPS at 2100K CCT. This light source will provide close to the IESNA recommended levels of illuminance of 16 lux.
- 2, 50 watt, T5 Twin Tube Fluorescent at 4100K CCT. Based on the unified photometry system, this light source will provide higher visual performance than the 100 watt HPS.
- A 70 watt fluorescing light source at 6500K CCT. Based on the unified photometry system, this light source will provide similar visual performance as the 100 watt HPS.

Parking Lot Lighting Results

Gillis Park and the Energy Control Center parking lots were found to have similar lighting conditions in terms of brightness, horizontal illuminance, and spatial light distribution. These parking lots were used to compare subject perceptions of safety, security, brightness, and color rendering under high illuminance (above 10 lux) and two different spectral lighting conditions (Gillis Park, HPS; Energy Control Center, fluorescent). Two additional parking lots, South Austin Community Health Center and the Parks and Recreation Headquarters, were used to compare subject perceptions of safety, security, brightness, and color rendering under lower illuminance (5 lux or less). South Austin Community Health Center utilized HPS lighting and Parks and Recreation used fluorescent lighting.

To ensure the two sets of parking lots had similar subject perceptions of safety and security, subjects were asked to rate these perceptions during daylight hours and at night with the parking lot lights turned off. Figures 17 and 18 show the results of the subject perceptions of safety and security for the parking lots with higher illuminance values, Gillis Park and Energy Control Center, during daylight hours and at night with the lights turned off. Figures 19 and 20 shows the results of the subject perceptions of safety and security for parking lots with lower illuminance values, South Austin Community Health Center and Parks and Recreations Headquarters, during daylight and at night with the lights turned off.

Figure 17: Daytime Subject Perceptions of Safety and Security, High Illuminance Parking Lots

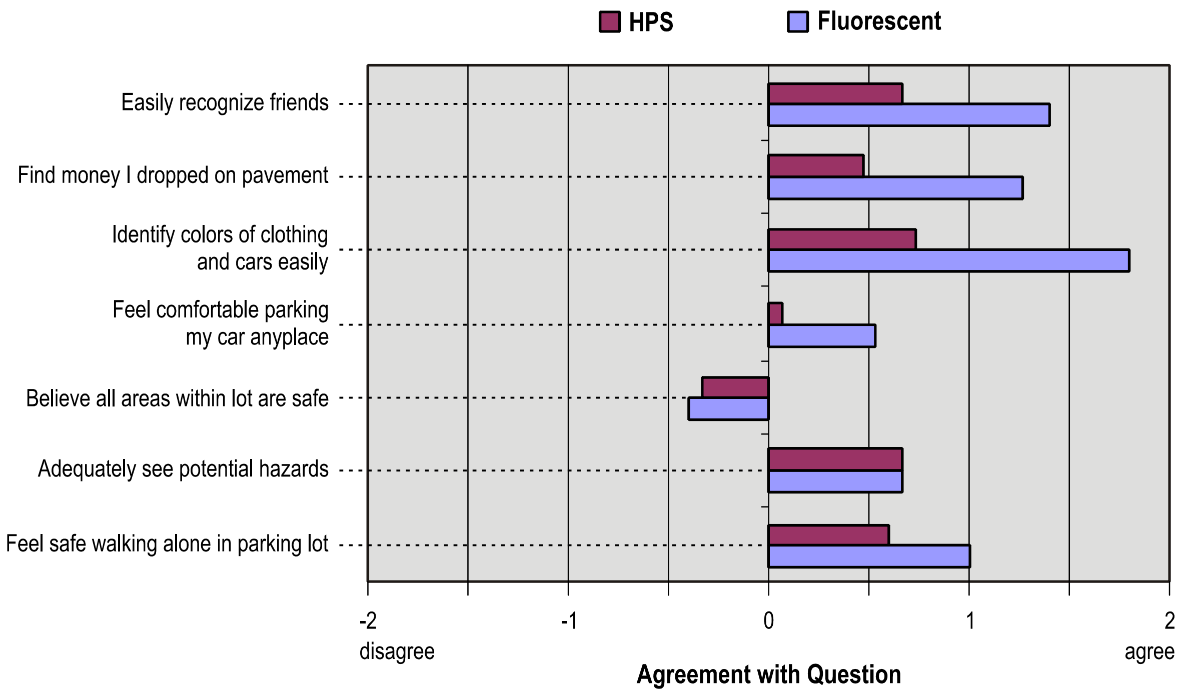


Figure 18: Night, No Lights, Subject Perceptions of Safety and Security, High Illuminance Parking Lots

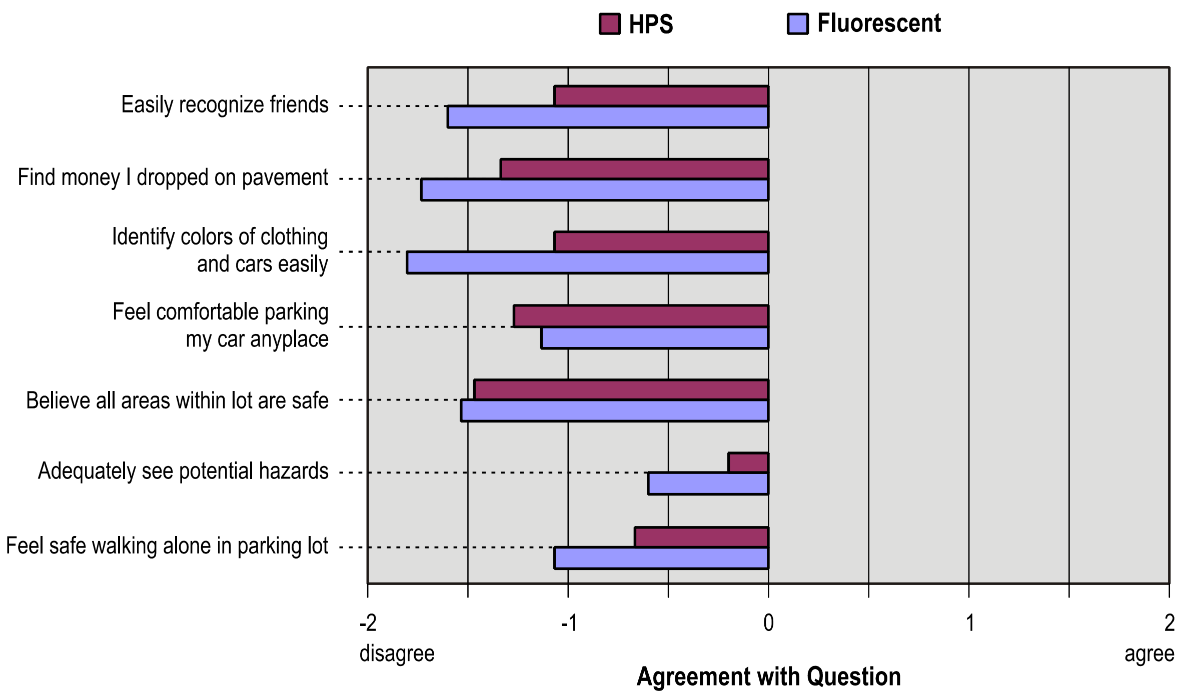


Figure 19: Daytime Subject Perceptions of Safety and Security, Low Illuminance Parking Lots

