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LED ROADWAY LIGHTING VOLUME 2: FIELD EVALUATIONS AND SOFTWARE COMPARISONS

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16. Abstract

The use of light-emitting diodes (LEDs) for roadway lighting can potentially save energy costs and reduce the frequency of maintenance. The objective of this study is to explore the current state of the art in LED roadway lighting technology. Three sets of LED roadway luminaires, along with a set of high-pressure sodium (HPS) luminaires, were selected for field testing. The LED luminaires were manufactured by GE Lighting (Evolve Series, 454239), Relume Lighting (Vue Series, 320-HE), and Cooper Lighting (Ventus Series, VSTA 08). There was generally fair agreement between illuminance measured in the field and data obtained using the lighting analysis software AGi32, except for one of the LEDs. Results showed that the field data and software results for two of the three sets of LED luminaires satisfied the IDOT illuminance design criteria for the test site conditions for a major roadway with medium pedestrian conflict. On the other hand, one of the sets satisfied the average maintained illuminance criterion for low pedestrian conflicts but not for medium pedestrian conflicts. Likewise, the field data for the HPS luminaire did not meet one of the illuminance uniformity criteria (average/minimum) in the test site conditions. Regarding luminance, measurements were collected in the field using a meter that provided accurate average values but not point-by-point maximum and minimum readings, given the greater aperture angle compared to that suggested by LM-50-99. Results from the field showed that the HPS and all three models of LED luminaires met the average IDOT luminance design criteria for the test site conditions (except one luminaire that met only the requirements in the center span). Software results also showed that the LED luminaires mostly satisfied the average luminance criterion for the specified roadway. However, one of the uniformity requirements (maximum/minimum) was not met by two of the LED sets, exceeding the recommended ratios. Lastly, a generic cost-benefit analysis of an LED luminaire was conducted as an example to analyze LED luminaires. A second phase of this project is proposed, including conducting more detailed cycle-life cost analysis for LED roadway luminaires, determining appropriate light loss factors, providing further information for a new IDOT specification, and examining other technologies such as ceramic metal halide, plasma, and induction.

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EXECUTIVE SUMMARY

Proper roadway lighting can improve highway safety and reduce energy consumption. Currently, approximately 40% of the street lights in the U.S. use high-pressure sodium (HPS) lamps. The rest of them use metal halide, mercury vapor, halogen quartz, fluorescent, and incandescent light sources. Recent technological advancements in light-emitting diodes (LEDs) have made LED luminaries a potential roadway lighting alternative. This study explored the current state of the art in LED roadway lighting technology and field-tested the performance of three LED roadway luminaires. A comprehensive literature review on the state of technology in LED roadway lighting, test procedures for photometric measurements, and IDOT roadway lighting requirements were presented in Volume 1 of this study.

For field testing, three sets of LED luminaires (each from a different manufacturer) and a set of HPS luminaires were installed. The LED luminaires were manufactured by GE Lighting (Evolve Series, 454239), Relume Lighting (Vue Series, 320-HE), and Cooper Lighting (Ventus Series, VSTA 08). Only one manufacturer's luminaires were installed and tested at a time, resulting in multiple setups. The mounting height was 30 ft, spacing was 150 ft, and the pavement type at the test site was R3. Luminaires were installed on four wood poles that could facilitate the testing of increased mounting heights up to 40 ft. The poles also could be relocated to accommodate spacing of up to 250 ft.

Field data were collected and also compared with results of AGi32, a lighting design software package developed by Lighting Analysts, Inc. Moreover, both the field data and software results were compared with the IDOT lighting design criteria for major roads with medium pedestrian conflict. See IESNA RP-8-00 for more information on roadway and pedestrian conflict classifications.

IDOT's design guidelines require the consideration of luminance, illuminance, and veiling luminance. In general, there were significant discrepancies between field measurements and results from AGi32, depending on the luminaire. The performance of the tested luminaires varied significantly from each other. For each LED, adjustment factors were proposed to estimate the field illuminance values based on the software computed values.

It is noted that the selection of luminance meters was constrained by budget and limited availability of off-the shelf devices. In addition, there was a need to use two luminance meters to shorten the duration of lane closures for data collection; thus, it was decided to buy one luminance meter by Konica Minolta (L-100) and use it in combination with another such meter that IDOT already had purchased for a previous project. This device does not have the acceptance angle to provide point-by-point readings using the grid from LM-50-99, and as a result, maximum and minimum values directly measured are not emphasized, but it may provide accurate average values comparable to those from individual grid points. In addition, this instrument is reliable and has a precision that exceeds LM-50-99.

Based on the field measurements for LED and HPS luminaires and their comparisons to AGi32 software results, the following conclusion are made.

HPS

- There was close agreement between the field-measured illuminance data and AGi32 software results except at the grid points in the immediate vicinity of the light poles. At those points, the field data returned considerably higher illuminance levels than the software results. Thus, the field data for the HPS did not satisfy the IDOT illuminance uniformity criterion (i.e., average/minimum) for the roadway classification major/medium; however, the AGi32 software results satisfied all illuminance design criteria for the roadway classification major/medium.

- The field data show that the HPS luminaires satisfied the average luminance design criterion for major roads.
- Software results for the HPS luminaires satisfied all luminance design criteria at the study site for major roads.

LED#1

- The illuminance results showed a very close agreement between the field data and AGi32 results.
- Both the field data and software results showed that LED#1 did not satisfy the average illuminance criterion at the study site for the roadway classification major/medium.
- The field data show that LED#1 satisfied the average luminance design criterion for major roads except in fixture cycles 1 and 3, where it did not meet the average maintained luminance value for major/high.
- According to the software results, LED#1 met all luminance design criteria for major/medium and major/low. However, it did not meet the average maintained luminance criterion for major/high.
- Software results for LED#1 satisfied luminance design criteria at the study site for the roadway classification major/medium and major/low. However, it did not meet the average maintained luminance criterion for major/high.

LED#2

- For illuminance, there were significant discrepancies between the field data and AGi32 results at the grid points in the immediate vicinity of the light poles. At those points, the software results returned considerably higher illuminance levels than the field data.
- Both the field data and software results for LED#2 satisfied all illuminance design criteria at the study site for the roadway classification major/medium.
- The field luminance data for LED#2 show that it satisfied the average maintained luminance criterion at the test site for major roads.
- The software luminance results for LED#2 did not satisfy one of the uniformity criteria (i.e., maximum/minimum).

LED#3

- For illuminance, there were considerable discrepancies between the field data and AGi32 results. At all grid points, the software results returned considerably higher illuminance levels than the field data.
- Both the field data and software results for LED#3 satisfied all illuminance design criteria at the study site for the roadway classification major/medium.
- The field luminance data for LED#3 satisfied the average maintained luminance design criterion at the test site for major roads.
- The software luminance results for LED#3 did not satisfy one of the uniformity ratio criteria (i.e., maximum/minimum).

In light of the results, a second phase of this study is proposed. The second phase should involve various tasks such as determining appropriate light loss factors for LED roadway luminaires; providing the required information for new IDOT specifications; examining the suitability of other technologies such as ceramic metal halide, plasma, and induction; and performing detailed life-cycle cost analysis for the roadway luminaires.

Appendix K includes a preliminary list of some suggested items for new specifications. Some of the suggestions are formed based on current LED roadway lighting specifications of other institutions. In the proposed second phase of the study, further detailed information should be provided to build appropriate LED roadway specifications for IDOT. Moreover, a detailed economic analysis should provide accurate economic comparison of the selected roadway luminaires and should help better identify their suitability for roadway applications.

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CHAPTER 1 INTRODUCTION

Roadway lighting is an essential public service to improve safety for motorists and pedestrians alike. Some benefits of roadway lighting include enhancing personal security and traffic safety, improving traffic flow at night, and reducing nighttime traffic crashes (Kodisingle 2008). With proper roadway lighting, drivers can see better and more easily recognize the condition and geometry of the roadway. Proper roadway lighting contributes considerably to highway safety by increasing driver visual comfort and reducing driver fatigue (IDOT 2010).

As of 2007, approximately 131 million bases of street and area lights were installed in the U.S., with a total annual electricity consumption of 178.3 kilowatt-hours (kWh). Approximately 54.7 million (41.7%) of those bases contain high-pressure sodium (HPS) light sources. The rest include metal halide (29.2%), mercury vapor (13.5%), halogen quartz (7.5%), fluorescent (5.7%), and incandescent (2.4%) light sources (Navigant Consulting, Inc. 2008).

As oil and gas reserves decrease and the demand for energy increases, energy conservation is an urgent priority. Thus, use of energy-efficient technology is required in roadway lighting to mitigate the effects of the energy crisis. Light-emitting diodes (LEDs) are fourth-generation light sources that have been developed as an energy-efficient alternative to high-intensity discharge (HID) street lighting. The use of LEDs as a light source in roadway lighting can potentially save energy costs and reduce the frequency of maintenance.

Recent technological advancements have increased the quality of LEDs by approximately ten times and reduced their production cost by approximately 90%, making LEDs more feasible for roadway lighting (Xiaoyun, Xiaojian, and Yan 2009). The advancements in LED technology are so rapid that new generations of LED devices are released every 4 to 6 months or so (U.S. Department of Energy 2009). Similar to the way inorganic semiconductor transistors displaced vacuum tubes in electrical switches, LEDs may displace conventional incandescent, fluorescent (You, He, and Shi 2007), and HID light sources in the near future.

1.1 OBJECTIVE

The primary purpose of this study is to explore the state of the art in LED roadway lighting technology. Through field-testing and software analysis, this study identifies suitable commercially available LED luminaires for IDOT roadway lighting applications. These LED roadway luminaires are selected on the basis of performance and reduced costs. The performance of each selected LED roadway luminaire is also compared to the performance of a selected HPS roadway luminaire that is tested as a reference for the LED luminaires.

1.2 STUDY TASKS

The following five basic tasks were conducted in this study:

1. *Literature review:* A comprehensive literature review was conducted. The literature review covered the current state of technology in LED roadway lighting, comparison of LED roadway luminaires with high-intensity discharge (HID) roadway luminaires, and test procedures for photometric measurements of roadway lighting installations. The findings from this task are presented in Volume 1 of the study report.

2. *Selection of LED roadway luminaires:* To select the appropriate LED roadway luminaires for field-testing, companies that provide LED roadway lighting were identified. The research team sent out a survey to 57 companies. A copy of the

LED roadway lighting survey is provided in Table A-1, and the list of the companies that received the survey is provided in Table A-2 of Appendix A, LED Roadway Luminaire Survey.

After the survey results were reviewed and current IDOT practices in street lighting were compiled, the luminaires listed in Table 1-1 were selected for field-testing based on the following factors:

- Characteristics such as delivered lumens, wattage, etc.
- Expected performance based on photometry and results from AGi32.
- Current IDOT practices, such as roadway luminaire mounting heights used, types of lamps, pole spacing, pole configuration (median vs. roadside), pole setback distance, arm length, lamp tilt, etc.
- How interested the companies were in donating luminaires for field-testing.

The manufacturer and series/model no. of the selected roadway luminaires is listed in Appendix A.

Table 1-1. General Characteristics of the Selected Roadway Luminaires

Luminaire	Wattage	Lumens	Luminaire Lifetime* (hr)	Lateral Distribution	Vertical Distribution	Cutoff
HPS	305	28,000	263,000	Type III	Medium	Full-cutoff
LED#1	157	9,600	50,000	Type III	Medium	Semi-cutoff
LED#2	173.2	12,475	50,000	Type II	Medium	Non-cutoff
LED#3	206	15,114	50,000–70,000	Type III	Short	Full-cutoff

**For the LED roadway luminaires, the luminaire lifetime is limited by the lamp lifetime because once the lifetime of the LED lamps is over, the entire luminaire is replaced. For HPS, periodic re-lamping and re-ballasting is necessary during the luminaire lifetime.*

3. *Preparation of the study site:* Following the selection of the roadway luminaires, the pole spacing and mounting height were determined for field-testing. Based on the photometry data in AGi32 software and the product descriptions obtained from the manufacturers, the pole spacing and mounting height were set at 150 ft and 30 ft, respectively.

   The study site was located near the Advanced Transportation Research Laboratory (ATREL) at Rantoul, Illinois. Four poles were installed to create three spans. The field tests were conducted in accordance with IESNA LM-50-99 ("Guide for Photometric Measurement of Roadway Lighting Installations"). The roadway was marked with grid points according to the relevant procedures given in IESNA LM-50-99. Further details about the study site are presented in Sections 2.1 and 2.2.

4. *Field data collection:* For each type of luminaire, the research team collected both illuminance and luminance data based on the procedures given in ANSI/ IESNA RP-8-00 and IESNA LM-50-99. In order to minimize inconsistency and inaccuracy in the field data, repeated measurements were taken. Further details about the data collection procedure are provided in Section 3.2.

5. *Data analysis:* Field data sets were checked for consistency and accuracy and then compared with the AGi32 results for each type of luminaire. The data for each type of LED luminaire were also compared with the data for the HPS to assess the potential

photometric benefits of the tested LED roadway luminaires. Chapters 4 through 7 present the detailed data analysis and results.

Given the objectives and tasks of this study, this report is divided into ten chapters. The chapters are accompanied by a series of appendices with detailed supporting information and additional analysis. For example, the primary findings from the field measurements are in the main body of the report, whereas the appendices contain the disaggregated data for each measurement that was taken at the test site.

In addition, the appendices include important analysis and supporting information such as a sample cost-benefit analysis of an LED luminaire, the survey sent to manufacturers of LED luminaires, and a framework for future LED roadway specifications for IDOT.

The chapters and appendices are organized as follows: Chapter 1 introduces the selected luminaires and briefly presents the tasks achieved in this study. Chapter 2 provides detailed information about the study site and the grid layout at the test site. In Chapter 3, details regarding the data collection equipment and procedure are given. Chapter 4 presents illuminance results for each type of roadway luminaire based on a comparison of field data with the software results. In Chapter 5, the field data and software results for each luminaire are checked against IDOT's illuminance design criteria for major roadways with medium pedestrian conflict, which is the assumed roadway classification for the study site. Chapter 6 contains luminance results for each type of roadway luminaire based on a comparison of the field data with the software results. In Chapter 7, both the field data and software results for each luminaire are checked against IDOT's luminance design criteria for major roadways with medium pedestrian conflict. Chapter 8 provides information about life-cycle cost and industry input. Chapter 9 presents IDOT's procedures for LED roadway lighting. Finally, conclusions drawn from the study are summarized in Chapter 10.

The report also includes 11 appendices. Appendix A contains the roadway luminaire survey, which played a significant role in selecting the three LED roadway luminaires for testing in this study. Appendix B presents close-up photos of the pavement surface at the study site, which were used to determine the pavement classification for the test section. In Appendix C, results of the software comparison of different roadway cross sections are presented. The software comparisons presented in Appendix C offer preliminary data about the adequacy of the selected roadway luminaires for different types of roadway cross sections. Appendix D presents the average field illuminance data and software illuminance results for each tested roadway luminaire. In Appendix E, the illuminance results for each LED roadway luminaire are compared in detail with those of the HPS. The average field luminance data and software luminance results for each tested roadway luminaire are provided in Appendix F. In Appendix G, the luminance results for each LED roadway luminaire are compared in detail with those of the HPS. IDOT's illuminance and luminance design criteria are presented in Appendix H. A preliminary economic analysis method is presented in Appendix I (and will be used in the second phase of this study). Appendix J is the questionnaire sent to the LED manufacturers to obtain detailed information on their product. The results of the questionnaire are not released at this phase of the study; they are reserved for the second phase of this study. Finally, Appendix K presents a preliminary framework for future LED roadway specifications for IDOT.

CHAPTER 2 STUDY SITE

2.1 GENERAL LAYOUT

The field tests were performed near the University of Illinois ATREL facilities at Rantoul, Illinois. The test section was a 450-ft long straight stretch of a two-lane road segment with 11-ft lane width. A sketch of the study site, including key dimensions of the layout, is shown in Figure 2-1. Four wood poles were installed on the east side of the road. The mounting height and pole spacing were set at 30 ft and 150 ft, respectively. The poles were installed at a 12-ft setback from the outer edge of the road. For each pole, the arm length was equal to 12 ft so that the center of each light source projected onto the outer edge of the traveled lane. Since there were four light poles, the test section of the road had three luminaire cycles, as shown in Figure 2-1. All field measurements were made at the three luminaire cycles.

Only one light pole existed in the vicinity of the test site as illustrated in Figure 2-1. That light pole was more than 150 ft away from any point on the test section of the road, and it was aimed in a different direction. Therefore, no significant man-made light source existed within the study site other than those installed for this study. Figure 2-2 shows some photos from the study site. In the analysis of the results, the following assumptions were made:

- The site represents a major roadway (two lanes per direction) with medium pedestrian conflict.
- The site has asphalt pavement with R3 classification (Q_0 = 0.7, pavement) or R3 (asphalt road surface), based on the AASHTO Roadway Lighting Design Guide. The pavement classification of R3 was determined by examining the close-up photos of the roadway surface at the study site (see Appendix B). The aggregate color and size, as well as the smoothness of the pavement surface, was observed to determine the pavement classification. Regarding Q_0, the representative mean luminance coefficient of 0.07 was used based on the clearly worn-out condition of the pavement, which has been in place for several years.
- The lighting configuration is one side only.