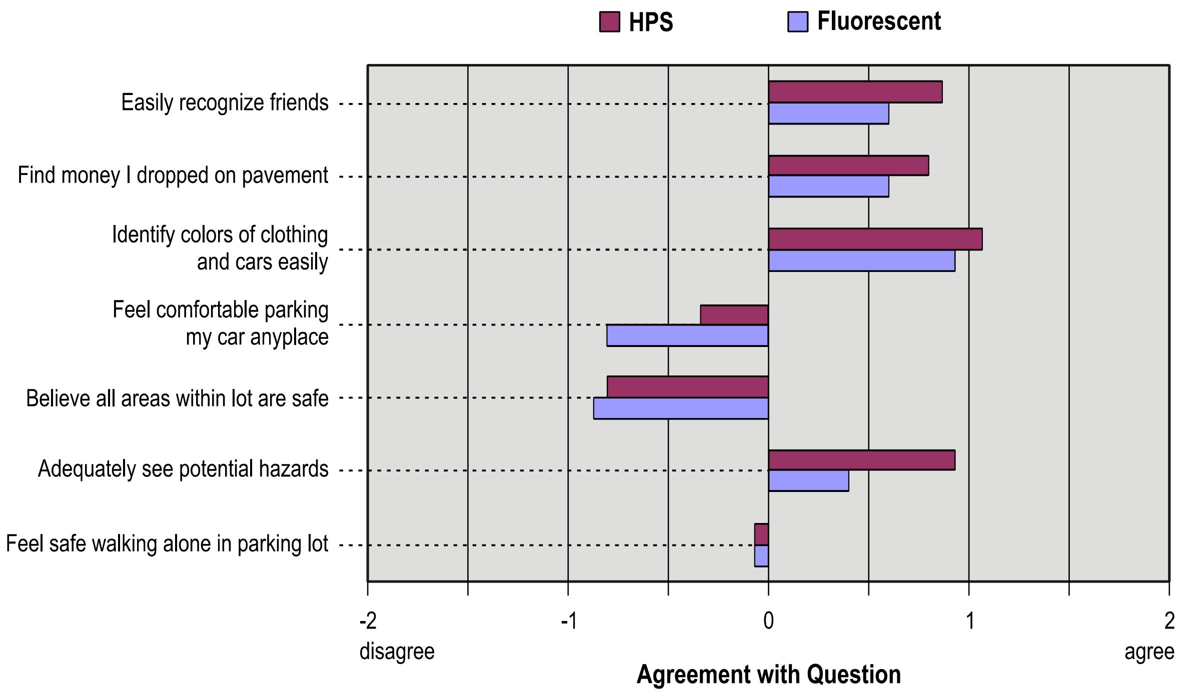
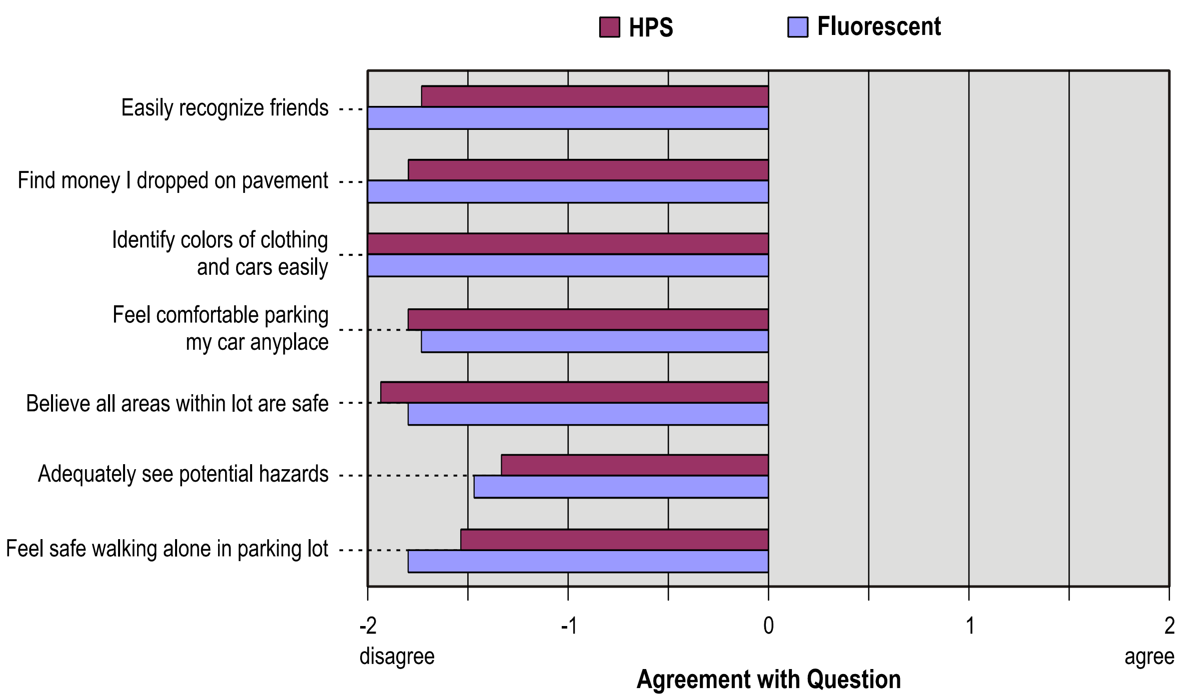


Figure 20: Night, No Lights Subject Perceptions of Safety and Security, Low Illuminance Parking Lots



Subjects' perceptions of safety and security were similar for the high illuminance parking lots during both daylight and at night with the lights turned off for the HPS (Gillis Park) and the fluorescent (Energy Control Center). The fluorescent parking lot (Energy Control Center) showed a slightly higher level of safety and security perception during the daytime than the HPS (Gillis Park) parking lot. This is probably true because the Energy Control Center parking lot is fenced in with a key card controlled gate. However, the same two parking lots under nighttime, no lighting conditions showed subjects' perceptions of safety and security for the fluorescent (Energy Control Center) to be less than for the HPS (Gillis Park) parking lot.

Based on the above findings and the average illuminance of each parking lot lighting system, the results show that subjects' perceptions of safety and security of the two parking lots with high illuminance levels under daytime and nighttime, no lighting conditions were similar. Therefore, the parking lots' lighting systems could be used successfully to measure subjects' perceptions of safety, security, brightness, and color rendering under the two spectral parking lot lighting conditions of HPS and fluorescent.

Similar results are depicted in Figures 19 and 20 for the low illuminance set of parking lots (South Austin Community Health Center, HPS; and Parks and Recreation Headquarters, fluorescent). However, there is a perception of lower levels of safety for the Parks and Recreation parking lot during daytime as shown in Figure 19 for the "Fee comfortable parking my car anyplace" question. Even with this discrepancy, it is believed these parking lots' lighting systems also could be used to measure subjects' perceptions of safety, security, brightness, and color rendering under low illuminance conditions and different spectral lighting, HPS and fluorescent.

After verifying that the two comparison parking lots within each set of parking lots (one set with high illuminance and one set with low illuminance) garnered similar subject perceptions of safety and security, subjects were asked to provide their perceptions of safety, security, brightness, and color rendering of all parking lot lighting systems at night with the lights turned on. The results of the subjects' perceptions are depicted in Figures 21 and 22.

Figure 21: Lighting Systems Comparison of Subjects' Perceptions under High Illuminance Conditions

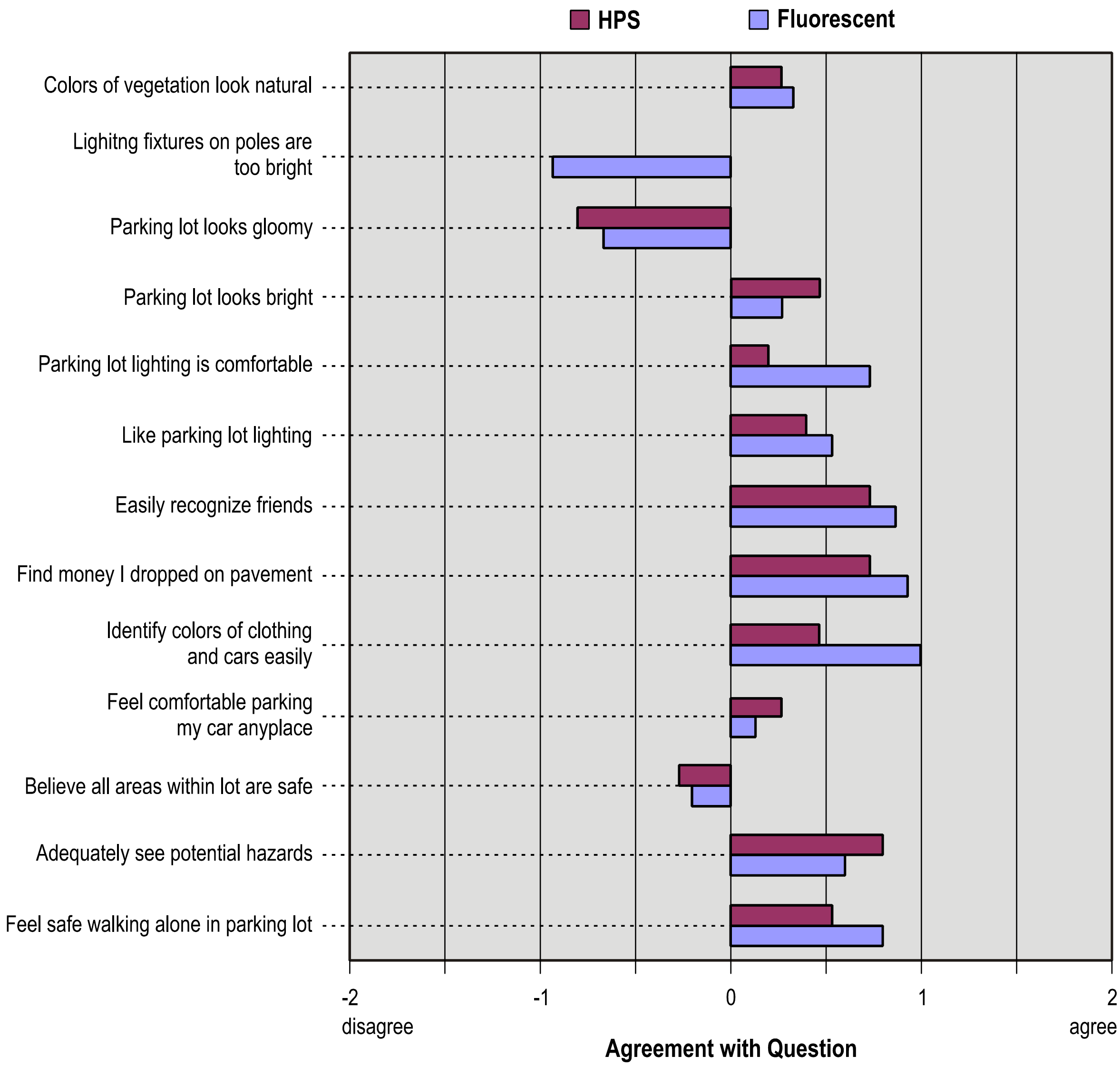
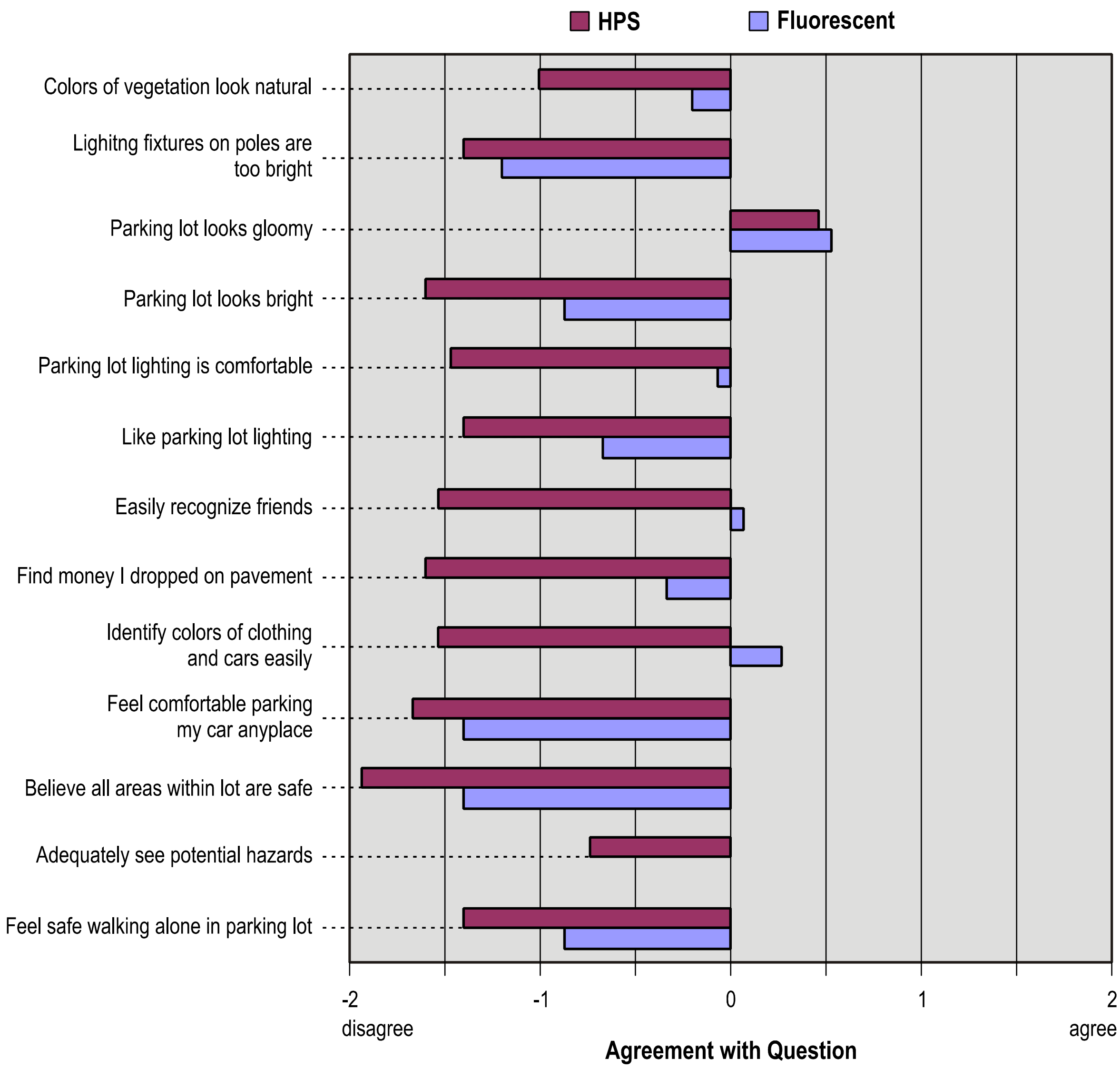