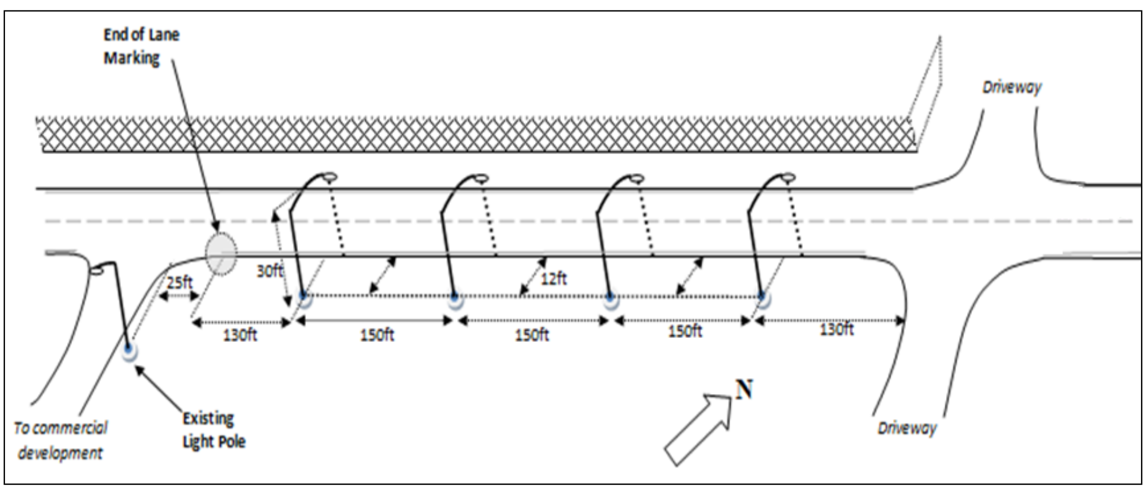
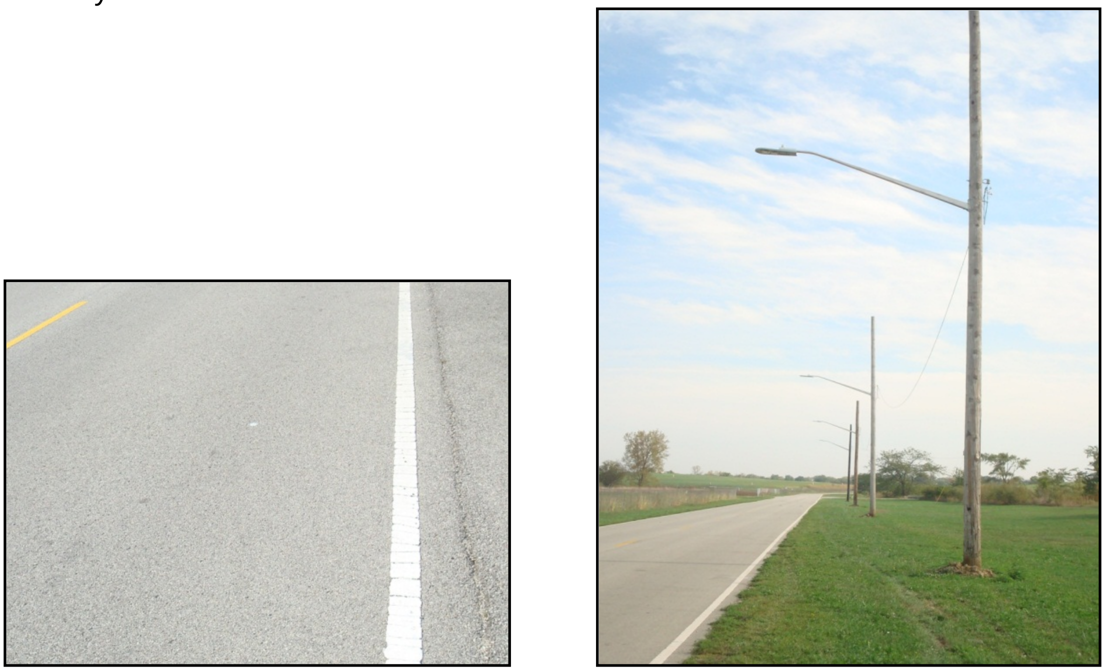


Figure 2-1. A sketch showing the layout of the study site at Rantoul, Illinois.

The definition of Q_0 is given in the user guide of AGi32 software as “the value of the luminance coefficient *q* averaged over a specified solid angle of incident light.” Thus, it is a measure of the average luminous coefficient of a road surface. In IESNA RP-8, the description of asphalt pavement with R3 classification and $Q_0 = 0.7$ is "asphalt road surface (regular and carpet seal) with dark aggregate (e.g., traprock, blast furnace slag); rough texture after months of use (typical highway)." The mode of reflectance is slightly specular for this type of pavement. Appendix B includes close-up photos of the pavement surface at the study site.



(a) (b)

Figure 2-2. Photos depicting the (a) pavement surface and (b) light poles at the study site in Rantoul, Illinois.

2.2 GRID LAYOUT AT THE TEST SECTION

The grid points are the locations where the illuminance and luminance values are measured in the field. The field tests were conducted in accordance with IESNA LM-50-99. According to the test standards, the layout of the grid points should satisfy the following criteria:

- There should be a minimum of ten longitudinal points located at equal spacing along each luminaire cycle.
- The transverse points should be at both quarter-points of each lane.
- The maximum spacing between two neighboring longitudinal points should be 16.5 ft (5.0 m).

Based on the requirements, the roadway was marked off in transverse and longitudinal lines similar to the grid system illustrated in Figure 2-3 (the figure shows three lanes; however, there were only two lanes at the test site, which had poles oriented one side only). In this project, since one luminaire cycle was 150 ft long, the longitudinal spacing between the grid points was set at 15 ft. The first longitudinal grid point was located 7.5 ft from the edge of the first light pole. Moreover, since the lane width was 11 ft, the transverse spacing between the first row of the grid points and the edge of the roadway was 2.75 ft (i.e., 11/4). There were two rows of grid points in each lane, and those rows were located at 5.50-ft transverse spacing from each other.

Each luminaire cycle included 20 grid points per lane (a total of 40 grid points on both lanes). There were three luminaire cycles; thus, the study site had 120 grid points. Figure 2-4 illustrates the detailed layout of the grid points at the study site.

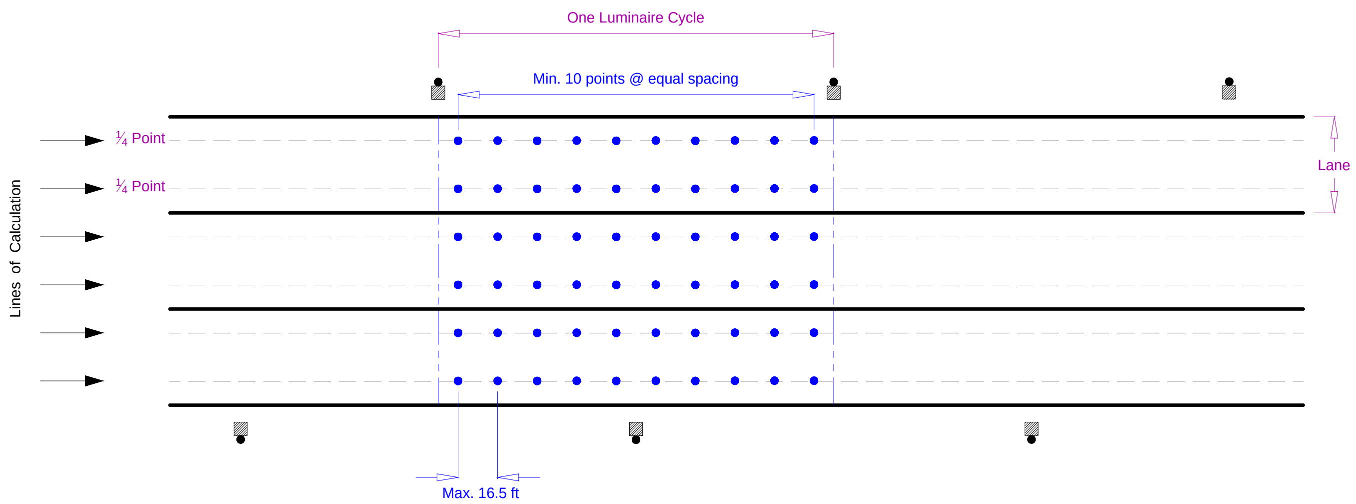
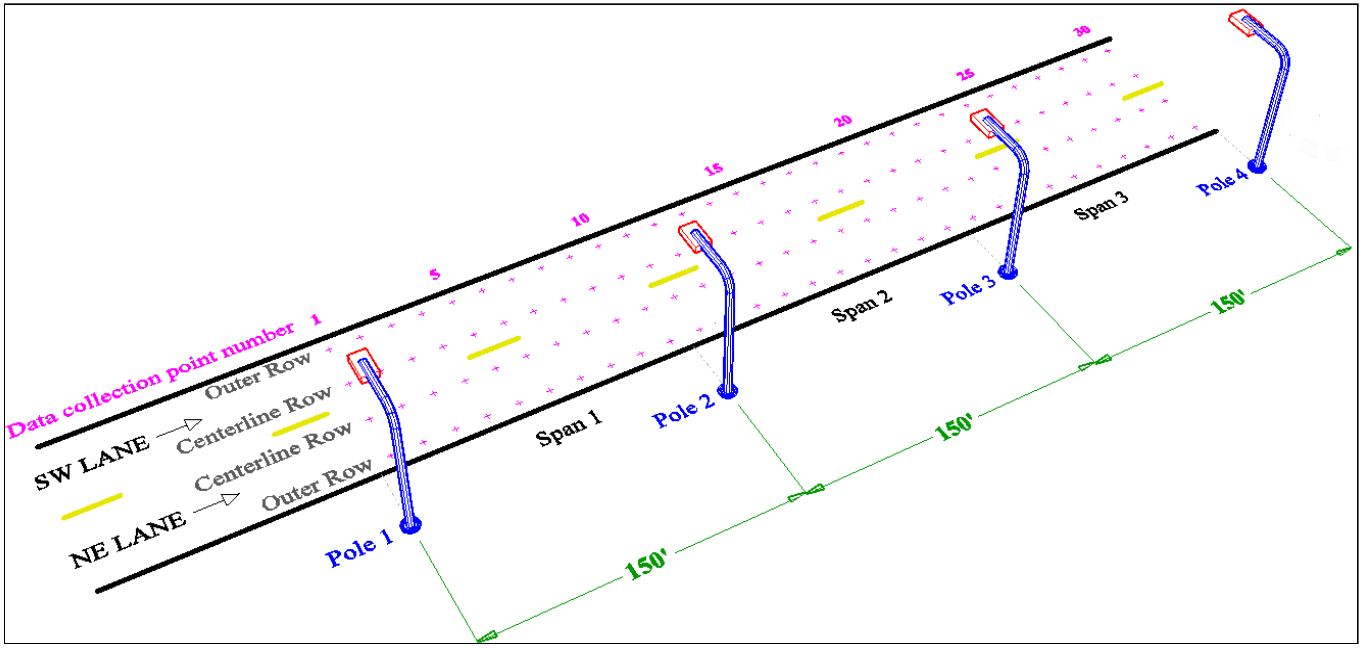
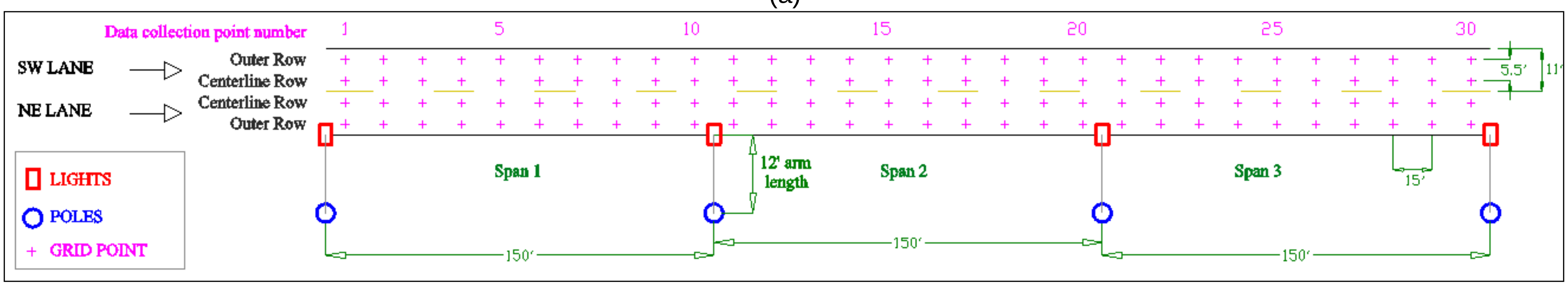


Figure 2-3. Test point locations for measuring illuminance and luminance on roadway, according to IESNA LM-50-99 (“Guide for Photometric Measurement of Roadway Lighting Installations”).



(a)



(b)

Figure 2-4. (a) Perspective view, (b) top view of the schematic layout of the grid points at the study site at Rantoul, Illinois.

CHAPTER 3 DATA COLLECTION

3.1 DATA COLLECTION EQUIPMENT

The research team collected both illuminance and luminance data for each type of roadway luminaire. Illuminance is defined as "The density of luminous flux incident on a surface area. It is the quotient of the luminous flux by the area of the surface when the latter is uniformly illuminated" (IDOT 2010). The U.S. Customary System unit for illuminance is footcandle (ft-cd), which equals a light flux of 1 lumen uniformly distributed on a surface 1 ft^2 in area. To measure illuminance, the research team used Konica Minolta T-10 illuminance meters. The meter has a measurement range of 0.001 ft-cd to 29,990 ft-cd. It also enables serial connection of up to 30 receptor heads so that multi-point measurements can be made.

To utilize the multi-point measurement capability of the device, the research team built a rectangular rolling cart. Figure 3-1 illustrates a schematic view of the rolling cart. The dimensions of the rolling cart were 15 ft by 5.5 ft, the longitudinal and transverse spacing of the grid points, respectively. When the rolling cart was located properly, each of the four corners was projected onto a grid point. There were four illuminance meters, each mounted on one corner of the rolling cart. According to IESNA LM-50-99, the illuminance meter should not be held higher than 6 in. (15 cm) above the pavement surface. Hence, the height of each corner of the rolling cart was no higher than 6 in. All four illuminance meters on the rolling cart were serially connected, and the first one was connected to a laptop computer. Using the rolling cart and the four illuminance meters, illuminance measurements were taken at four grid points at a time. Since the illuminance meters were connected to a laptop computer, the data were directly stored in the computer.

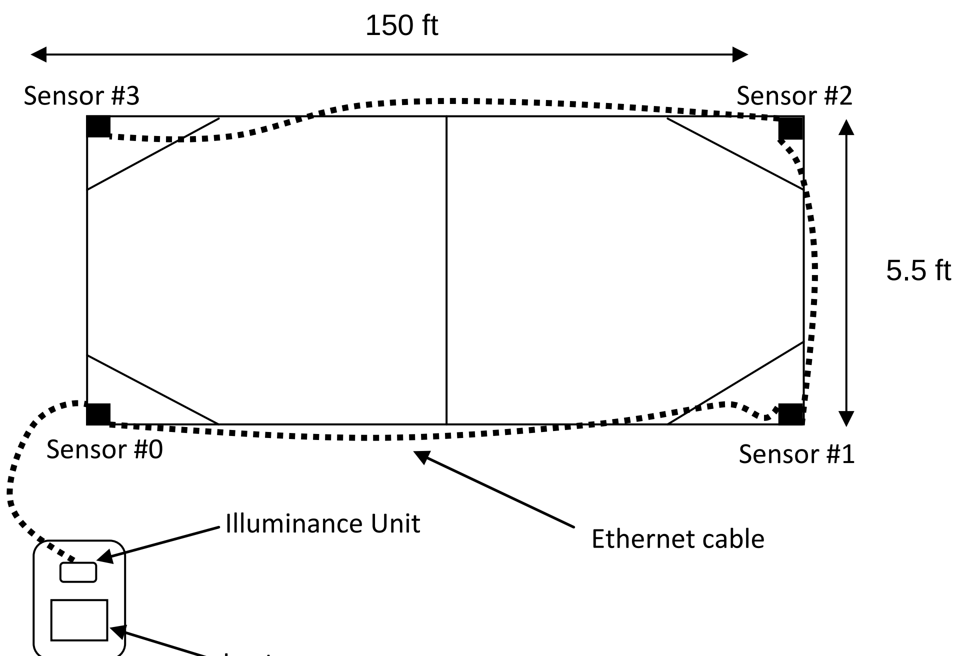


Figure3-1. Multi-point installation equipment for measuring illuminance.

Luminance is defined as "the luminous intensity of a surface in a given direction per unit of projected area of the surface as viewed from that direction" (IDOT 2010). In this study, the metric unit of candela per square meter (cd/m^2) is used in luminance measurements. Candela per square meter is defined as "the uniform luminance of a perfectly diffusing surface emitting or reflecting light at the rate of one lumen per square meter or the average luminance of any surface emitting of reflecting light at that rate" (IDOT 2010). The research team used a Konica Minolta L-100 luminance meter to measure luminance. The meter has a measurement range of 0.01 cd/m^2 to 999,990 cd/m^2. During the field data collection, the research team used two luminance meters simultaneously. Further details about the data collection procedure are given in Section 3.2.

3.2 DATA COLLECTION PROCEDURE

The field data collection was conducted in accordance with IESNA LM-50-99, "Guide for Photometric Measurement of Roadway Lighting Installations." During the illuminance measurements, the rolling cart shown in Figure 3-1 was moved in a northeast-bound direction on each lane. The rolling cart was placed properly such that each corner projected onto a different grid point, then it was rolled to the next set of points. Thus, illuminance measurements were made four grid points at a time. All four illuminance meters were serially connected to a laptop computer, and the illuminance measurements were controlled and stored by the same computer.