Figure 21 results for high illuminance levels indicate that subjects' perceptions of safety and security were similar, regardless of the lamp spectral distribution. Answers to questions regarding safety or security, such as "easy to recognize friends," "feel comfortable parking my car anyplace," "believe all areas within the parking lot are safe," "adequate to see potential hazards," and "feel safe walking alone in the parking lot," indicate both the HPS lamp source and the fluorescent lamp source provided similar results. For some questions ("feel comfortable parking my car anyplace" and "adequately see potential hazards"), the HPS source scored more positively. For the remaining questions, the fluorescent source was believed to have provided higher safety or security.

Perceptions of brightness, as indicated in the results shown in Figure 21 for questions of "light fixtures on poles too bright," "parking lot looks gloomy," "parking lot looks bright," "like parking lot lighting," and "find money dropped on pavement" indicated similar subject responses, regardless of the lamp spectral distribution. However, perceptions of color rendering seemed to slightly favor the fluorescent light source.

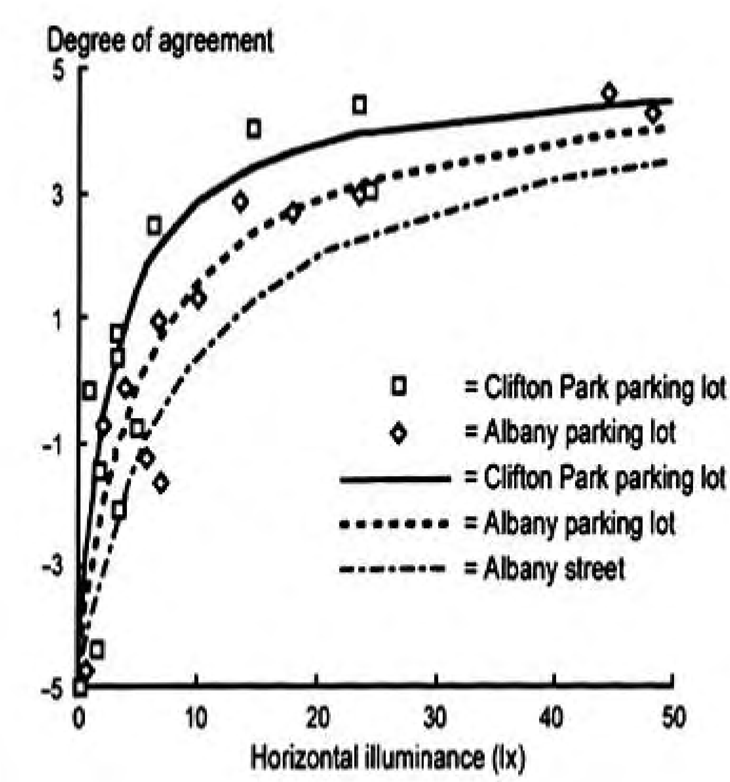
Figure 22: Lighting Systems Comparison of Subjects' Perceptions Under Low Illuminance Conditions



The low illuminance comparison of HPS and fluorescent, as depicted in Figure 22, indicated that subjects' perceptions of safety, security, and brightness were similar for both the fluorescent and HPS light sources. However, the results were all negative. The spatial distribution of light within these parking lots was poor, as can be seen in Figures 12a, 12b, 13a, and 13b. Also, the low illuminance levels added to the perception of poor safety. Perceptions of color rendering appeared to favor the fluorescent light source.

A major study was conducted in 2000 by Dr. Peter Boyce and colleagues, titled *Perception of Safety at Night in Different Lighting Conditions*.[7] This study compared HPS outdoor lighting conditions in more than 20 parking lots in the greater Albany, New York, area. The study asked subjects to rate the safety and security of each parking lot. Each parking lot had different values of horizontal illuminance. Figure 23 shows the results of this study. As illuminance increased to approximately 10 lux, the perception of safety dramatically increased. Between 10 lux and 30 lux, perceptions of safety continued to increase but at a decreasing rate. Over 30 lux, the perception of safety increased very little as horizontal illuminance continued to increase.

Figure 23: Perception of Safety at Night in Different Lighting Conditions[7]



The Austin parking lots examined as part of this study had differing horizontal illuminance values. When comparing these parking lot illuminance values to the results from the Boyce et al. study, one can see why the parking lots within the "high illuminance" set and within the "low illuminance" set would have similar subject perceptions of safety and security. The two high illuminance parking lots, Gillis Park (19.32 lux average) and the Energy Control Center (11.36 lux average), both had horizontal illuminance values greater than 10 lux. Figure 23 indicates that these parking lots should feel relatively safe to subjects and should produce relatively similar perceptions of safety and security. The results from the Austin area parking lot study, as depicted in Figure 21, bear this out.

Similarly, the two parking lots with low illuminance, Parks and Recreation Headquarters (2.69 lux average) and the South Austin Community Health Center (5.36 lux average), would be expected to have low perceptions of safety and security based on Boyce et al.'s study. The results of the subject surveys, as depicted in Figure 22, prove that low levels of horizontal illuminance below 10 lux produced a sense of insecurity for both the Parks and Recreation parking lot and the health center parking lot.

Similar results for the subjects' perceptions of safety, security, and brightness were recorded for the two matched sets (high and low illuminance) of parking lots. Each set had one parking lot with HPS and a second parking lot with fluorescent light sources. Similar results were achieved using the fluorescent light source at 100 watts of lamp energy, compared with 250 watts for the HPS source. This reduction in energy use is possible by tuning the light source closer to how the eye adjusts under low illuminance levels. Also, as seen in Boyce et al.'s study, horizontal parking lot surface illuminances above 10 lux will produce higher perceptions of safety. However, the increase in illuminance from 11 lux for the fluorescent parking lot (Energy Control Center) to 19 lux for the HPS lot (Gillis Park) will not provide dramatically higher perceptions of safety, as predicted using Boyce's study.

Brightness, more so than illuminance, will guide people's perceptions of safety and security. In reports by Rea[8] and Fotios et al.[9], 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.

The background photopic luminance of both Gillis Park (0.43) and the Energy Control Center (0.25) fall within this range. The ratio of Gillis Park HPS luminance to the Energy Control Center luminance is 1.7. The fluorescent lighting of the Energy Control Center has a similar CCT (4100 K vs. 4000 K) as the metal halide used in the Rea experiment. Therefore, Rea's outcome would predict that subjects viewing the lighting at Gillis Park and the Energy Control Center would have similar perceptions of brightness. In fact, the outcome from the subject surveys verifies that people perceive the brightness to be similar in both parking lots.

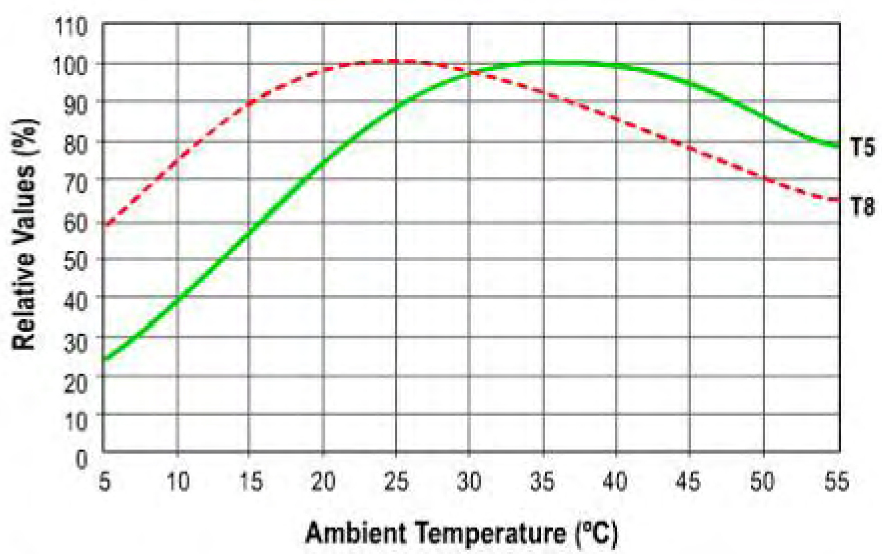
Performance and Economics Considerations

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 lamps than for HPS lamps. HPS lamps experience minimal losses in lumen output as the ambient temperature changes.

Fluorescent lamps are rated for maximum lumen output at a certain ambient temperature, 25°C for T8 and 35°C for T5. Fluorescent 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.[10] Figure 24 illustrates the effects of ambient temperature on T5 and T8 lamps. An ambient temperature of 50°C (122°F), which is highly possible in Austin, Texas, 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 20°C (68°F) will reduce light output by approximately 25%. (Winter temperatures in Austin, Texas go below 20°F on a regular basis. Therefore, a 68^{o} F within the enclosed fixture can be expected.)

Figure 24: Light Output and Ambient Temperature[10]



This diagram is quoted from SILHOUETTE T5, T5 HO & T5 Circular Fluorescent Lamp Technology Guide, Philips Lighting Company.

Replacing a 250-watt HPS light source (300 watts with ballast[11]) with a 100-watt fluorescent light source (106 watts with ballast[5]) saves a considerable amount of energy. Assuming 4,100 hours of operation per year[12], the 250-watt HPS system will use 1,230 kilowatt-hours, compared to the 100-watt fluorescent system at 435 kilowatt-hours (kWh). This is a 65% reduction in annual energy use. Cost savings to the user of the fluorescent system at 4.844 cents per kWh[13] for off-peak energy purchases would be $38.53 per year ($59.58 for 250-watt HPS versus $21.05 for 100-watt fluorescent). Other wattages of either the HPS or fluorescent systems would produce different energy savings.

Using fluorescent T5 twin-tube systems with lower wattages in lieu of HPS outdoor lighting systems for either parking lots or streetlights would slightly reduce annual maintenance costs. Lamp costs for the twin-tube fluorescent are $19.17[14] each, and two lamps are required. HPS lamp costs are $84.41.[14] The lamp life, as published in a lamp manufacturer's catalog, is 20,000 hours[15] for twin-tube fluorescent lamps. Lamp life is determined by cycling the lamps at three hours on and 20 minutes off. Lamps used in outdoor applications will usually start only once per day, which will extend fluorescent lamp life. Therefore, a lamp life of 27,000 hours was used for the payback analysis below. The lamp life for an HPS 250-watt non-cycling lamp is 30,000 hours.[6] The cost for a utility crew to change a streetlight lamp is estimated to be $100.[16] Therefore, the annual maintenance cost with 4,100 burn hours per year is $21.01 for the 100-watt fluorescent system and $25.20 for the 250-watt HPS system.

To determine the simple payback of using the fluorescent lighting system, the capital cost of the fluorescent and HPS systems must be determined and the savings from using the fluorescent 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 fluorescent versus the HPS lighting system is used. For retrofit situations, the full cost of the fluorescent system plus the labor costs to install the system must be considered.

The following assumptions were used in calculating simple payback:

- Capital cost for the fluorescent system less lamp and photo cell is $260[*,17]
- Capital cost for HPS system less lamp and photo cell is $80[*,16]
- Labor to install a new area or streetlight is $150[16]
- The outdoor lighting system operates 4,100 hours per year[12]
- Lamp costs are $19.17[14] for a 50-watt twin-tube fluorescent and $53.75[14] for a 250-watt HPS
- Labor to change a lamp on an existing outdoor fixture is $100.[17] This includes travel time to the site and use of bucket truck.
- Lamp life is 27,000 hours[15] for the 50-watt twin-tube fluorescent and 30,000 hours[6] for the 250-watt HPS
- Energy cost is $0.04844 per kWh[13] for off-peak energy
- Total system wattage for fluorescent is 106 watts[5] and for HPS 300 watts[11]

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

Simple Payback: New Outdoor Lighting Installations

Differential Capital Cost, Fluorescent versus HPS = (Fluorescent fixture cost + lamp costs + labor cost) – (HPS fixture cost + lamp cost + labor cost)
= ($260 + 2 lamps @ $19.17 ea. + $150) – ($80 + $53.75 + $150)
= $448.34 – $283.75
Differential Capital Cost = $164.59

Annual Energy Savings, Fluorescent versus HPS = (HPS wattage – Fluorescent wattage)/1000 × 4,100 hours of operation × $0.04844 per kWh
= (300 W – 106 W)/1000 × 4,100 × $0.04844
Annual Energy Savings = $38.53

Annual Maintenance Savings, Fluorescent versus HPS = (HPS lamp cost + labor cost) × (annual operating hours / lamp life) – (Fluorescent lamp costs + labor cost) × (annual operating hours / lamp life)
= ($53.75 + $100) × (4,100/30,000) – (2 lamps × $19.17 + $100) × (4,100/27,000)
Annual Maintenance Savings = $21.01 – $21.01 = $4.19

Simple Payback = Differential Capital Cost / (Annual Energy Savings + Annual Maintenance Savings)
= $133.93 / $38.53
Simple Payback = 3.5 years

Simple Payback: Retrofit Outdoor Lighting Installations

Capital Cost of Fluorescent System = Fixture cost + lamp costs + labor
= $260 + 2 lamps @ $19.17 ea. + $150
Capital cost = $448.34

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

Simple Payback = Capital Cost / (Annual Energy Savings + Annual Maintenance Savings)
= $448.34 / $38.53
Simple Payback = 11.6 years

Conclusions

Limited conclusions based on the Austin street lighting survey results could be drawn because of the low number of survey responses. However, the LRC has conducted other street lighting research utilizing fluorescing lamp sources and metal halide lamps in comparison to HPS. The results of these studies presented above are the basis for the street lighting conclusions and recommendations provided here. The minimal results from the five Austin street lighting surveys were similar to the results achieved in the other LRC research projects.

Based on LRC research and the Unified Photometry System, street lighting in mesopic illuminance ranges can be used to reduce lamp wattages by 30% without affecting perceptions of visibility, safety, or security if the lamp possesses a CCT within the white light range of approximately 6500K. For white light sources, mesopic sensitivity is better at 6500K CCT than at 4100K CCT.

The replacement of 100-watt HPS (118 watts with ballast[12]) for the Austin street lighting scenario with two 50-watt, twin-tube fluorescent lamps (106 watts with ballast[5]) saves a minimal amount of energy. There annual maintenance costs for the HPS and fluorescent systems are virtually the same.

The fluorescent and HPS comparison parking lot sets, one set with high illuminance and one set with low illuminance, were found to have similar subject perceptions of safety and security during daylight hours and at night with the lights turned off. The similarities allowed for successful comparison research to be conducted on the two different lighting systems.

The fluorescent lamps selected for both the street and parking lots studies were chosen before the LRC became involved in this project and the Unified Photometry System was not considered as the basis for the selection. The Unified Photometry System allows for lamp substitution based on the lamp's scotopic-to-photopic ratio and the desired luminance on the road surface while providing equal visibility. However, the 4100 K CCT lamps chosen by Austin Energy and Magnaray® are closer to the optimum mesopic vision range than the HPS lamp source.

Currently, Austin Energy is over lighting these intersections by more than double the IESNA recommended illuminance levels.

Similar subject perceptions of safety, security, and brightness were recorded within the high illuminance set of comparison parking lots and within the low illuminance set of comparison parking lots, regardless of the spectral distribution of the lamp used. In both the fluorescent and HPS high illuminance parking lots, subjects indicated they felt safe and secure. However, in the parking lots with low illuminance, subjects indicated they felt unsafe. The low illuminance and poor spatial light distribution in both low illuminance parking lots were the causes for subjects' perceptions of inadequate safety and security.

The results of perceptions of safety and security follow closely with the results achieved by Boyce et al.'s research, *Perception of Safety at Night in Different Lighting Conditions*.[7] Parking lots with horizontal illuminance greater than 10 lux will exhibit acceptable subject perceptions of safety and security. Both Gillis Park and the Energy Control Center had average illuminance values greater than 10 lux, and survey respondents indicated acceptable levels of safety and security. Conversely, the Parks and Recreation Headquarters and the South Austin Community Health Center had considerably lower average horizontal illuminance values. Subjects' perceptions of safety and security were poor for both these parking lots, regardless of the spectral distribution of the light source.

Subjects found color rendering to be better with the fluorescent light sources in both the high and low illuminance conditions.

Spatial light distribution influences subject perceptions of safety and security as much as average illuminance values. Parking lots with reasonable distributions of light, such as Gillis Park and the Energy Control Center, are perceived as being safer compared to parking lots such as South Austin Community Health Center and the Parks and Recreation Headquarters with poor light distribution. Good lighting design that provides some uniformity in light levels rather than pools of light surrounded by dark areas is as important as providing enough illuminance.