As for the luminance measurements, IESNA LM-50-99 requires an observer stationed a distance parallel to the roadway. The observer should keep a detector height of 4.75 ft (1.45 m) and a line of sight of 1.0 degree down over a longitudinal distance of 274 ft (83.5 m). During the luminance measurements, the research team used two observers and two luminance meters at a time. Figure 3-2 shows a schematic representation of the luminance measurements in the field. Two observers were located in a lane, each on one row of grid points. The height of the luminance meters was set at 4.6 ft as required by IESNA LM-50-99. Both observers aimed their luminance meters at the corresponding grid point located at a longitudinal distance of 274 ft ahead. In order to help the observers accurately aim the luminance meters at the grid points, a third member of the research team placed small LED lamps on the two grid points that were to be measured. When the two observers finished aiming the luminance meters at the proper grid points, the third person removed the LED lamps from the road, then the two observers took three luminance readings for each grid point.

Each luminance meter was connected to a laptop computer so that the data were stored in the computers. The laptop computers also controlled the luminance meters so that the observers did not have to touch the devices during the luminance measurements, eliminating any possible error caused by shaking of the instruments.

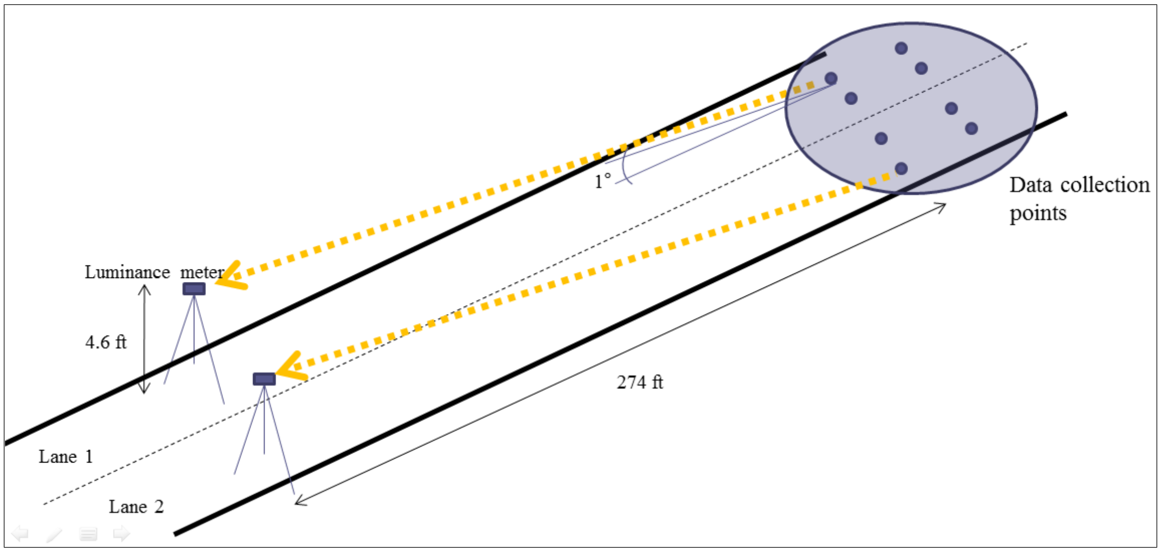


Figure 3-2. Schematic representation of the field luminance measurements.

3.3 WEATHER CONDITIONS DURING DATA COLLECTION

During data collection, the pavement was dry and no other visible factors affected its surface. The weather conditions were observed and documented, as shown in Table 3-1. Most of the datasets were collected during clear sky conditions. The effect of the moonlight was measured on October 14 at three different locations, where illuminance readings without the luminaires were equal or less than 0.04 ft-cd. In addition, measurements taken on April 20, 2011, under close to full-moon conditions (93% of lunar disk illuminated) were compared to the dataset collected on April 28, 2011 (when about 20% of the lunar disk was illuminated; Timeanddate.com 2011). The average discrepancies between the two datasets were approximately 0.06 ft-cd.

3.4 CONSISTENCY BETWEEN THE DATASETS

Two sets of illuminance and luminance data were collected for each type of luminaire. Each dataset was collected on a different day (which often was consecutive). To minimize any possible inaccuracy and inconsistency in field data, three illuminance and luminance readings were taken from each grid point in each dataset. Thus, six illuminance and luminance readings were taken from each grid point for each luminaire. For each type of roadway luminaire, the average of the three readings of illuminance/luminance taken at a particular grid point on the first day of data collection was compared with the average of the corresponding three readings taken on the next day of data collection. The discrepancy in the field data between day one and day two was then computed for each grid point. The absolute value of those discrepancy values was summed, and the average absolute discrepancy between day one and day two was found for each type of luminaire. Table 3-2 lists the average discrepancy in field data between day one and day two. As shown in Table 3-2, the discrepancies were trivial, and consistency in field data collection was achieved for each type of luminaire.

Table 3-1. Weather Conditions During the Field Data Collection

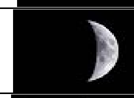
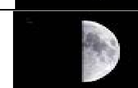
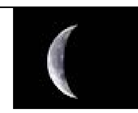
Roadway luminaire	Dataset no.	Date	Sky condition	Temperature range	Moon phase
HPS	Dataset 1	Sep 13, 2010	Clear	70°F – 65°F	
	Dataset 2	Sep 14, 2010	Clear	70°F – 63°F	
LED#1	Dataset 1	Sep 29, 2010	Clear	65°F – 57°F	
	Dataset 2	Sep 30, 2010	Clear	64°F – 55°F	
LED#2	Dataset 1	Oct 13, 2010	Clear	55°F – 45°F	
	Dataset 2	Oct 14, 2010	Clear	58°F – 55°F	
LED#3	Dataset 1	Apr 20, 2011	Clear	44°F – 35°F	
	Dataset 2	Apr 28, 2011	Partly cloudy	50°F – 45°F	

Table 3-2. Average Discrepancy in Field Data Between Day One and Day Two

Luminaire	Average discrepancy in illuminance (ft-cd)	Average discrepancy in luminance (cd/m^2)
HPS	0.07	0.10
LED#1	0.03	0.06
LED#2	0.03	0.08
LED#3	0.06	0.08

CHAPTER 4 ILLUMINANCE RESULTS: FIELD DATA VS. SOFTWARE

In this section, the field illuminance measurements are compared with the software results. In this study, the AGi32 lighting analysis software is used to estimate the field illuminance and luminance levels. The study site is modeled in AGi32 using IES files for the roadway luminaires that were provided by the manufacturers. In order to compare the field data with the software calculations for new luminaires, no depreciation in the luminaire outputs was considered in the AGi32 models of all roadway luminaires. Thus, all luminaire maintenance (i.e., light loss) factors were input as 1.0 in the software calculations. This enables accurate comparison of the field data with the AGi32 results for new roadway luminaires. Appropriate light loss factors are needed to conduct analysis of the performance of the luminaires at the end of their lifetime. However, these factors are not currently available for LED luminaires, primarily because of the unknown decrease in output related to dirt depreciation if the luminaire lenses are not periodically cleaned during the lifetime of the unit.

4.1 HPS

Figure 4-1, Figure 4-2, Figure 4-3, and Figure 4-4 graphically compare the average field illuminance data for the HPS with the AGi32 illuminance results for the northeast (NE) lane outer row, NE lane center row, southwest (SW) lane center row, and SW lane outer row, respectively. Detailed tabulation of the average field data and AGi32 results are presented in Appendix D, Illuminance Measurements, and illuminance levels produced by the HPS are compared in detail with those produced by each LED in Appendix E, Comparison of the Illuminance Results for HPS vs. LEDs. Based on the results, the following are found:

- Both the field data and AGi32 results indicate that the maximum illuminance in a particular row was attained at the points adjacent to the light poles. On the other hand, the minimum illuminance in a particular row was attained at the midpoints between the light poles.

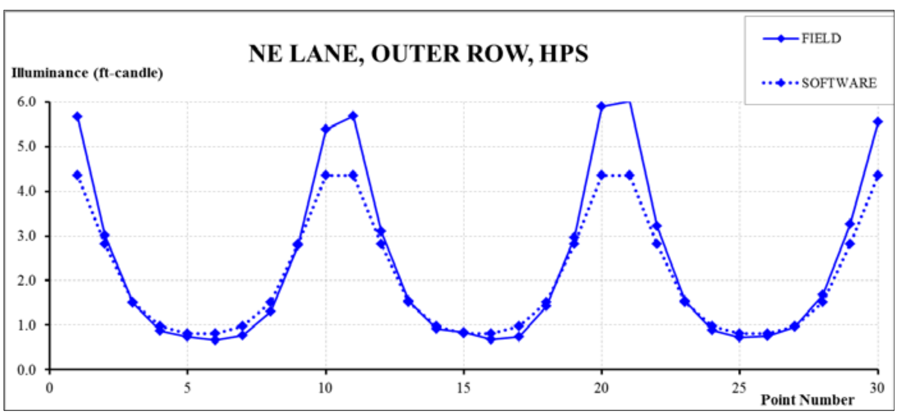


Figure 4-1. Comparison of the field illuminance data with the AGi32 results for the HPS (NE lane, outer row).

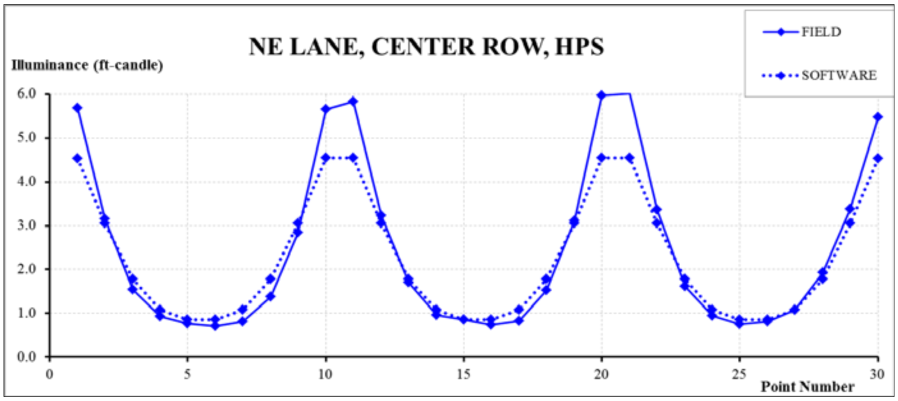


Figure 4-2. Comparison of the field illuminance data with the AGi32 results for the HPS (NE lane, center row).

- For all four rows, the average field data match well with the AGi32 results, except for the grid points in the immediate vicinity of the light poles. For the points in the immediate vicinity of the light poles, the field illuminance data turned out to be considerably greater than the AGi32 results. For those grid points, the discrepancies between the average field data and AGi32 results ranged from 0.88 ft-cd to 1.77 ft-cd.

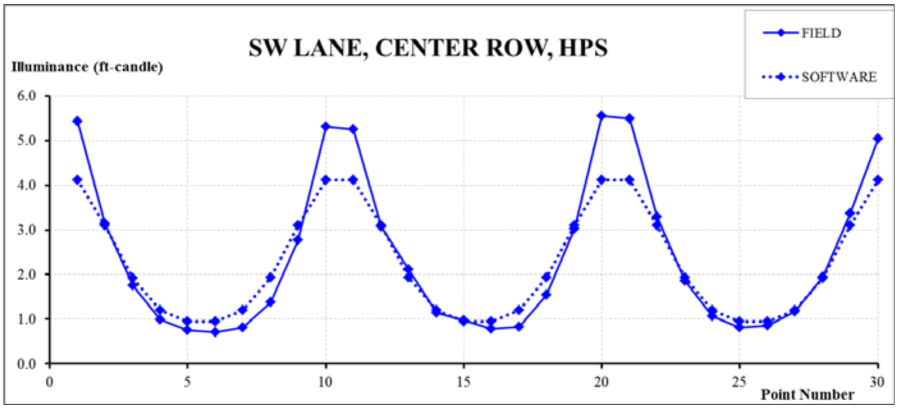


Figure 4-3. Comparison of the field illuminance data with the AGi32 results for the HPS (SW lane, center row).

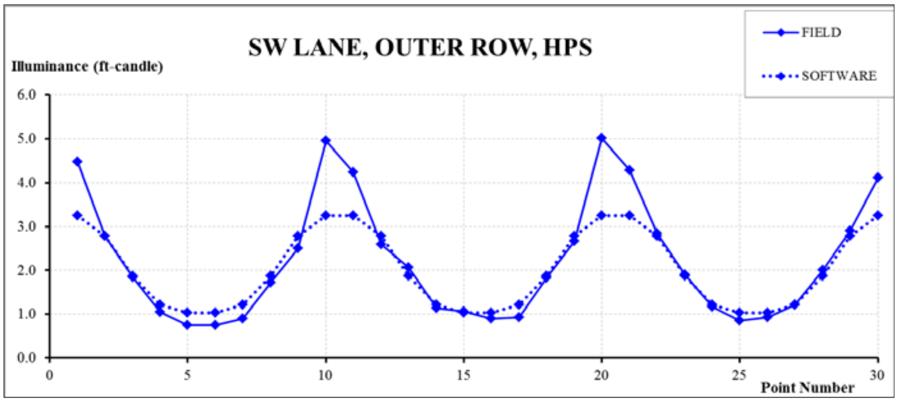


Figure 4-4. Comparison of the field illuminance data with the AGi32 results for the HPS (SW lane, outer row).

- For the other grid points, the absolute discrepancy between the average field data and AGi32 results ranged from 0.00 ft-cd to 0.55 ft-cd.

4.2 LED#1

A graphical comparison of the average field illuminance data for LED#1 with the AGi32 illuminance results is shown in Figure 4-5, Figure 4-6, Figure 4-7, and Figure 4-8. For detailed reference, the average field data and AGi32 results are presented in Appendix D, Illuminance Measurements. The following are inferred from the results:

- Both the field data and AGi32 results indicate that the maximum illuminance in a particular row was attained at the points adjacent to the light poles. On the other hand, the minimum illuminance in a particular row was attained at the midpoints between the light poles.
- For all four rows, the average field data match very well with the AGi32 results in the second span, which includes the grid points 11 through 20. For those grid points, the average absolute discrepancy between the field data and AGi32 results is only 0.08 ft-cd.
- Likewise, the average field data and AGi32 results match very well in the third span, which includes the grid points 21 through 30 in all four rows. For those grid points, the average absolute discrepancy between the field data and AGi32 results is only 0.09 ft-cd.

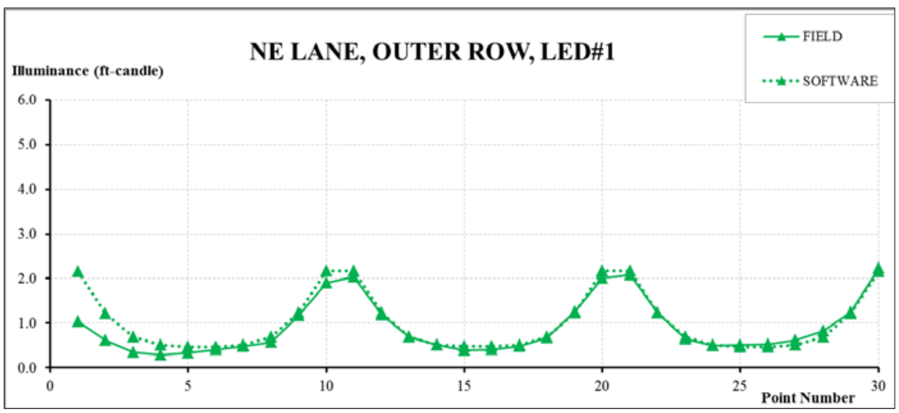


Figure 4-5. Comparison of the field illuminance data with the AGi32 results for LED#1 (NE lane, outer row).

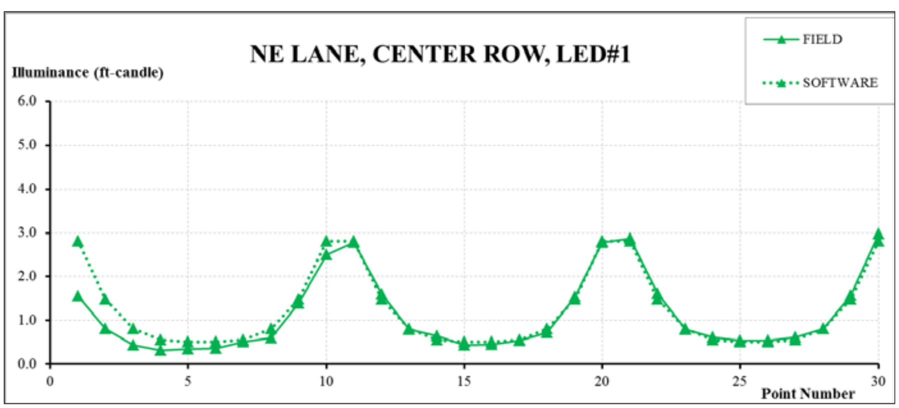


Figure 4-6. Comparison of the field illuminance data with the AGi32 results for LED#1 (NE lane, center row).