Considerable energy savings (65%) is possible when utilizing the 100-watt (106 watts with ballast[5]) fluorescent lighting system compared to the standard HPS 250-watt (300 watts with ballast[11]) outdoor lighting system while maintaining similar perceptions of safety, security, and brightness. At 4.844 cents per kWh[13], the energy savings translates into an annual cost savings of $38.53 per light fixture.

The annual maintenance costs are the same, even though the fluorescent lamps have a shorter lamp life than the HPS lamps, 27,000 hours[15] versus 30,000 hours.[6] This occurs because the fluorescent lamps' purchase price is less than the HPS lamps.

The use of the 100-watt fluorescent outdoor lighting system for newly lit parking lots provides a reasonable payback for the higher initial cost to the City of Austin (3.5 years). Retrofitting existing HPS 250-watt parking lot lighting with the 100-watt fluorescent system has a longer payback of 11.6 years. The latter case may be beyond the financial criteria for the City to retrofit existing parking lot lighting.

Recommendations

Street Lighting Recommendations

- Using a fluorescing lamp source tuned to optimize mesopic vision within the white light range (6500 K CCT) offers opportunities to reduce lamp wattages by 30% from the HPS lamp it would replace without negatively impacting perceptions of visibility, safety, or security. Austin Energy should consider a program of replacing 100-watt HPS streetlights with a fluorescing lamp source of around 70 watts, and 70-watt HPS streetlights with a fluorescing lamp source of approximately 50 watts.

- Other fluorescing light sources, such as electrodeless lamps, should be explored beyond the T5 twin tubes. Electrodeless lamps provide longer lamp life that could reduce maintenance costs. This exploration should occur prior to Austin Energy deciding to convert any outdoor lighting from HPS. An economic analysis such as presented in this report can be used to determine the cost effectiveness of all HPS replacement options.

- Strive to utilize lamps in outdoor lighting installations that are spectrally closer to the optimum mesopic vision range of 6500 K CCT.

- Metal halide (even ceramic metal halide) used in street lighting has some serious shortcomings of shorter lamp life (20,000 hours) than HPS (30,000 hours) and higher lumen depreciation over the life of the lamp. These shortcomings cause the LRC to be concerned in recommending the use of metal halide as a replacement for HPS. The added maintenance costs will more than offset any energy savings, causing higher total costs for Austin Energy.

- The recommended potential replacements for the 250 watt HPS at the intersections are based on providing sufficient lighting to meet the IESNA recommended practices or to meet the unified photometry system recommendations for mesopic street lighting to match or exceed the visual performance provided by 100 watt HPS lighting. The following are the recommended replacements for the 250 watt HPS intersection lighting.
  - 150 watt HPS at 2100K CCT. This light source will still provide average illuminance values (24.6 lux) that exceed IESNA recommended levels.
  - 100 watt HPS at 2100K CCT. This light source will provide close to the IESNA recommended levels of illuminance of 16 lux.
  - 2, 50 watt, T5 Twin Tube Fluorescent at 4100K CCT. Based on the unified photometry system, this light source will provide higher visual performance than the 100 watt HPS.
  - A 70 watt fluorescing light source at 6500K CCT. Based on the unified photometry system, this light source will provide similar visual performance as the 100 watt HPS.

Parking Lot Lighting Recommendations

- Parking lot lighting design should strive to provide average horizontal illuminance values greater than 10 lux with good spatial light distribution to ensure high degrees of perceived safety and security. The use of the Illuminating Engineering Society of North America's guideline RP-20 for the design of parking lot lighting is encouraged.

- Strive to utilize lamps in outdoor lighting installations that are spectrally closer to maximizing mesopic vision within the white light range at 6500 K CCT.[1]

- Other fluorescing light sources, such as electrodeless lamps, should be explored beyond the T5 twin tubes. Electrodeless lamps provide longer lamp life that could reduce maintenance costs. This exploration should occur prior to Austin Energy deciding to convert any outdoor lighting from HPS. An economic analysis such as presented in the report can be used to determine the cost effectiveness of all HPS replacement options.

- Based on the Unified Photometry System[3], properly designed parking lot lighting systems can reduce lamp wattage by approximately 30% while maintaining visual performance if the light source is tuned at 6500K CCT to maximize mesopic vision within the white light range.

- The use of the Unified Photometry System[3] to determine replacement wattages of lamps with different spectral distributions that will provide similar visibility is encouraged. Austin Energy can examine replacing HPS wattages other than 250 watts by use of this system. Once replacement lamps are selected, an economic analysis can be performed to determine if a reasonable payback is possible.

References

1. Rea M, Bullough JD, Freyssinier JP, Bierman A. 2003. X. CIE Expert Symposium on Temporal and Spatial Aspects of Light and Colour Perception and Measurement (pp. 51-58), Veszprem, Hungary, August 22-23, 2002. Vienna, Austria: Commission Internationale de l'Eclairage.

2. Akashi Y, Rea MS. 2002. Peripheral Detection While Driving Under a Mesopic Light Level, *Journal of the IESNA*, 31,1.

3. Rea M, Bullough JD, Freyssinier JP, Bierman A. 2004. A Proposed Unified System of Photometry. *Lighting Research and Technology*, 36(2).

4. Akashi Y, Rea MS, Morante P. April 9, 2004. Unified Photometry: An Energy-efficient Street Lighting Demonstration in Easthampton, Massachusetts. Proceedings of the CIE Symposium '05, Vision and Lighting in Mesopic Conditions

5. Magnaray® International. 2007. Visually and Energy Efficient Street Lighting brochure.

6. OSRAM Sylvania. 2007. Lamp and Ballast Product Catalog, p. 84.

7. Boyce PR, Eklund NH, Hamilton BJ, Bruno LD. 2000. Perception of Safety at Night in Different Lighting Conditions, *Lighting Research and Technology*, 30, 175-181.

8. Rea M. October 1996. Essay by Invitation. *Lighting Design and Application.* pp. 15-16.

9. Fotios SA, Cheal C. 2007. Lighting for Subsidiary Streets: Investigation of Lamps of Different SPD. Part 2 – Brightness, *Lighting Research and Technology*, 39,3, 233-252.

10. Akashi Y. 2002. T5 Fluorescent Systems. *National Lighting Product Information Program: Lighting Answers.*

11. Advance Transformer Company. 2006-2007. Advance Atlas, Catalog Number 71A8251.

12. Connecticut Light and Power Company. Rates and Tariff. Rate 116: Street and Area Lighting. (Note: Annual hours of operation adjusted for change in locale.)

13. Austin Energy. 2007. Rates: Fuel Adjustment Clause and General Service – Demand.

14. Grainger Catalog Number 296. 2005-2006. pp. 638 and 650.

15. Philips Lighting Company. 2006. SAG100 Catalog, p. 63. (Note: Adjusted for one start per day.)

16. Morante P. Expert knowledge based on experience managing utility streetlight programs.

17. Leetzow L. October 23, 2007. Memo to P. Morante.

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Donna Watson, Tammadge Market Research, for recruiting subjects for the parking lot study and somehow ensuring that all 15 subjects invited showed up for the study.

Appendix A: Street Lighting Survey Questionnaire

START TIME: ________

CCR #10-2771
08/28/07 – V2

AUSTIN ENERGY STREETLIGHT SURVEY

NAME: ______________________________ PHONE #: (_____)____________________

INTERVIEWER:______________________________DATE:______________________

ASK TO SPEAK TO PERSON ON LIST. MUST SPEAK TO PERSON ON LIST.

Hi ______, this is (YOUR NAME) from Creative Consumer Research calling on behalf of Austin Energy. We called you a few days ago and asked that you view some street lights in your area so that we could ask you a few questions and send you a $10 Whole Foods gift card. Did you have a chance to look at the lighting on both of these streets?

Yes 1 CONTINUE
No 2 SCHEDULE CALLBACK:
When would be a good time to call you back to give you a chance to look at these lights?

IF THE PERSON WANTS SPONSOR INFORMATION:

Please call the Peter Morante at 518-687-7173

CONTINUE WITH THE SURVEY.

For this survey, please think about the street lights you observed at night on West Avenue between 9th, 10th, and 11th street, and tell me which response most closely describes the degree of your agreement with each statement: (READ LIST)

Strongly disagree, disagree, are neutral, agree, or strongly agree.

Overall

1. I like the lighting on West Ave. between 9th and 10th Streets. (READ LIST AS NEEDED TO PROMPT THROUGHOUT SURVEY)

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

2. The lighting on West Ave. between 9th and 10th Streets is comfortable.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

3. West Ave. between 9th and 10th Streets looks bright.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

4. West Ave. between 9th and 10th Streets looks gloomy.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

5. The light fixtures on the poles on West Ave. between 9th and 10th Streets are too bright

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

6. Colors of traffic signs along West Ave. between 9th and 10^{th} Streets appear clear.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

7. Colors of vegetation along West Ave. between 9th and 10th Streets look natural.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

8. The lighting on West Ave. between 9th and 10^{th} Streets is too warm in color for a street

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

9. The lighting on West Ave. between 9th and 10^{th} Streets is too cool in color for a street.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

10. The lighting on West Ave. between 9th and 10^{th} Streets looks better than other portions of West Ave.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

11. The street lights between 9th and 10th street are a good example of security lighting

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

As a driver, with this lighting,

12. I can see the roadway pavement on West Ave. between 9th and 10th Streets clearly.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

13. I can see other vehicles approaching on West Ave. between 9th and 10th Streets clearly.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

14. I can see pedestrians approaching on West Ave. between 9th and 10th Streets clearly.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

15. I feel safe while driving along West Ave. between 9th and 10th Streets.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

As a pedestrian, with this lighting,

16. I can see other pedestrians approaching on West Ave. between 9th and 10th Streets clearly.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

17. I can see faces of pedestrians on West Ave. between 9th and 10th Streets clearly.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

18. I can see vehicles approaching on West Ave. between 9th and 10th Streets clearly.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

19. I feel secure while walking on the sidewalk of West Ave. between 9th and 10th Streets.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

West Avenue between 10th and 11th streets

Overall

20. I like the lighting on West Ave. between 10th and 11th Streets.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

21. The lighting on West Ave. between 10th and 11th Streets is comfortable.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

22. West Ave. between 10th and 11th Streets looks bright.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

23. West Ave. between 10th and 11th Streets looks gloomy.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

24. The light fixtures on the poles on West Ave. between 10th and 11th Streets are too bright

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

25. Colors of traffic signs along West Ave. between 10th and 11th Streets appear clear.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

26. Colors of vegetation along West Ave. between 10th and 11th Streets look natural.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

27. The lighting on West Ave. between 10th and 11th Streets is too warm in color for a street

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

28. The lighting on West Ave. between 10th and 11th Streets is too cool in color for a street.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

29. The lights on West Ave. between 10th and 11th Streets looks better than other portions of West Ave.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

30. The street lights between 10th and 11th streets are a good example of security lighting

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

As a driver, with this lighting,

31. I can see the roadway pavement on West Ave. between 10th and 11th) Streets clearly.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

32. I can see other vehicles approaching on West Ave. between 10th and 11th Streets clearly.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

33. I can see pedestrians approaching on West Ave. between 10th and 11th) Streets clearly.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

34. I feel safe while driving along West Ave. between 10th and 11th Streets.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

As a pedestrian, with this lighting,

35. I can see other pedestrians approaching on West Ave. between 10th and 11th Streets clearly.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

36. I can see faces of pedestrians on West Ave. between 10th and 11th Streets clearly.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

37. I can see vehicles approaching on West Ave. between 10th and 11th Streets clearly.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

38. I feel secure while walking on the sidewalk of West Ave. between 10th and 11th Streets.

Strongly disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly agree	5

DEMOGRAPHICS

These last few demographic questions will allow us to group your responses with those of other Austin residents for analytical purposes.

39. BY OBSERVATION: Gender

Male	1
Female	2

40. To be sure that we talk to a variety of Austin area residents, please tell me which of the following categories includes your age. Would it be . . . (READ LIST.)

18 to 24	1
25 to 30	2
31 to 35	3
36 to 40	4
41 to 45	5
46 to 50	6
51 to 55	7
56 to 60	8
61 to 65	9
66 years of age or older	x
(Do Not Read) Refused	x

41. Again to be sure that we talk to a variety of Austin area residents, please tell me which of the following best describes your ethnic background or race. Are you … (READ LIST)

Of Hispanic origin, such as Mexican American, Latin American, Puerto Rican, or Cuban	1
White	2
African-American	3
Asian, Pacific Islander	4
Aleutian, Eskimo, or American Indian	5
Other: ________________________	❑
(Do not read) DK/unsure	7
(Do not read) Refused	8

42. What is the highest grade of school you have completed? Is it . . . **(READ LIST)**

Some high school	1
Graduated high school	2
Some college	3
Graduated college	4
Post-graduate work	5
(Do Not Read) DK/unsure	6
(Do Not Read) Refused	7

43. What is your marital status? Are you . . . **(READ LIST)**

Single	1
Married	2
Separated	3
Divorced	4
Widowed	5
In transition	6
(Do Not Read) Refused	7

44. Which of the following **best** describes your residence? (READ LIST. ACCEPT ONLY ONE RESPONSE.)

Single-family home..1
Townhouse/Duplex..2
Condo...3
Apartment 4
Other ***(Specify)*** ________________________________................θ

45. Do you rent or own your current place of residence?

Rent	*1*
Own	*2*
DK/unsure	3

46. How long have you lived in the Austin metropolitan area? **(DO NOT READ LIST)**

Less than 1 year	1
1 year to 5 years	2
6 to 10 years	3
11 to 15 years	4
16 to 20 years	5
21 to 30 years	6

31 to 40 years	7
41 to 50 years	8
More than 50 years	9
Refused	10

47. Do you currently wear any of the following?

Contact lenses	1
Reading glasses	2
Everyday glasses	3
Any other corrective eyewear (SPECIFY)___________	4
None	5

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.

(CONFIRM RESPONDENT NAME,
AREA CODE AND TELEPHONE NUMBER;
RECORD ON FRONT PAGE OF SURVEY.)

THAT CONCLUDES OUR SURVEY.
THANK YOU VERY MUCH FOR YOUR PARTICIPATION!

END
TIME: __________

Appendix B: Parking Lot Lighting Questionnaire Daytime and Night No Lights

Lighting Questionnaire for Daytime Gillis Park, Austin, Texas

Lighting Research Center, Rensselaer Polytechnic Institute, 21 Union Street, Troy, NY 12180

Austin Energy and the Lighting Research Center (LRC) are conducting an evaluation of outdoor lighting. We would like to know your opinions of the parking lot lighting, under the present conditions. Please observe the parking lot and the lighting, 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.

1. I would feel safe walking alone in this parking lot …………………. -2 -1 0 +1 +2
2. I can adequately see potential hazards and threats in this parking lot. -2 -1 0 +1 +2
3. I believe all areas within this parking lot are safe ……………………-2 -1 0 +1 +2
4. I would feel comfortable parking my car anyplace within this lot …...-2 -1 0 +1 +2
5. I can identify the colors of clothing and cars easily within this lot …..-2 -1 0 +1 +2
6. If I dropped some money on this parking lot pavement, I could find it easily ……………………………………………………………….-2 -1 0 +1 +2
7. I would be able to easily recognize a friend, appearing unexpectedly, in this parking lot …………………………………………………….-2 -1 0 +1 +2

Thank you for your cooperation.

Appendix C: Parking Lot Lighting Questionnaire, Lights On

Lighting Questionnaire for Lights Gillis Park, Austin, Texas

Lighting Research Center, Rensselaer Polytechnic Institute, 21 Union Street, Troy, NY 12180

Austin Energy and the Lighting Research Center (LRC) are conducting an evaluation of outdoor lighting. We would like to know your opinions of the parking lot lighting, under the present conditions. Please observe the parking lot and the lighting, 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.

1. I would feel safe walking alone in this parking lot................................-2 -1 0 +1 +2
2. I can adequately see potential hazards and threats in this parking lot. .-2 -1 0 +1 +2
3. I believe all areas within this parking lot are safe.................................-2 -1 0 +1 +2
4. I would feel comfortable parking my car anyplace within this lot. ......-2 -1 0 +1 +2
5. I can identify the colors of clothing and cars easily within this lot. .....-2 -1 0 +1 +2
6. If I dropped some money on this parking lot pavement, I could find it easily...-2 -1 0 +1 +2
7. I would be able to easily recognize a friend, appearing unexpectedly, in this parking lot. ....-2 -1 0 +1 +2
8. I like the parking lot lighting. ....-2 -1 0 +1 +2
9. The parking lot lighting is comfortable. ....-2 -1 0 +1 +2
10. The parking lot looks bright...-2 -1 0 +1 +2

11. The parking lot looks gloomy. ....-2 -1 0 +1 +2

12. The light fixtures on the poles are too bright. ....-2 -1 0 +1 +2

13. The colors of vegetation surrounding the parking lot look natural.......-2 -1 0 +1 +2

Thank you for your cooperation.

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

Magnaray International

Paclantic International

Lighting Research Center
Rensselaer Polytechnic Institute
21 Union Street
Troy, NY 12180
518-687-7100
518-687-7120 (fax)

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

Yukio Akashi, Mark Rea, Peter Morante

Lighting Research Center
Rensselaer Polytechnic Institute
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.

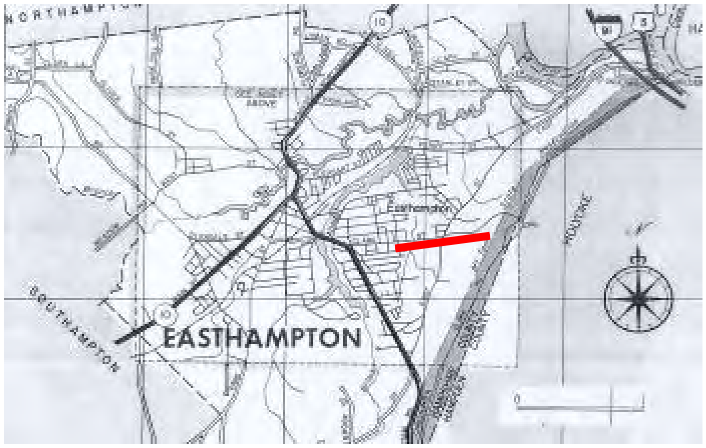

Figure 1. Demonstration site, Clark Street in Easthampton, Mass. (shown in red)

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

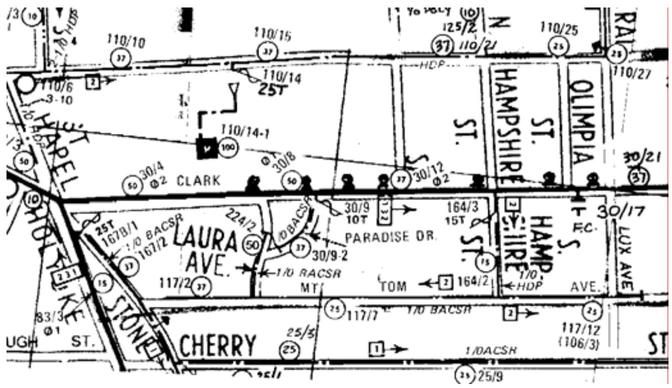

Figure 4. Luminaire layout along Clark Street

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.