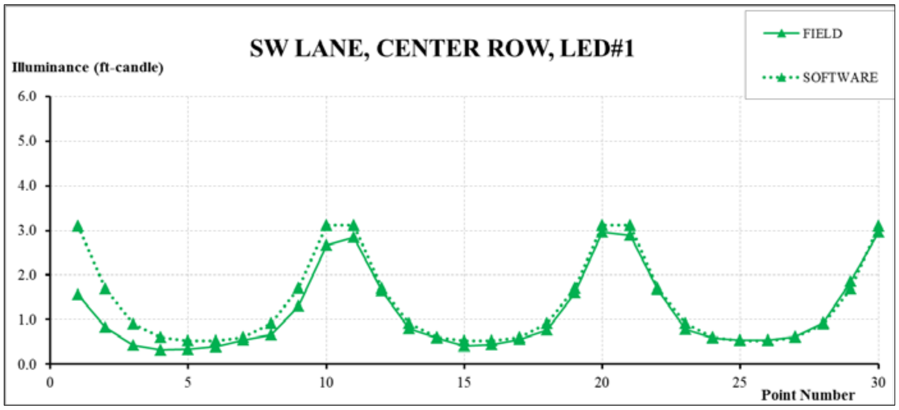


Figure 4-7. Comparison of the field illuminance data with the AGi32 results for LED#1 (SW lane, center row).

- On the other hand, the average field data and AGi32 results do not match that well in the first half of the first span, which includes the grid points 1 through 5 for all four rows. For those grid points, the absolute discrepancy ranged from 0.13 ft-cd to 1.54 ft-cd. No obvious reason was found for this.
- The average field data and AGi32 results match fairly well in the second half of the first span, which consists of the grid points 6 through 10 for all four rows. For those grid points, the average absolute discrepancy between the field data and AGi32 results is 0.15 ft-cd.

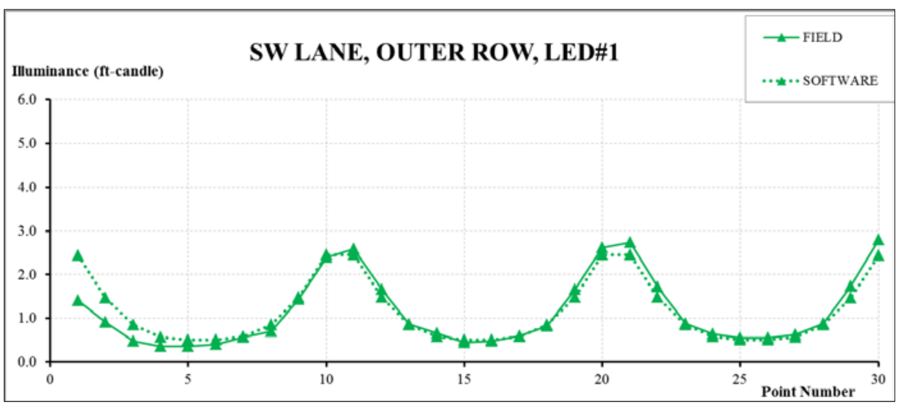


Figure 4-8. Comparison of the field illuminance data with the AGi32 results for LED#1 (SW lane, outer row).

4.3 LED#2

Figure 4-9, Figure 4-10, Figure 4-11, and Figure 4-12 graphically compare the average field illuminance data for LED#2 with the AGi32 illuminance results. Detailed tabulation of the average field data and AGi32 results is presented in Appendix D, Illuminance Measurements. Based on the results, the following are found:

- The illuminance distribution pattern for LED#2 differs from that of the HPS and LED#1. For both the HPS and LED#1, the minimum illuminance level in a particular row was attained at the midpoints between the light poles. In contrast, the AGi32 results for LED#2 show that the minimum illuminance level in a particular row was attained at the third grid point on either side of the light poles. The field data also show a similar illuminance distribution pattern.

- Both the software results and field data for LED#2 show that the maximum illuminance level in a particular row was attained at the grid points in the immediate vicinity of the light poles.

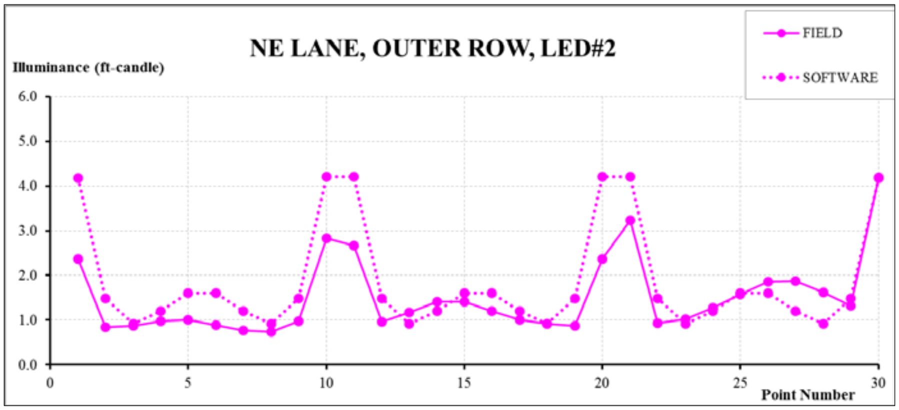


Figure 4-9. Comparison of the field illuminance data with the AGi32 results for LED#2 (NE lane, outer row).

- The average field data for LED#2 do not match that well with the AGi32 results. For each row, the largest discrepancies between the average field data and AGi32 results are observed at the grid points in the immediate vicinity of the light poles. For those points, the average field data returned considerably lower illuminance levels than the AGi32 results. The highest absolute discrepancy between the average field data and AGi32 results was 2.36 ft-cd, and it was observed at the first grid point of the NE lane, center row.

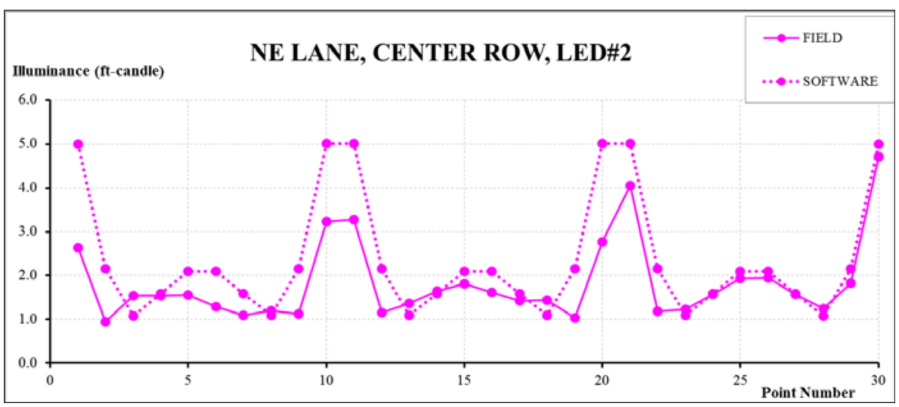


Figure 4-10. Comparison of the field illuminance data with the AGi32 results for LED#2 (NE lane, center row).

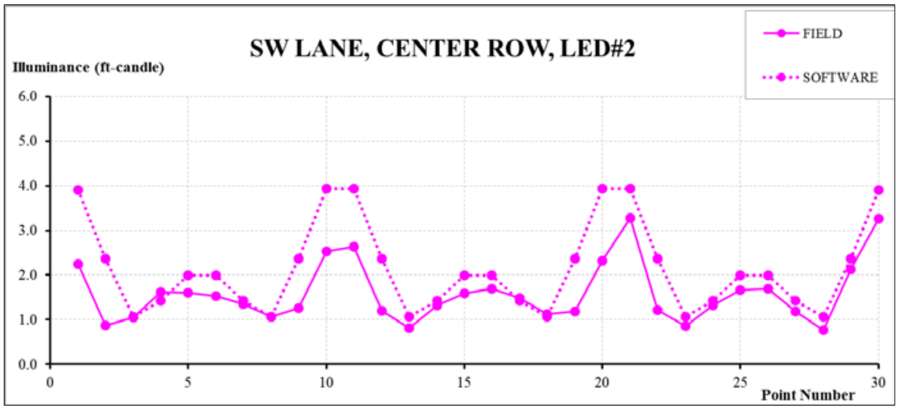


Figure 4-11. Comparison of the field illuminance data with the AGi32 results for LED#2 (SW lane, center row).

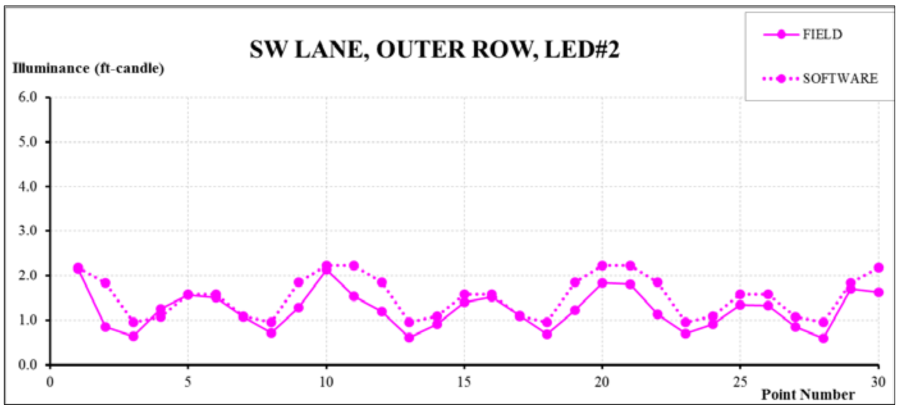


Figure 4-12. Comparison of the field illuminance data with the AGi32 results for LED#2 (SW lane, outer row).

4.4 LED#3

Graphical comparison of the average field illuminance data for LED#3 with the AGi32 illuminance results is shown in Figure 4-13, Figure 4-14, Figure 4-15, and Figure 4-16. For detailed reference, the average field data and AGi32 results are provided in Appendix D, Illuminance Measurements. The following are inferred for LED#3 from the results:

- Both the field data and AGi32 results indicate that the maximum illuminance in a particular row was attained at the points adjacent to the light poles. On the other hand, the minimum illuminance in a particular row was attained at the midpoints between the light poles.
- For all four rows, the average field illuminance levels are continuously below the AGi32 results. For a particular row, the magnitude of the discrepancy between the average field data and AGi32 results displays slight variations.
- The average absolute discrepancy between the average field data and AGi32 results was 0.68 ft-cd for the NE lane outer row, 0.64 ft-cd for the NE lane center row, 0.76 ft-cd for the SW lane center row, and 0.79 ft-cd for the SW lane outer row.

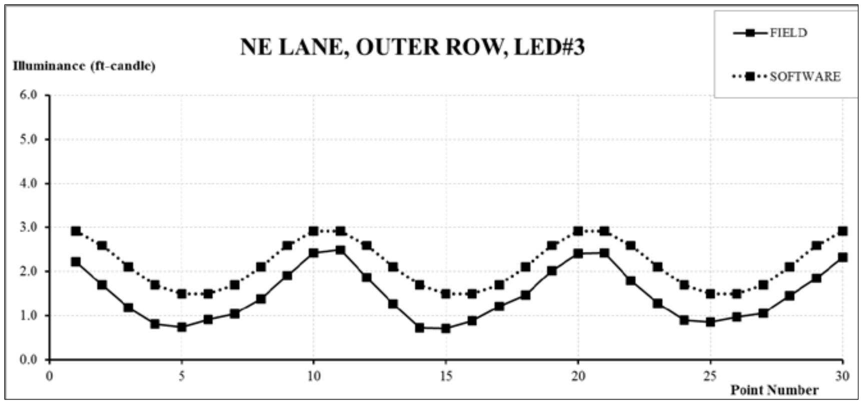


Figure 4-13. Comparison of the field illuminance data with the AGi32 results for LED#3 (NE lane, outer row).

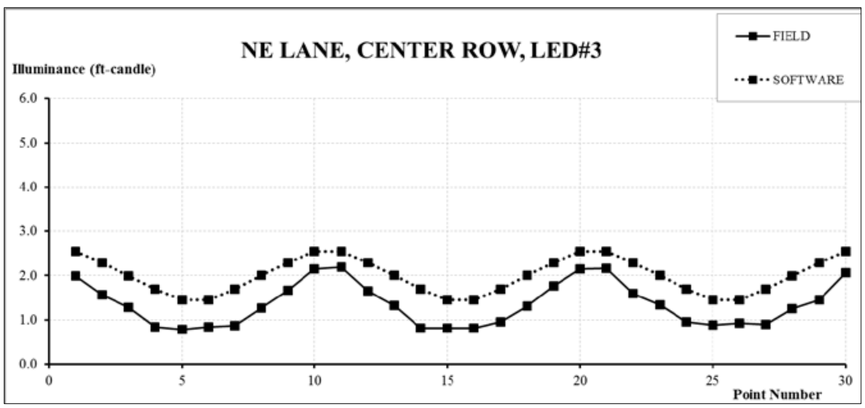


Figure 4-14. Comparison of the field illuminance data with the AGi32 results for LED#3 (NE lane, center row).

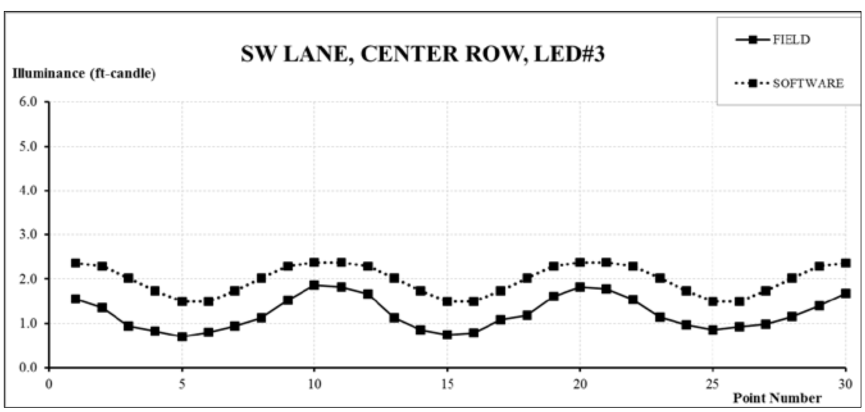


Figure 4-15. Comparison of the field illuminance data with the AGi32 results for LED#3 (SW lane, center row).

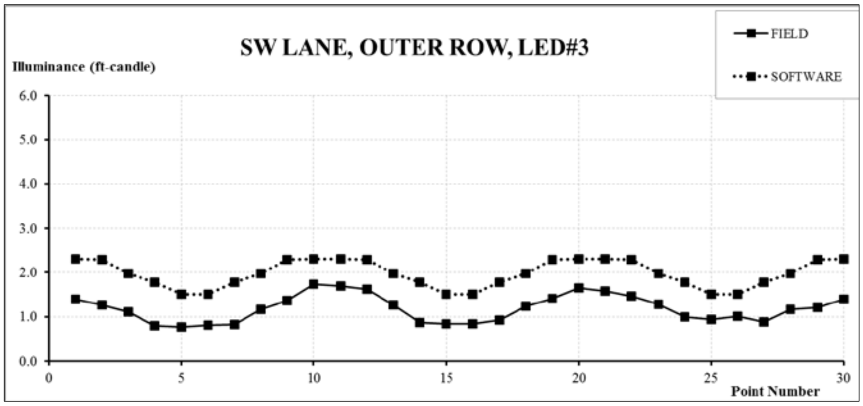


Figure 4-16. Comparison of the field illuminance data with the AGi32 results for LED#3 (SW lane, outer row).

4.5 ESTIMATING FIELD ILLUMINANCE FROM SOFTWARE RESULTS

For each type of luminaire, comparison of the field illuminance data and software results revealed some discrepancies between the two. In this section, multiplicative factors are proposed to estimate the corresponding field values from the software results. For a particular type of luminaire, when the suggested multiplicative factors are applied to the AGi32 results, the field illuminance levels can be accurately estimated. For each type of luminaire, the multiplicative factors are computed by comparing the field illuminance levels observed in the mid-span of the test site with the AGi32 results. These values are given in Table 4-1 and explained in the following sections. The suggested factors are valid for this test condition and may be used for similar conditions, but the factors may differ for other mounting heights, pole spacings, lane widths, and lane configurations.

Table 4-1. Factors for Estimating Field Illuminance from AGi32 Results

	Number of grid point for all four rows in a single luminaire cycle									
Roadway luminaire	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
HPS	1.34	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	1.34
LED#1	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96
LED#2	0.61	0.61	0.94	0.94	0.94	0.94	0.94	0.94	0.61	0.61
LED#3	0.76	0.76	0.57	0.57	0.57	0.57	0.57	0.57	0.76	0.76

4.6 HPS

For the test site conditions, the field illuminance levels can be estimated from the AGi32 results by applying the following procedure:

- At the grid points in the immediate vicinity of the light poles, the field data are approximately 1.34 times the software results.
- At all other grid points, the field data are approximately 0.94 times the software results.

When the multiplicative factors are applied to the AGi32 results, the field illuminance levels can be estimated from the adjusted AGi32 results. Figure 4-17, Figure 4-18, Figure 4-19, and Figure 4-20 compare the adjusted AGi32 results with the field illuminance data collected from the mid-span. All four figures show close agreement between the adjusted AGi32 results and the field illuminance data from the mid-span of the study site.