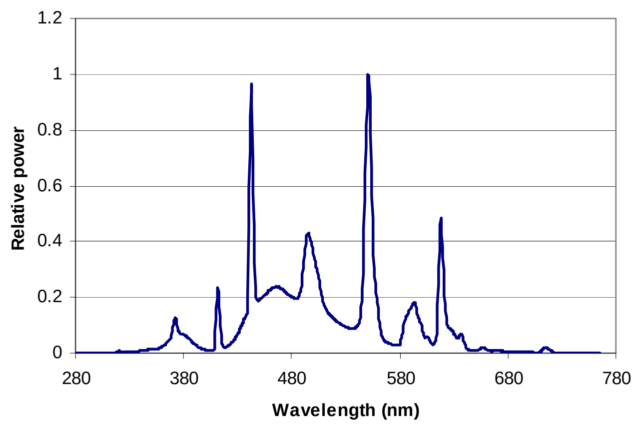

Figure 5. Spectral power distribution of fluorescent lamp

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

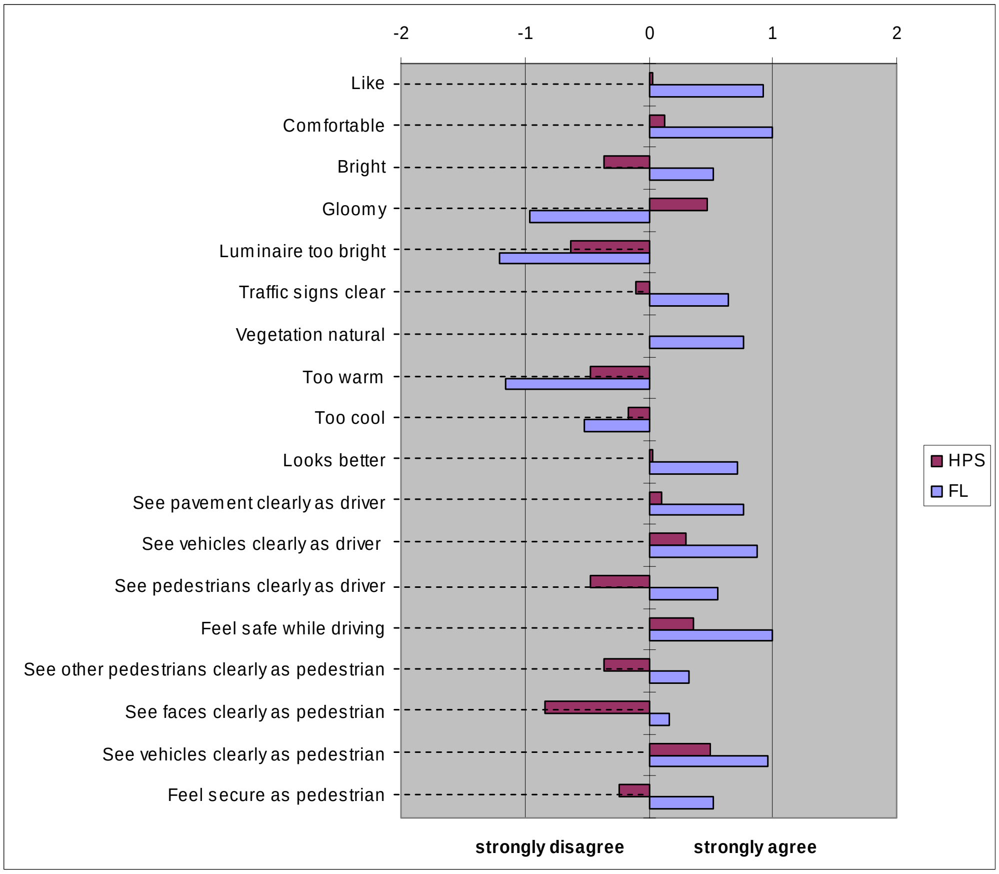

Figure 8. Mean evaluation results (30 responses for HPS and 25 responses for fluorescent lighting)

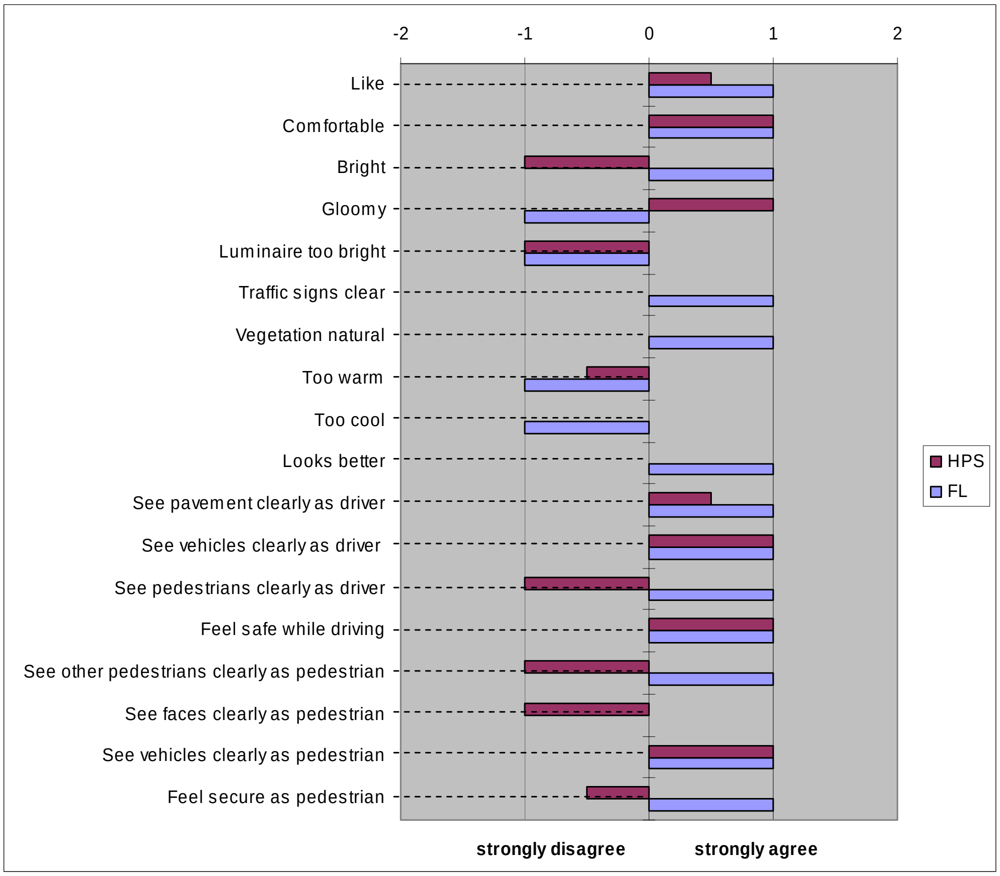

Figure 9. Median evaluation results (30 responses for HPS and 25 responses for fluorescent lighting)

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.

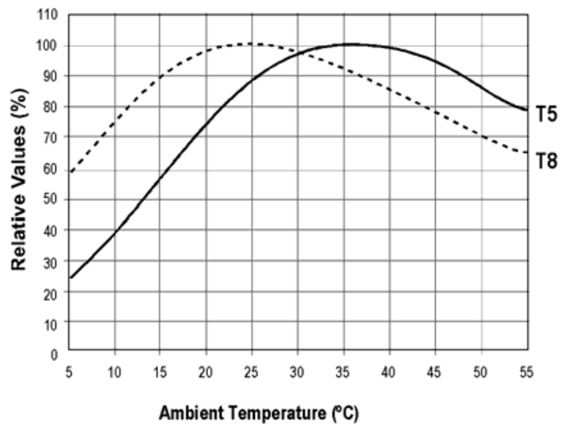

Figure 10. Relative light output variation as a function of ambient temperature for T5 and T8 fluorescent lamps.

(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.

REFERENCES

Akashi, Y. 2003a. Research Recap: Are T5s better than T8s? *Lighting Design + Application (LD+A)*, 33, 1, 6-8.

———. 2003b. Research Recap: Room brightness perception, *Lighting Design + Application (LD+A)*, 33, 7, 12-13.

Akashi, Y. and J. Neches. 2004. Detectability and acceptability of illuminance reduction for load shedding, *Journal of the IESNA*, 33, 1, 3-13.

Akashi, Y., and M.S. Rea. 2002. Peripheral detection while driving under a mesopic light level, *Journal of the IESNA*, 31, 1, 85-94.

Bullough, J., and M.S. Rea. 2000. Simulated driving performance and peripheral detection at mesopic light levels, *Lighting Research and Technology*, 32, 4, 194-198.

Gillet, M., and P. Rombauts. 2001. Precise Evaluation of Upward Flux from Outdoor Lighting Installations (applied in the case of roadway lighting), *London (UK) Light Trespass Symposium*, *Nov. 2001*.

He, Y., A. Bierman, and M.S. Rea. 1998. A system of mesopic photometry. *Lighting Research and Technology*, 30, 4, 169-175.

He, Y., M.S. Rea, A. Bierman, and J. Bullough. 1997. Evaluating light source efficacy under mesopic conditions using reaction times, *Journal of the IESNA*, 26, 1, 125-138

Lingard, R., and M.S. Rea. 2002. Off-axis detection at mesopic light levels in a driving context, *Journal of the IESNA*, 31, 1, 33-39

Rea, M.S., ed. 2000. *IESNA Lighting Handbook Reference and Application*, Illuminating Engineering Society of North America, NY.

Rea, M. S., J. D. Bullough, J. P. Freyssinier and A. Bierman. 2003. X. CIE Expert Symposium on Temporal and Spatial Aspects of Light and Colour Perception and Measurement (pp. 51-58), Veszprém, Hungary, August 22-23, 2002. Vienna, Austria: Commission Internationale de l'Éclairage.

———. 2004 (in press). A proposed unified system of photometry. *Lighting Research and Technology* 36(2).