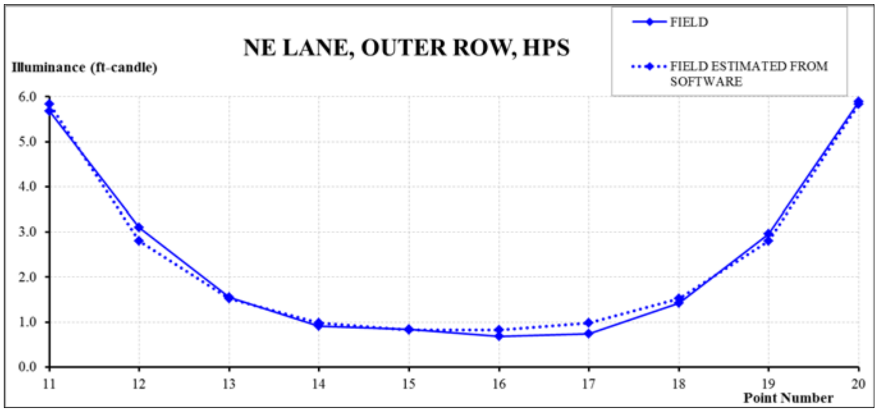


Figure 4-17. Comparison of the field illuminance data with the adjusted AGi32 results for the HPS (NE lane, outer row).

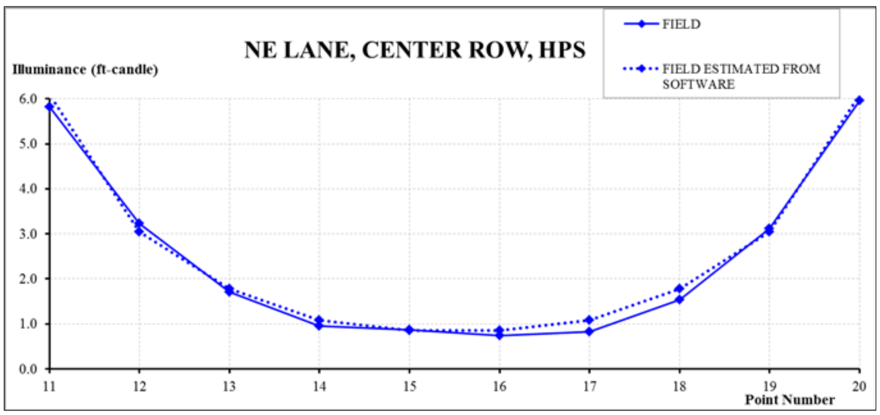


Figure 4-18. Comparison of the field illuminance data with the adjusted AGi32 results for the HPS (NE lane, center row).

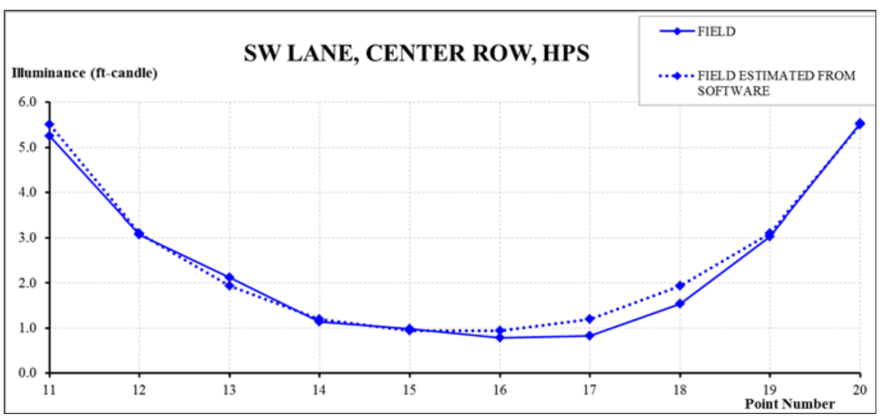


Figure 4-19. Comparison of the field illuminance data with the adjusted AGi32 results for the HPS (SW lane, center row).

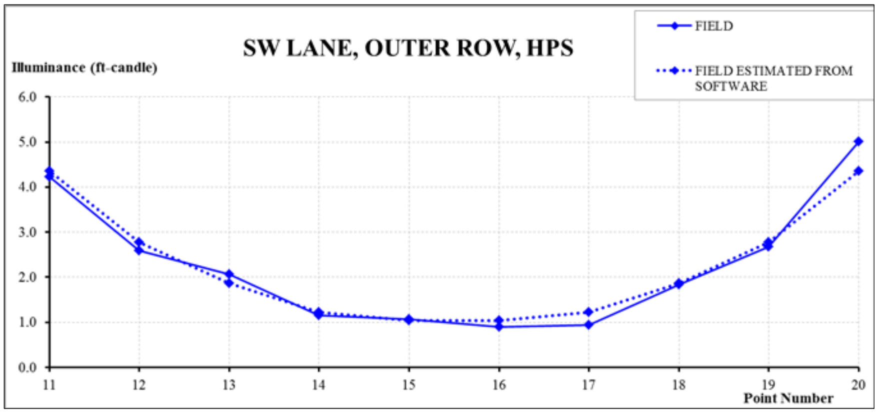


Figure 4-20. Comparison of the field illuminance data with the adjusted AGi32 results for the HPS (SW lane, outer row).

4.7 LED#1

For the test site conditions, the field illuminance levels can be estimated from the AGi32 results by applying the following procedure:

- At all grid points, the field data are approximately 0.96 times the software results.

There is already close agreement between the field illuminance data and AGi32 results for LED#1. Figure 4-21, Figure 4-22, Figure 4-23, and Figure 4-24 compare the adjusted AGi32 results with the field illuminance data collected from the mid-span. All four figures show very close agreement between the adjusted AGi32 results and the field illuminance data collected from the mid-span at the test site.

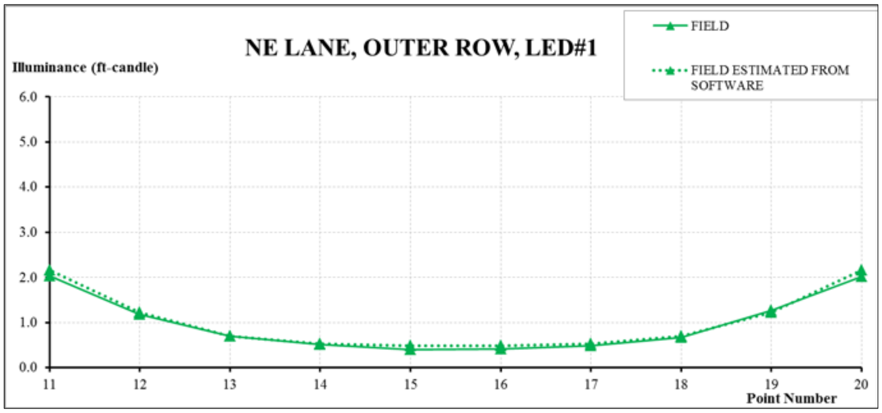


Figure 4-21. Comparison of the field illuminance data with the adjusted AGi32 results for LED#1 (NE lane, outer row).

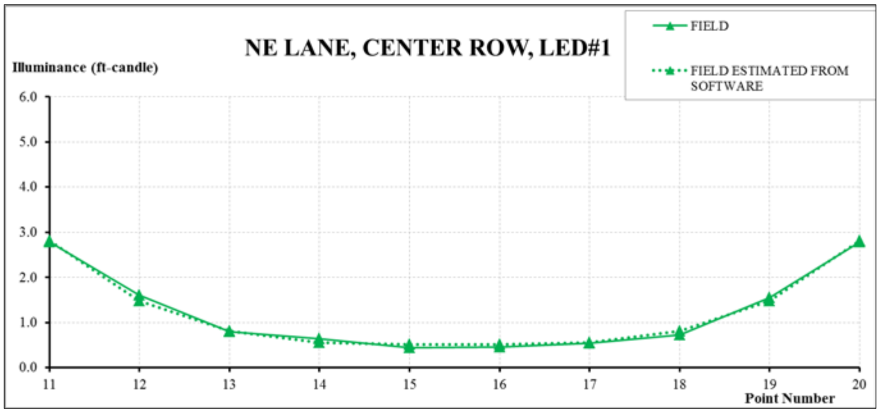


Figure 4-22. Comparison of the field illuminance data with the adjusted AGi32 results for LED#1 (NE lane, center row).

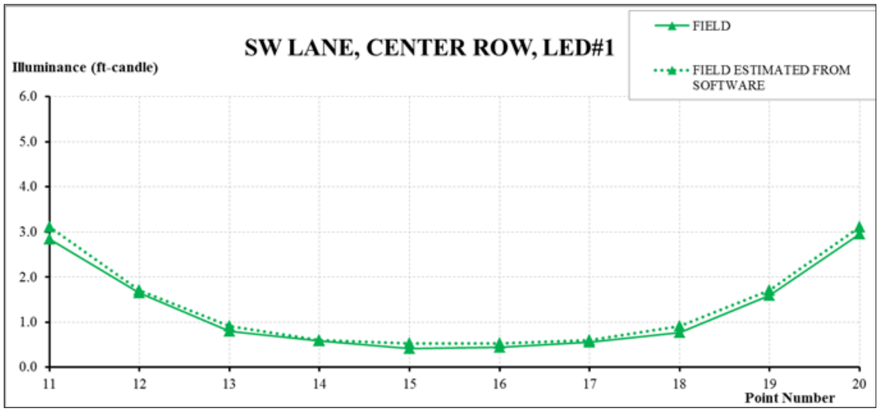


Figure 4-23. Comparison of the field illuminance data with the adjusted AGi32 results for LED#1 (SW lane, center row).

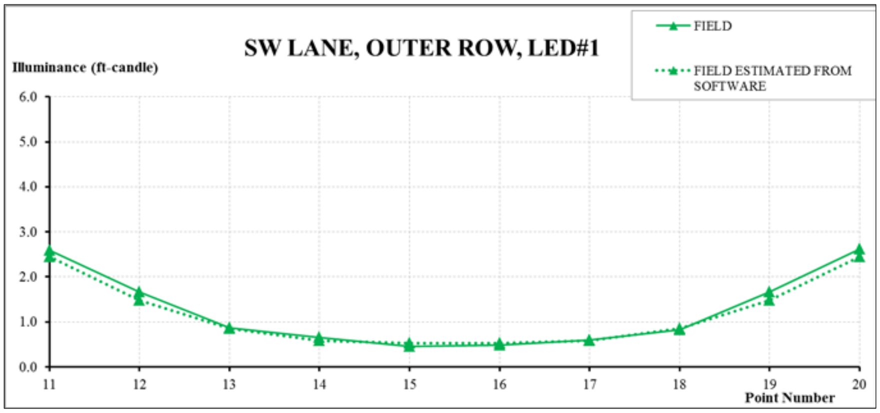


Figure 4-24. Comparison of the field illuminance data with the adjusted AGi32 results for LED#1 (SW lane, outer row).

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4.8 LED#2

For the test site conditions, the field illuminance levels can be estimated from the AGi32 results by applying the following procedure:

- At the first and second grid points away from the light poles, the field data are approximately 0.61 times the software results.
- At all other grid points, the field data are approximately 0.94 times the software results.

When the multiplicative factors are applied to the AGi32 results, the field illuminance levels can be estimated from the adjusted AGi32 results. Figure 4-25, Figure 4-26, Figure 4-27, and Figure 4-28 compare the adjusted AGi32 results with the field illuminance data collected from the mid-span. All four figures show close agreement between the adjusted AGi32 results and the field illuminance data from the mid-span of the study site.

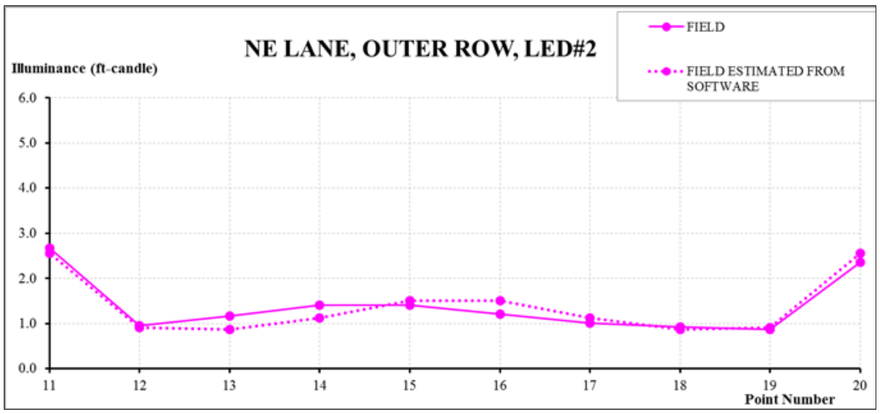

Figure 4-25. Comparison of the field illuminance data with the adjusted AGi32 results for LED#2 (NE lane, outer row).

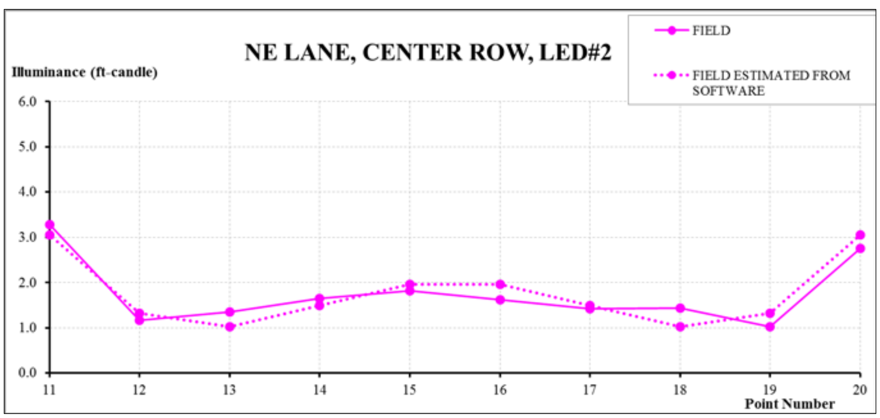

Figure 4-26. Comparison of the field illuminance data with the adjusted AGi32 results for LED#2 (NE lane, center row).

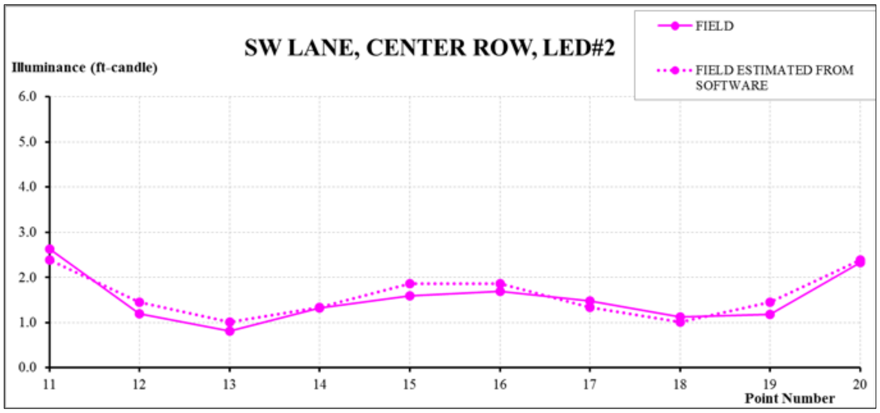

Figure 4-27. Comparison of the field illuminance data with the adjusted AGi32 results for LED#2 (SW lane, center row).

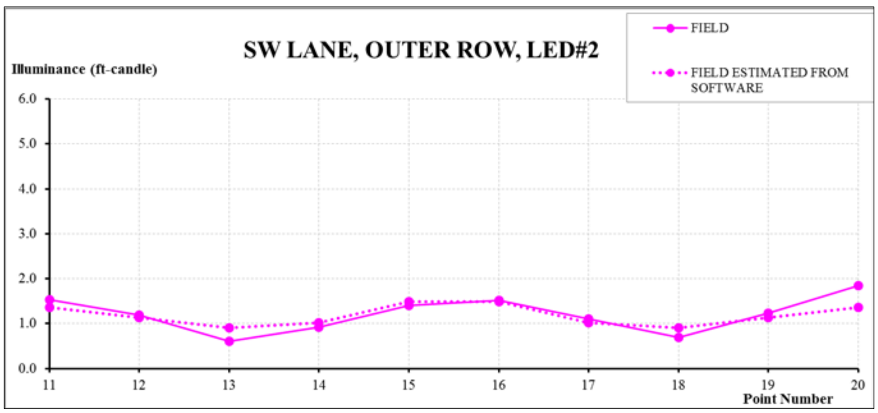

Figure 4-28. Comparison of the field illuminance data with the adjusted AGi32 results for LED#2 (SW lane, outer row).

4.9 LED#3

For the test site conditions, the field illuminance levels can be estimated from the AGi32 results by applying the following procedure:

- At the first and second grid points away from the light poles, the field data are approximately 0.76 times the software results.
- At all other grid points, the field data are approximately 0.57 times the software results.

Alternatively, one can subtract 0.65 ft-cd from the software results to estimate the field illuminance levels. Figure 4-29, Figure 4-30, Figure 4-31, and Figure 4-32 compare the AGi32 results adjusted by the multiplicative factors with the field illuminance data collected from the mid-span. All four figures show close agreement between the adjusted AGi32 results and the field illuminance data from the mid-span of the study site.

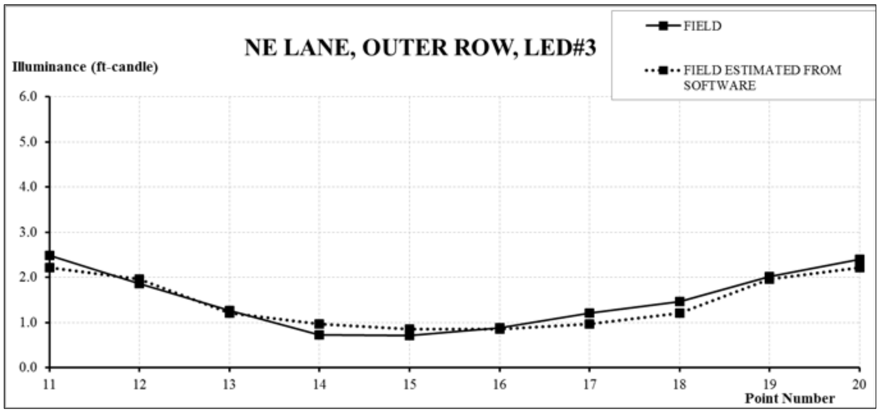

Figure 4-29. Comparison of the field illuminance data with the adjusted AGi32 results for LED#3 (NE lane, outer row).

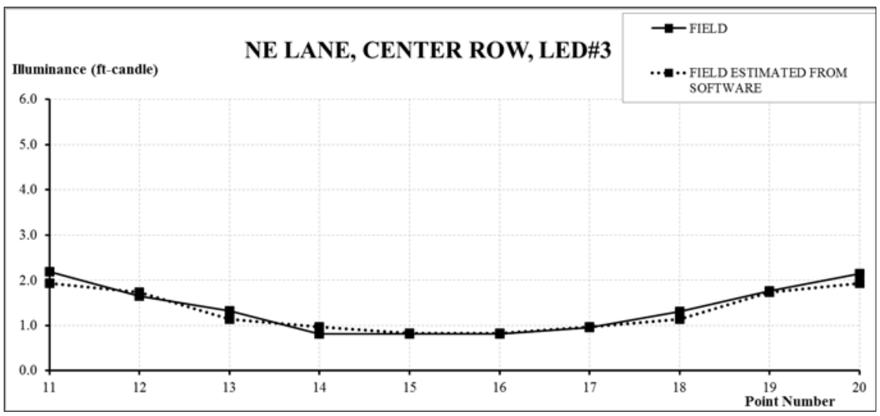

Figure 4-30. Comparison of the field illuminance data with the adjusted AGi32 results for LED#3 (NE lane, center row).

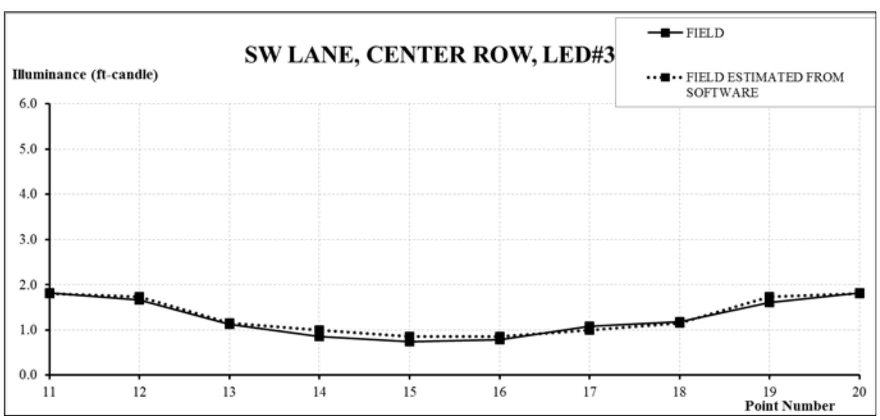

Figure 4-31. Comparison of the field illuminance data with the adjusted AGi32 results for LED#3 (SW lane, center row).

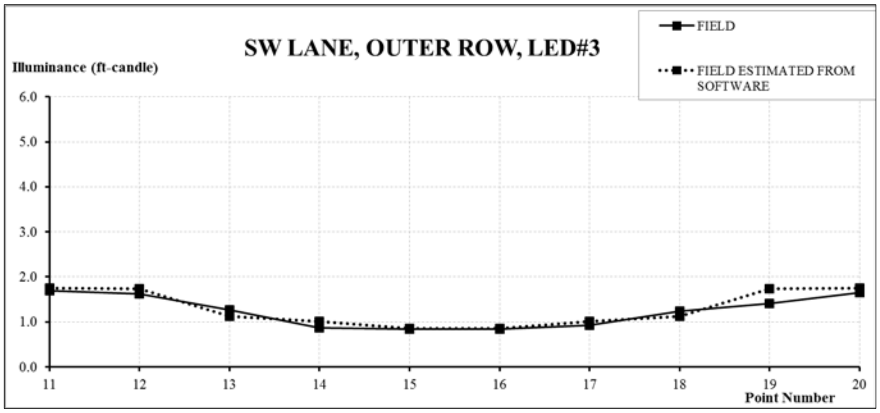

Figure 4-32. Comparison of the field illuminance data with the adjusted AGi32 results for LED#3 (SW lane, outer row).

CHAPTER 5 COMPARISON OF ILLUMINANCE RESULTS TO IDOT LIGHTING DESIGN CRITERIA

There are two methods that must be used in IDOT highway lighting design: illuminance and luminance. The illuminance criterion, which is the oldest and the simplest, is used to

- “Determine the combined amount of luminous flux reaching critical pavement locations from contributing luminaires” and
- “Calculate how uniformly the luminaires’ combined luminous flux is horizontally distributed over the pavement surface” (IDOT 2010).

Hence, the illuminance design criteria set the minimum threshold value for average maintained horizontal illuminance as well as the maximum allowed value for uniformity ratio. The uniformity ratio is defined as the average maintained horizontal illuminance divided by the minimum horizontal illuminance. The IDOT illuminance design criteria are based on ANSI/IESNA RP-8, and they vary according to road type as well as the level of pedestrian conflict, provided that pedestrians are allowed on the road.

Generally, the highest illuminance level occurs under the luminaire, and the illuminance level generally decreases as one goes away from the light source. The illuminance criterion does not take into account the effects of reflected light from a surface or an object, which is known as brightness. To overcome this limitation, a new metric called veiling luminance ratio was incorporated into the illuminance design (IDOT 2010). Veiling luminance is defined as the “effect produced by bright sources or objects in the visual field that causes decreased visibility and visual performance” (Acuity Lighting Group 2004). For a given luminaire cycle, the veiling luminance ratio is computed by dividing the maximum veiling luminance by the average maintained luminance. In this study, veiling luminance ratio was not measured in the field because there were not bright sources in the visual field.

The following sections present the comparison of the field data and AGi32 results with the IDOT lighting design requirements for illuminance. Regarding the IDOT design criteria, the roadway facility classification selected is a major roadway. Furthermore, it is assumed that the study site is a medium pedestrian conflict area. In addition, the illuminance requirements for major roads with low and high pedestrian conflict areas are also presented. The high, medium, and low pedestrian conflict areas represent the area classifications of commercial, intermediate, and residential, respectively (IDOT 2010). Appendix H, IDOT Design Criteria, includes the complete set of the IDOT illuminance and luminance design criteria.

5.1 HPS

For the HPS luminaires, Table 5-1 presents the comparison of the field data and Agi32 results with the IDOT illuminance requirements for major roads. Two types of software analysis were conducted. The results from the first one are presented under the column heading “Agi32 calculations”. In this type of analysis, a dxf model of the test site was made by using the AutoCAD software program, and then the dxf file was imported to the Agi32 software. Subsequently, the illuminance computations were done by the Agi32 software based on the imported dxf model. The results from the second type of software analysis are presented under the column heading “Roadway Optimizer”. In that type of analysis, the Roadway Optimizer tool of the Agi32 software was used rather than a dxf model. Using the Roadway Optimizer tool, one intermediate luminaire cycle (i.e., adjoined by other luminaire cycles on both sides) was modeled based on the dimensions of the study site. Then the illuminance calculations were made for the intermediate luminaire cycle using the Roadway Optimizer.

The Roadway Optimizer tool of Agi32 can be used either for optimizing luminaire spacing under particular constraints defined by the user or for computing illuminance and luminance levels on a user-defined road surface. In this study, the Roadway Optimizer tool was used for computing the illuminance and luminance levels produced by the selected roadway luminaires at the study site. In order to obtain comparable results from both types of software analysis, the dxf model of the study site was built such that the study site was adjoined by other luminaire cycles on both sides. This was done because the Roadway Optimizer can model only one luminaire cycle, which always has to be an intermediate luminaire cycle. By adjoining other luminaire cycles on both sides of the study site in the dxf model, all three luminaire cycles of the study site were converted to intermediate luminaire cycles in the dxf model. To assess whether the luminaries met the IDOT criteria, only the mid-span results are used. According to the results shown in Table 5-1:

- The field data confirm that the HPS met the average maintained horizontal illuminance requirements for major roads, but it slightly exceeded the uniformity ratio criterion (the ratio of Avg/Min exceeds 3.0 in all three luminaire cycles).
- The Agi32 results indicate that the HPS met the average Illuminance and uniformity ratio requirements.

5.2 LED#1

Table 5-2 presents the comparison of the field data and AGi32 results for LED#1 with the IDOT illuminance requirements for major roads. According to the results given in Table :

- Both the field data and AGi32 results show that LED#1 satisfied the average maintained horizontal illuminance requirements for major roads with low pedestrian conflict but not with high or medium pedestrian conflict.
- Both the field data and AGi32 results indicate that LED#1 satisfied the uniformity ratio criterion for major roads.

5.3 LED#2

Table 5-3 presents the comparison of the field data and AGi32 results for LED#2 with the IDOT illuminance requirements for major roads. According to the results given in Table 5-3:

- The field data show that LED#2 met the average maintained horizontal illuminance requirements for major roads with low and medium pedestrian conflict but not with high pedestrian conflict except in fixture cycle 3. LED#2 satisfied the uniformity ratio criterion for major roads with all three levels of pedestrian conflict.
- According to the software results, LED#2 met all illuminance requirements for major roads.

Table 5-1. Comparison of the IDOT Illuminance Requirements with the Field Data and Software Results for the HPS

		FIELD DATA	SOFTWARE RESULTS		IDOT REQ.[1]		
			AGi32 calculations	Roadway Optimizer	Major road, high pedestrian conflict	Major road, medium pedestrian conflict	Major road, low pedestrian conflict
Luminaire cycle 1	Average[2]	2.27	2.16	2.16	1.70	1.30	0.90
	Maximum[3]	5.68	4.54	4.54			
	Minimum[4]	0.66	0.82	0.82			
	Avg/Min[5]	3.43	2.64	2.63	Max. 3.0	Max. 3.0	Max. 3.0
	Max/Min[6]	8.56	5.54	5.54			
	Max/Avg[7]	2.50	2.10	2.10			
Luminaire cycle 2	Average[2]	2.38	2.16	2.16	1.70	1.30	0.90
	Maximum[3]	5.97	4.54	4.54			
	Minimum[4]	0.68	0.82	0.82			
	Avg/Min[5]	3.48	2.64	2.63	Max. 3.0	Max. 3.0	Max. 3.0
	Max/Min[6]	8.72	5.54	5.54			
	Max/Avg[7]	2.50	2.10	2.10			
Luminaire cycle 3	Average[2]	2.43	2.16	2.16	1.70	1.30	0.90
	Maximum[3]	6.01	4.54	4.54			
	Minimum[4]	0.73	0.82	0.82			
	Avg/Min[5]	3.34	2.64	2.63	Max. 3.0	Max. 3.0	Max. 3.0
	Max/Min[6]	8.28	5.54	5.54			
	Max/Avg[7]	2.48	2.10	2.10			

[1]Pavement classification = R3.
[2]Average maintained horizontal illuminance in ft-cd.
[3]Maximum maintained horizontal illuminance in ft-cd.
[4]Minimum maintained horizontal illuminance in ft-cd.
[5]The ratio of the average maintained horizontal illuminance to the minimum maintained horizontal illuminance.
[6]The ratio of the maximum maintained horizontal illuminance to the minimum maintained horizontal illuminance.
[7]The ratio of the maximum maintained horizontal illuminance to the average maintained horizontal illuminance.

Table 5-2. Comparison of the IDOT Illuminance Requirements
with the Field Data and Software Results for LED#1

		FIELD DATA	SOFTWARE RESULTS		IDOT REQ.[1]		
			AGi32 calculations	Roadway Optimizer	Major road, high pedestrian conflict	Major road, medium pedestrian conflict	Major road, low pedestrian conflict
Luminaire cycle 1	Average[2]	0.86	1.20	1.20	1.70	1.30	0.90
	Maximum[3]	2.66	3.11	3.11			
	Minimum[4]	0.29	0.47	0.48			
	Avg/Min[5]	2.91	2.55	2.50	Max. 3.0	Max. 3.0	Max. 3.0
	Max/Min[6]	9.06	6.62	6.48			
	Max/Avg[7]	3.12	2.59	2.59			
Luminaire cycle 2	Average[2]	1.18	1.20	1.20	1.70	1.30	0.90
	Maximum[3]	2.96	3.11	3.11			
	Minimum[4]	0.40	0.48	0.48			
	Avg/Min[5]	2.97	2.50	2.50	Max. 3.0	Max. 3.0	Max. 3.0
	Max/Min[6]	7.46	6.48	6.48			
	Max/Avg[7]	2.51	2.59	2.59			
Luminaire cycle 3	Average[2]	1.25	1.20	1.20	1.70	1.30	0.90
	Maximum[3]	2.98	3.11	3.11			
	Minimum[4]	0.50	0.47	0.48			
	Avg/Min[5]	2.51	2.55	2.50	Max. 3.0	Max. 3.0	Max. 3.0
	Max/Min[6]	5.98	6.62	6.48			
	Max/Avg[7]	2.38	2.59	2.59			

[1] *Pavement classification = R3.*
[2] *Average maintained horizontal illuminance in ft-cd.*
[3] *Maximum maintained horizontal illuminance in ft-cd.*
[4] *Minimum maintained horizontal illuminance in ft-cd.*
[5] *The ratio of the average maintained horizontal illuminance to the minimum maintained horizontal illuminance.*
[6] *The ratio of the maximum maintained horizontal illuminance to the minimum maintained horizontal illuminance.*
[7] *The ratio of the maximum maintained horizontal illuminance to the average maintained horizontal illuminance.*

Table 5-3. Comparison of the IDOT Illuminance Requirements with the Field Data and Software Results for LED#2

		FIELD DATA	SOFTWARE RESULTS		IDOT REQ.[1]		
			AGi32 calculations	Roadway Optimizer	Major road, high pedestrian conflict	Major road, medium pedestrian conflict	Major road, low pedestrian conflict
Luminaire cycle 1	Average[2]	1.42	1.99	1.99	1.70	1.30	0.90
	Maximum[3]	3.23	5.01	5.01			
	Minimum[4]	0.64	0.91	0.92			
	Avg/Min[5]	2.21	2.18	2.16	Max. 3.0	Max. 3.0	Max. 3.0
	Max/Min[6]	5.03	5.51	5.45			
	Max/Avg[7]	2.28	2.52	2.52			
Luminaire cycle 2	Average[2]	1.47	1.99	1.99	1.70	1.30	0.90
	Maximum[3]	3.28	5.01	5.01			
	Minimum[4]	0.61	0.92	0.92			
	Avg/Min[5]	2.43	2.17	2.16	Max. 3.0	Max. 3.0	Max. 3.0
	Max/Min[6]	5.41	5.45	5.45			
	Max/Avg[7]	2.23	2.51	2.52			
Luminaire cycle 3	Average[2]	1.74	1.99	1.99	1.70	1.30	0.90
	Maximum[3]	4.72	5.01	5.01			
	Minimum[4]	0.60	0.91	0.92			
	Avg/Min[5]	2.90	2.18	2.16	Max. 3.0	Max. 3.0	Max. 3.0
	Max/Min[6]	7.87	5.51	5.45			
	Max/Avg[7]	2.71	2.52	2.52			

[1]Pavement classification =R3.
[2]Average maintained horizontal illuminance in ft-cd.
[3]Maximum maintained horizontal illuminance in ft-cd.
[4]Minimum maintained horizontal illuminance in ft-cd.
[5]The ratio of the average maintained horizontal illuminance to the minimum maintained horizontal illuminance.
[6]The ratio of the maximum maintained horizontal illuminance to the minimum maintained horizontal illuminance.
[7]The ratio of the maximum maintained horizontal illuminance to the average maintained horizontal illuminance.

5.4 LED#3

For LED#3, Table 5-4 presents the comparison of the field data and AGi32 results with the IDOT illuminance requirements for major roads. According to the results given in Table 5-4:

- The field data show that LED#3 satisfied the average illuminance requirement for major roads with low and medium pedestrian conflict but not with high pedestrian conflict.
- LED#3 satisfied the uniformity ratio criterion for major roads.

- The software results show that LED#3 satisfied all the illuminance design criteria for major roads.