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

12. I like the lighting on Clark Street.	(-2 -1 0 +1 +2)
13. The lighting on Clark Street is comfortable.	(-2 -1 0 +1 +2)
14. Clark Street looks bright.	(-2 -1 0 +1 +2)
15. Clark Street looks gloomy.	(-2 -1 0 +1 +2)
16. The light fixtures on the poles in Clark Street are too bright.	(-2 -1 0 +1 +2)
17. Colors of traffic signs along Clark Street appear clear.	(-2 -1 0 +1 +2)
18. Colors of vegetation along Clark Street look natural.	(-2 -1 0 +1 +2)
19. The lighting on Clark Street is too warm in color for a street.	(-2 -1 0 +1 +2)
20. The lighting on Clark Street is too cool in color for a street.	(-2 -1 0 +1 +2)
21. 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,

22. I like the new white lighting on Clark Street. .... -2 -1 0 1 2
23. The lighting on Clark Street is comfortable. .... -2 -1 0 1 2
24. Clark Street looks bright. .... -2 -1 0 1 2
25. Clark Street looks gloomy. .... -2 -1 0 1 2
26. The light fixtures on the poles in Clark Street are too bright. .... -2 -1 0 1 2
27. The colors of traffic signs along Clark Street appear clear. .... -2 -1 0 1 2
28. The colors of vegetation along Clark Street look natural. .... -2 -1 0 1 2
29. The lighting on Clark Street is too warm (orange) in color for a street. ..... -2 -1 0 1 2
30. The lighting on Clark Street is too cool (blue) in color for a street. .... -2 -1 0 1 2
31. 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

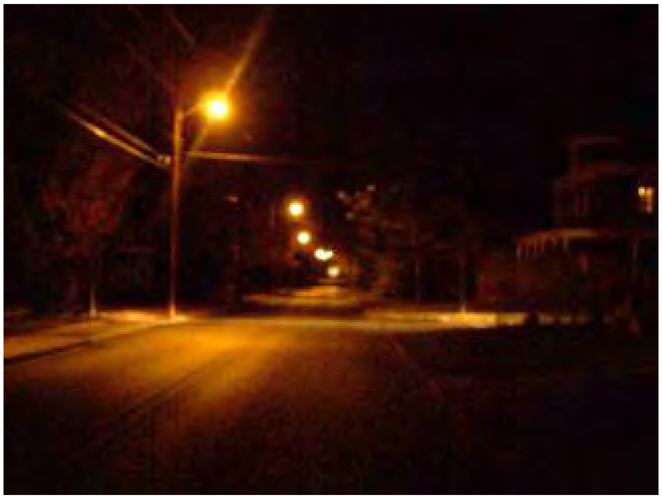

Figure A4-1. HPS lighting

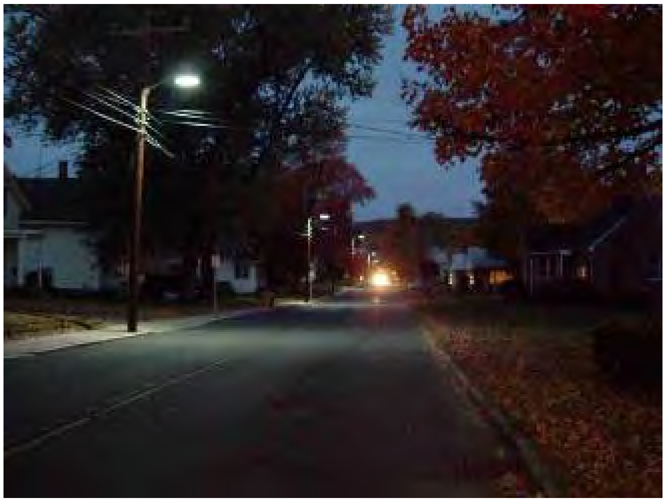

Figure A4-2. Fluorescent lighting with flat lens

Figure A4-3. Fluorescent lighting with drop lens

Appendix 5: Photopic illuminance measurements between two luminaires

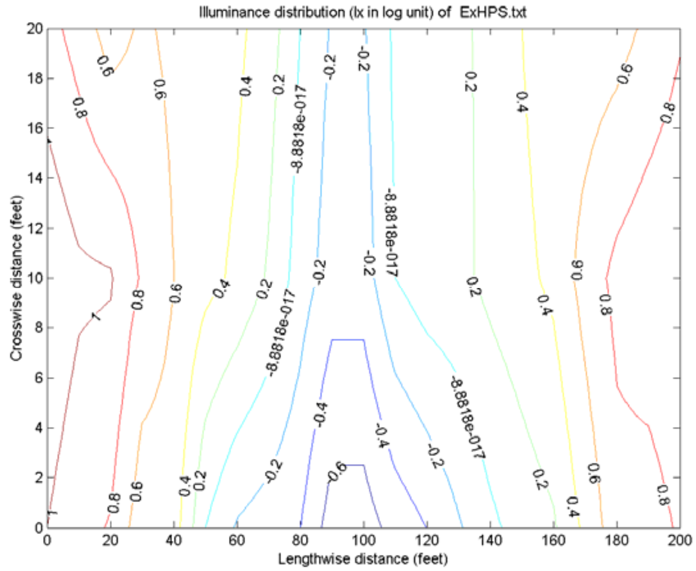

Figure A5-1. Illuminance distribution between two poles for HPS lighting (log lx)

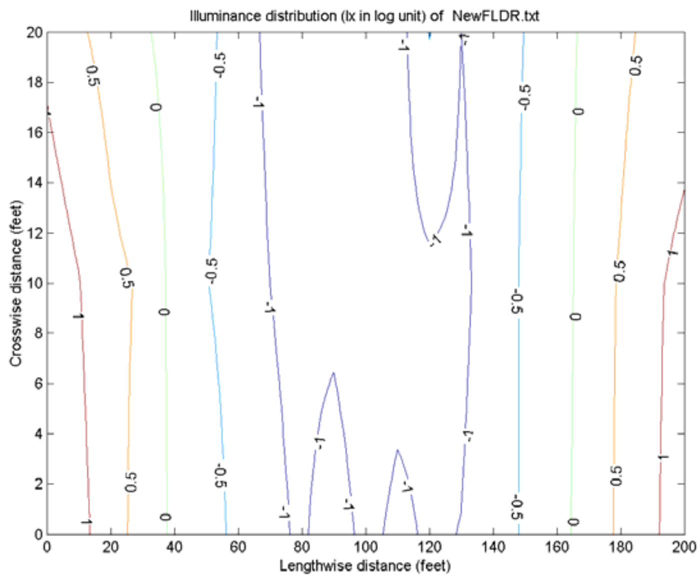

Figure A5-2. Illuminance distribution between two poles for fluorescent lighting (log lx)

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

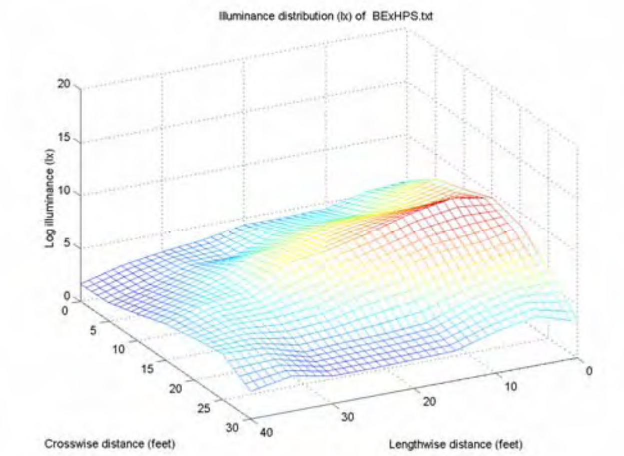

Figure A6-1. Illuminance distribution around a pole for the existing HPS lighting (log lx)

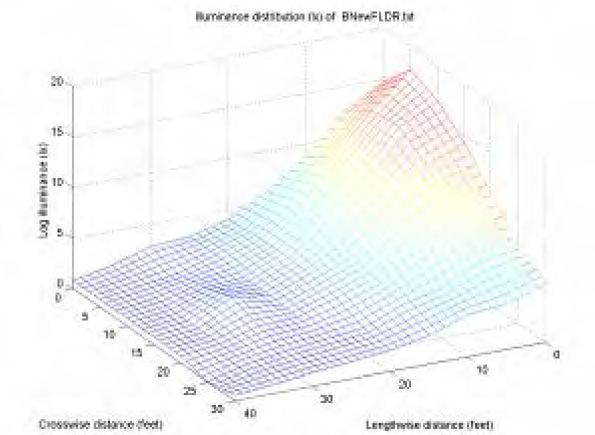

Figure A6-2. Illuminance distribution around a pole for the fluorescent lighting (log lx) (data measured at 32°F)

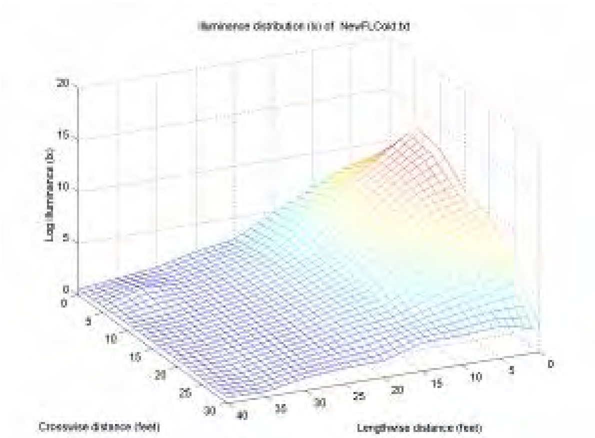

Figure A6-3. Illuminance distribution around a pole for the fluorescent lighting (log lx) (data measured at 15°F)

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**