Table 5-4. Comparison of the IDOT Illuminance Requirements with the Field Data and Software Results for LED#3

		FIELD DATA	SOFTWARE RESULTS		IDOT REQ.[1]		
			AGi32 calculations	Roadway Optimizer	Major road, high pedestrian conflict	Major road, medium pedestrian conflict	Major road, low pedestrian conflict
Luminaire cycle 1	Average[2]	1.26	2.03	2.03	1.70	1.30	0.90
	Maximum[3]	2.40	2.91	2.92			
	Minimum[4]	0.70	1.45	1.45			
	Avg/Min[5]	1.79	1.40	1.40	Max. 3.0	Max. 3.0	Max. 3.0
	Max/Min[6]	3.40	2.01	2.01			
	Max/Avg[7]	1.90	1.44	1.44			
Luminaire cycle 2	Average[2]	1.35	2.03	2.03	1.70	1.30	0.90
	Maximum[3]	2.52	2.92	2.92			
	Minimum[4]	0.73	1.45	1.45			
	Avg/Min[5]	1.84	1.40	1.40	Max. 3.0	Max. 3.0	Max. 3.0
	Max/Min[6]	3.44	2.01	2.01			
	Max/Avg[7]	1.87	1.44	1.44			
Luminaire cycle 3	Average[2]	1.32	2.03	2.03	1.70	1.30	0.90
	Maximum[3]	2.46	2.91	2.92			
	Minimum[4]	0.85	1.45	1.45			
	Avg/Min[5]	1.55	1.40	1.40	Max. 3.0	Max. 3.0	Max. 3.0
	Max/Min[6]	2.89	2.01	2.01			
	Max/Avg[7]	1.86	1.44	1.44			

[1]*Pavement classification = R3.*
[2]*Average maintained horizontal illuminance in ft-cd.*
[3]*Maximum maintained horizontal illuminance in ft-cd.*
[4]*Minimum maintained horizontal illuminance in ft-cd.*
[5]*The ratio of the average maintained horizontal illuminance to the minimum maintained horizontal illuminance.*
[6]*The ratio of the maximum maintained horizontal illuminance to the minimum maintained horizontal illuminance.*
[7]*The ratio of the maximum maintained horizontal illuminance to the average maintained horizontal illuminance.*

CHAPTER 6 LUMINANCE RESULTS: FIELD DATA VS. SOFTWARE

6.1 HPS

Figure 6-1, Figure 6-2, Figure 6-3, and Figure 6-4 compare the average field luminance data for the HPS with the AGi32 luminance results. Detailed tabulation of the average field data and AGi32 results is presented in Appendix F, Luminance Results. Moreover, the luminance levels produced by the HPS are compared in detail with those produced by each LED in Appendix G, Comparison of the Luminance Results for HPS and LEDs. The results are summarized as follows:

- There is considerable disagreement between the average field data and AGi32 results. For a given row, the field data show little change in luminance with distance. Similarly, the peaks and valleys in luminance levels are not very apparent in the field data. Furthermore, the field data mostly indicate higher luminance levels than the AGi32 results.
- On the other hand, the AGi32 results indicate clear peaks and valleys in luminance levels, especially for the row closest to the light poles.
- The peaks and valleys of the average field data do not coincide with those of the AGi32 results. Take the case of the NE lane outer row, for instance. According to the AGi32 results, the minimum luminance levels occur at the grid points 2, 12, and 22. In contrast, the field data show that the minimum (though not very apparent) luminance levels correspond to the grid points 10, 19, and 29.
- The absolute discrepancy between the field data and AGi32 results ranged from 0.02 to 1.69 cd/m^2 (mean value = 0.70) for the NE lane outer row, 0.04 to 1.57 cd/m^2 (mean value = 0.81) for the NE lane center row, 0.10 to 1.59 cd/m^2 (mean value = 0.89) for the SW lane center row, and 0.02 to 1.34 cd/m^2 (mean value = 0.83) for the SW lane outer row.

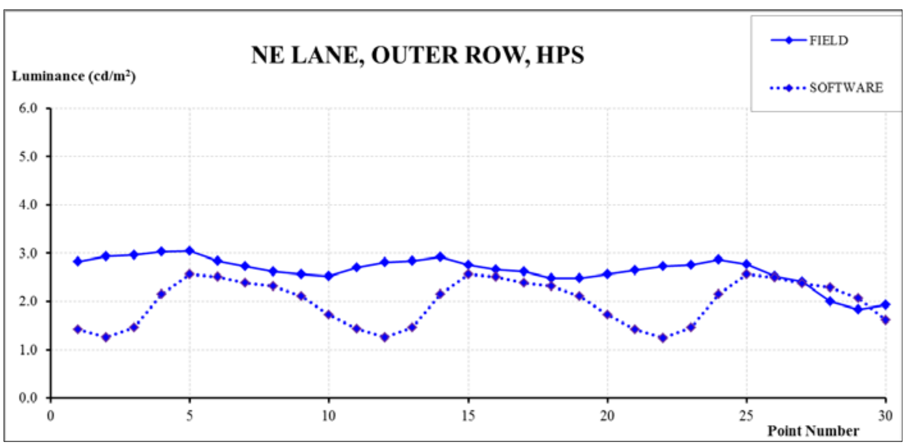

Figure 6-1. Comparison of the field luminance data with the AGi32 results for the HPS (NE lane, outer row).

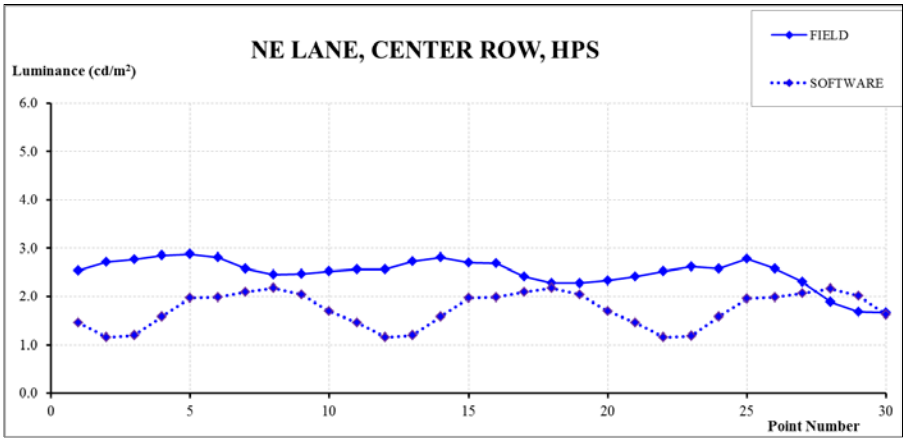

Figure 6-2. Comparison of the field luminance data with the AGi32 results for the HPS (NE lane, center row).

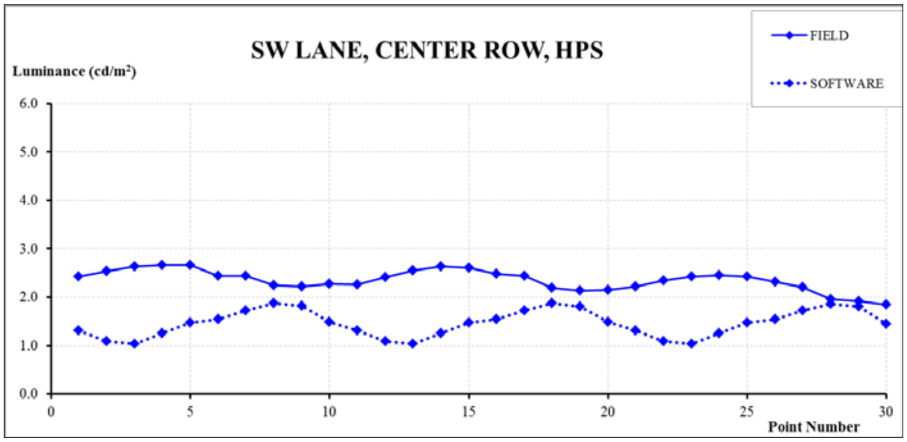

Figure 6-3. Comparison of the field luminance data with the AGi32 results for the HPS (SW lane, center row).

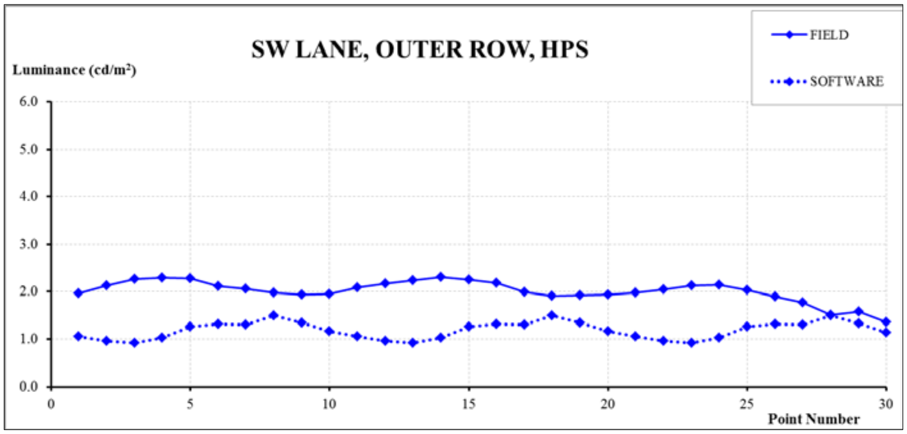

Figure 6-4. Comparison of the field luminance data with the AGi32 results for the HPS (SW lane, outer row).

6.2 LED#1

Graphical comparison of the average field luminance data for LED#1 with the AGi32 luminance results is shown in Figure 6-5, Figure 6-6, Figure 6-7, and Figure 6-8. For detailed reference, average field data and AGi32 results are available in Appendix F, Luminance Results. The following are inferred for LED#1 from the results:

- There is disagreement between the average field data and AGi32 results. For each row, the field data show little change in luminance with distance. In a given row, the field data indicate no clear peaks and valleys in luminance levels.
- On the other hand, the AGi32 results indicate distinct peaks and valleys in luminance levels, especially for the NE lane.
- The absolute discrepancy between the average field data and AGi32 results ranged from 0.00 to 0.57 cd/m^2 (mean = 0.18) for the NE lane outer row, 0.02 to 0.66 cd/m^2 (mean = 0.23) for the NE lane center row, 0.04 to 0.66 cd/m^2 (mean = 0.32) for the SW lane center row, and 0.03 to 0.72 cd/m^2 (mean = 0.38) for the SW lane outer row.

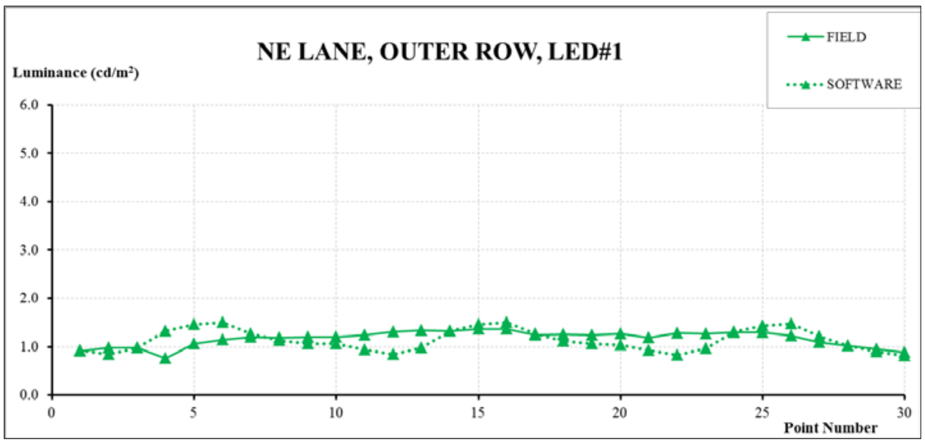

Figure 6-5. Comparison of the field luminance data with the AGi32 results for LED#1 (NE lane, outer row).

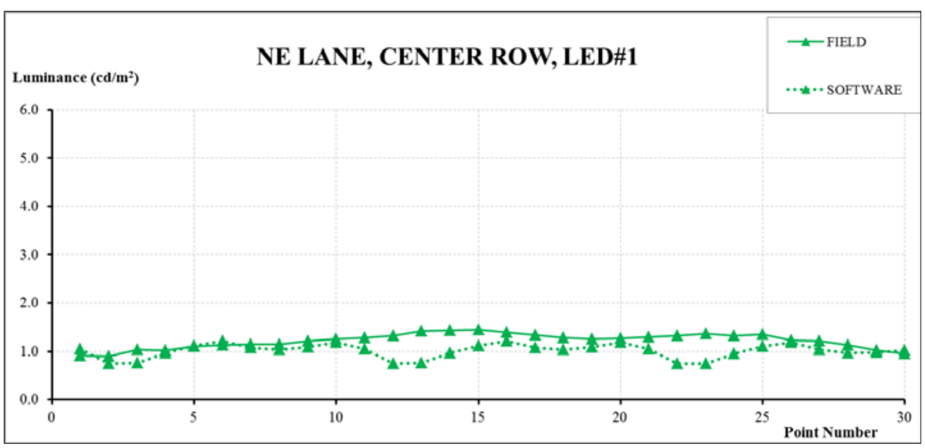

Figure 6-6. Comparison of the field luminance data with the AGi32 results for LED#1 (NE lane, center row).

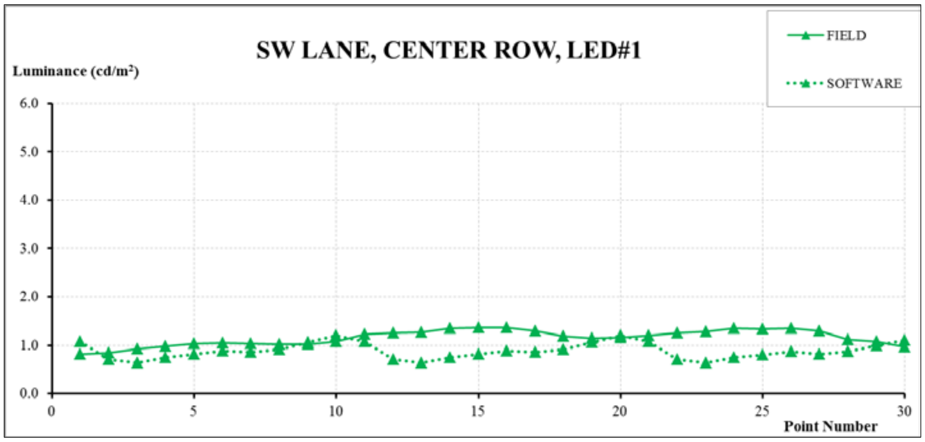

Figure 6-7. Comparison of the field luminance data with the AGi32 results for LED#1 (SW lane, center row).

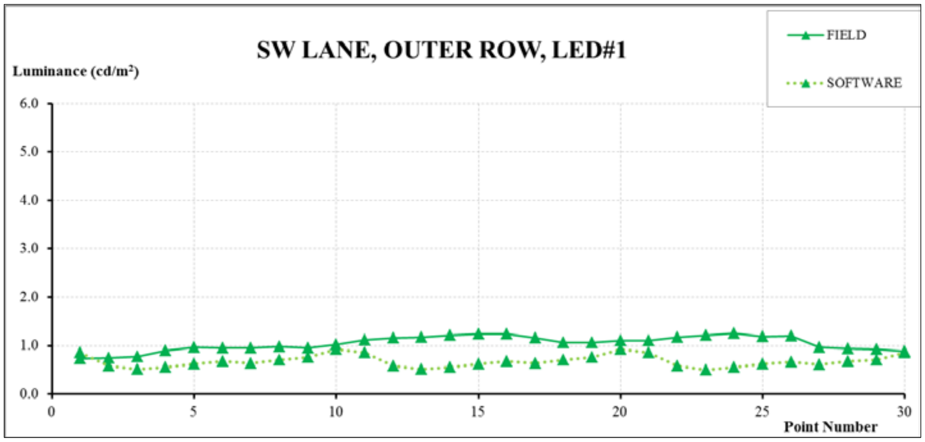

Figure 6-8. Comparison of the field luminance data with the AGi32 results for LED#1 (SW lane, outer row).

6.3 LED#2

Figure 6-9, Figure 6-10, Figure 6-11, and Figure 6-12 graphically compare the average field luminance data for LED#2 and the AGi32. Detailed tabulation of the average field data and AGi32 results is presented in Appendix F, Luminance Results. Based on the results, the following are concluded:

- There is disagreement between the average field data and AGi32 results. For each row, the field data show little variation in luminance with distance. On the other hand, the AGi32 results indicate sharp peaks and valleys in luminance levels. According to the AGi32 results, the maximum luminance levels in a given row are attained at the mid grid points between the light poles. On the other hand, the minimum luminance levels in a given row occur at grid points in close vicinity of the light poles.
- The absolute discrepancy between the average field data and AGi32 results ranged from 0.00 to 3.05 cd/m^2 (mean = 1.06) for the NE lane outer row, 0.15 to 2.56 cd/m^2 (mean = 0.99) for the NE lane center row, 0.10 to 1.50 cd/m^2 (mean = 0.66) for the SW lane center row, and 0.07 to 0.88 cd/m^2 (mean = 0.46) for the SW lane outer row.

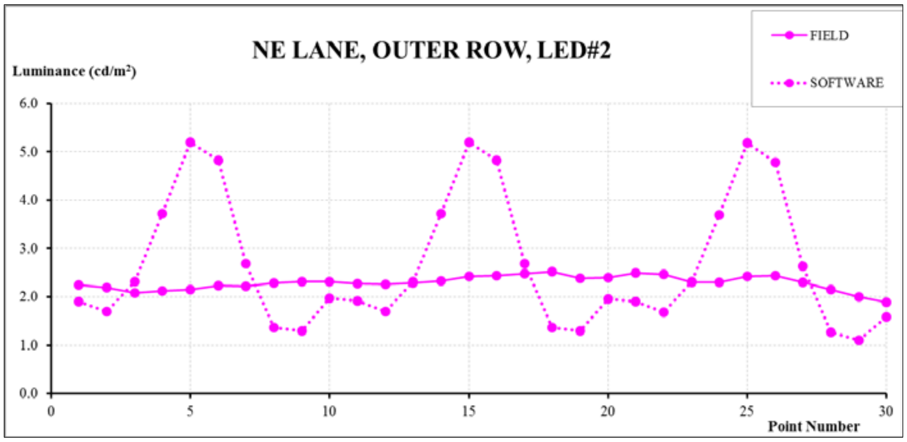

Figure 6-9. Comparison of the field luminance data with the AGi32 results for LED#2 (NE lane, outer row).

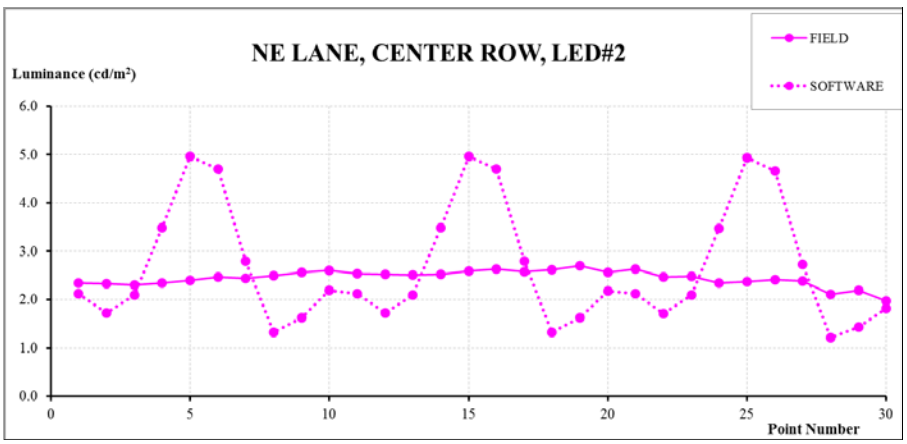

Figure 6-10. Comparison of the field luminance data with the AGi32 results for LED#2 (NE lane, center row).

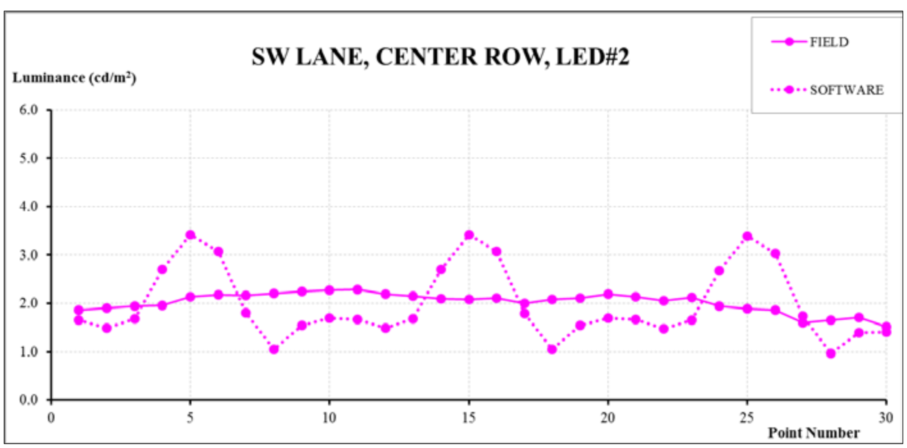

Figure 6-11. Comparison of the field luminance data with the AGi32 results for LED#2 (SW lane, center row).

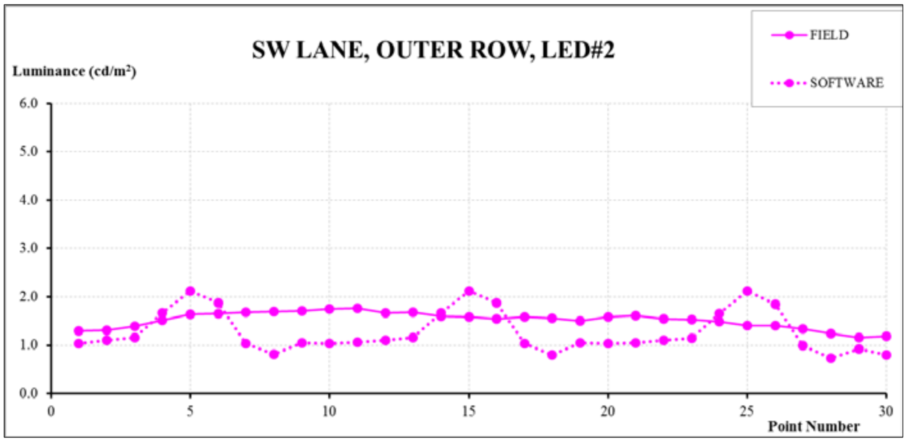

Figure 6-12. Comparison of the field luminance data with the AGi32 results for LED#2 (SW lane, outer row).

6.4 LED#3

Graphical comparison of the average field luminance data for LED#3 with the AGi32 luminance results is shown in Figure 6-13, Figure 6-14, Figure 6-15, and Figure 6-16. For detailed reference, average field data and AGi32 results are provided in Appendix F, Luminance Results. The following are inferred for LED#3 from the results:

- For each row, the field data show little variation in luminance with distance. On the other hand, the AGi32 results indicate sharp peaks and valleys in luminance levels. For a given row, the AGi32 resulted in the maximum luminance levels at the mid grid points between the light poles. On the other hand, the minimum luminance levels occurred at grid points in close vicinity of the light poles.
- The absolute discrepancy between the average field data and AGi32 results ranged from 0.15 to 2.95 cd/m^2 (mean = 1.29) for the NE lane outer row, 0.11 to 2.04 cd/m^2 (mean = 0.89) for the NE lane center row, 0.04 to 1.40 cd/m^2 (mean = 0.60) for the SW lane center row, and 0.04 to 0.82 cd/m^2 (mean = 0.41) for the SW lane outer row.

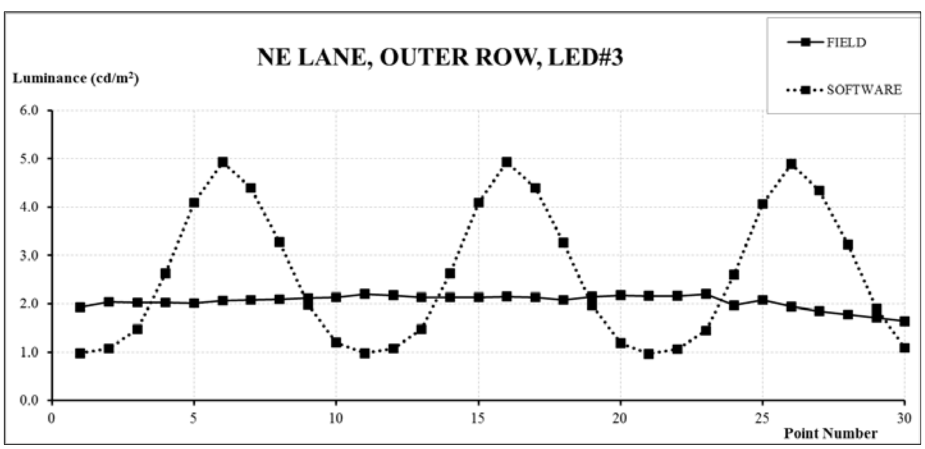

Figure 6-13. Comparison of the field luminance data with the AGi32 results for LED#3 (NE lane, outer row).

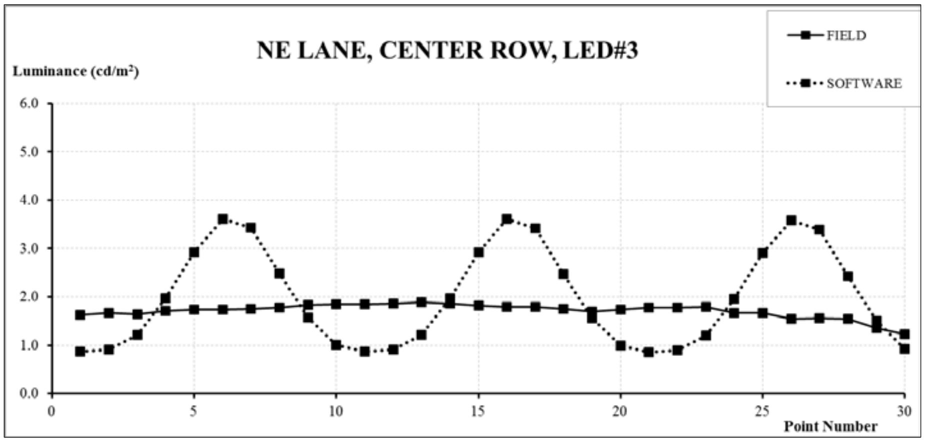

Figure 6-14. Comparison of the field luminance data with the AGi32 results for LED#3 (NE lane, center row).

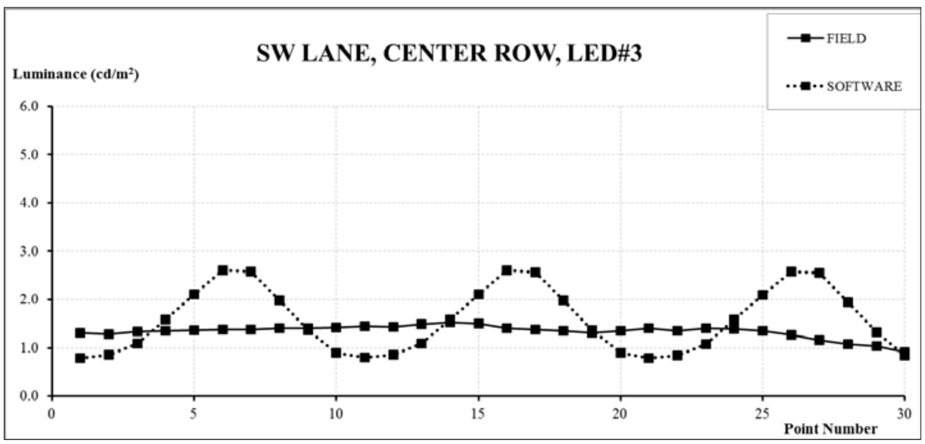

Figure 6-15. Comparison of the field luminance data with the AGi32 results for LED#3 (SW lane, center row).

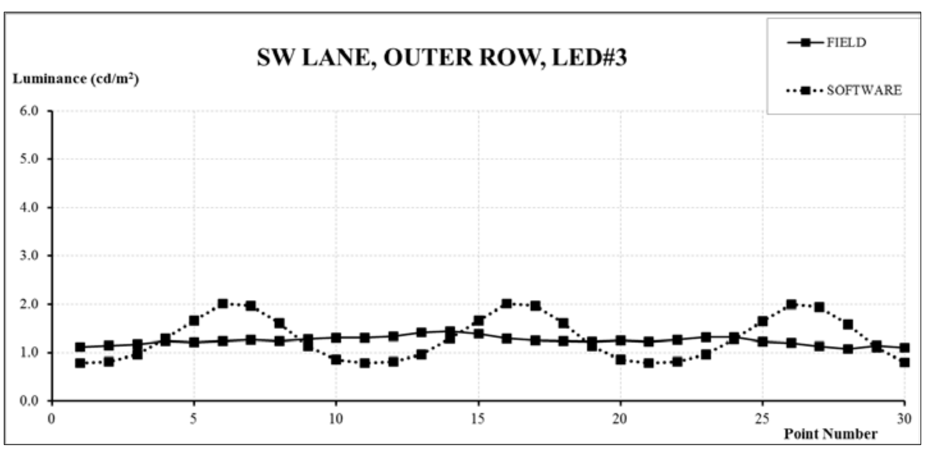

Figure 6-16. Comparison of the field luminance data with the AGi32 results for LED#3 (SW lane, outer row).

6.5 DISCUSSION OF LUMINANCE FIELD DATA

The research team is aware of the requirements for the equipment to measure luminance according to IESNA LM-50-99, where an aperture of 2.0 min of an arc is specified. However, for this project the allocated budget was on the order of a few thousand dollars and allowed for off-the-shelf devices with acceptance angles of 1 degree, as opposed to devices that have smaller acceptance angles but are custom made and cost $15,000 to $20,000. In addition, there was a need for two luminance meters to shorten the duration of lane closures for data collection. Given that IDOT already was in possession of one luminance meter by Konica Minolta (L-100), it was decided to purchase one more to complete data collection using two similar devices. This device does not have the acceptance angle to provide point-by-point readings using the grid from LM-50-99; as a result maximum and minimum values are not emphasized, but it may provide accurate average values that are comparable to those from individual grid points (see Chapter 7 for explanation). In addition, this instrument is reliable and has a precision that exceeds LM-50-99. Hence, two Konica Minolta L-100 luminance meters (with 1.0 degree acceptance angle) were used in this study.

In order to determine the actual length of the roadway covered by a single reading of the luminance meter, the research team set the device at the height and distance required by IESNA LM-50-99 so that the downward-aiming angle was 1.0 degree. After aiming the luminance meter at the selected grid point, the length of the roadway covered by the elliptical surface within the acceptance angle was measured, as shown in Figure 6-17. A total of three measurements at different grid points were obtained. After completing this set of measurements, the research team scaled both h and d_1 by a factor of 1/2 and obtained readings for d_2 and d_3, also for three selected grid points. Next, a third set of measurements were obtained to find d_2 and d_3 when both h and d_1 were scaled by a factor of 1/3. For each value of h and d_1, the average values of d_2 and d_3 are given in Table 6-1. According to the results given in Table 6-1:

- When the research team used the detection height and distance as required by IESNA LM-50-99, the length of the road segment that the luminance meter covered was approximately 363 ft (i.e., 94 + 269 ft). Hence, the research team actually measured a road segment approximately 363 ft long at every luminance measurement. Since the longitudinal distance between two adjacent grid points is 15 ft, a road segment of 363 ft corresponds to about 24 grid points (i.e., 363/15).
- When the detection height and longitudinal distance required by IESNA LM-50-99 was scaled by a factor of 1/2, the length of the road segment that the luminance was measured was approximately 184 ft (i.e., 46 + 138 ft). Since the longitudinal distance between two adjacent grid points is 15 ft, a road segment of 184 ft corresponds to about 12 grid points (i.e., 184/15).
- When the detection height and longitudinal distance required by IESNA LM-50-99 was scaled by a factor of 1/3, the length of the road segment that the luminance was measured was approximately 123 ft (i.e., 31 + 92 ft). Since the longitudinal distance between two adjacent grid points is 15 ft, a road segment of 123 ft corresponds to about 8 grid points (i.e., 123/15).

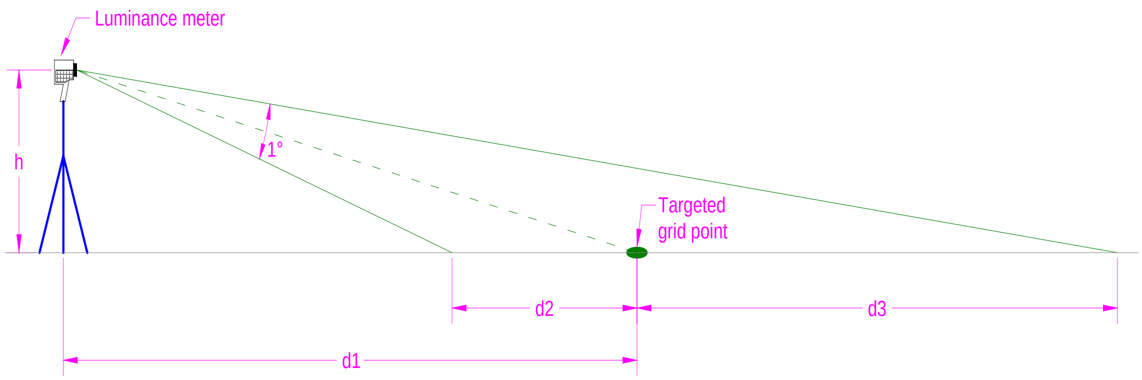

Figure 6-17. Schematic side view of the luminance measurements with Konica Minolta L-100 luminance meter (figure drawn not to scale).

Table 6-1. Average Measured Values of d_2 and d_3 for the Selected Values of Detection Height and Longitudinal Distance

h (ft)	d_1 (ft)	Average measured value of d_2 (ft)	Average measured value of d_3 (ft)
1.59	91.3	31	92
2.38	137	46	138
4.76	274	94	269

CHAPTER 7 COMPARISON OF THE LUMINANCE RESULTS TO IDOT LIGHTING DESIGN CRITERIA

The luminance criterion is based on the amount of light reflected by the pavement surface to a driver's eye. In that way, the luminance concept simulates a motorist's visibility. The luminance design criterion sets the minimum threshold value for average maintained luminance and the maximum allowed values for two different uniformity ratios. The first uniformity ratio is the ratio of the average maintained luminance to the minimum maintained luminance. The second uniformity ratio is the ratio of the maximum maintained luminance to the minimum maintained luminance. Moreover, the final design criterion is the maximum allowed veiling luminance ratio, which is the ratio of the maximum veiling luminance to the average maintained luminance. In this study, veiling luminance ratio was not measured in the field. As already mentioned in 0, the design criteria are based on ANSI/IESNA RP-8, and they vary according to road type and the level of pedestrian conflict, provided that pedestrians are allowed on the road (IDOT 2010).

One disadvantage of the luminance methodology is that it is highly dependent on the reflectance characteristics of the pavement surface, which may vary. Pavement reflectivity is affected by several time-dependent factors such as initial surface type, pavement deterioration, resurfacing material type, and even weather conditions. Since these factors change over time, it is hard to control and predict them (IDOT 2010).

The following sections present the comparison of the field data and AGi32 results with the IDOT requirements for luminance. Similar to Chapter 5, the IDOT luminance requirements are given for major roads with high, medium, and low pedestrian conflict. Appendix H, IDOT Design Criteria, includes complete IDOT illuminance and luminance design criteria.

As mentioned in Section 6.5, the luminance levels measured in the field were obtained using a meter with an acceptance angle of 1 degree. As a result, a single luminance reading covered an area much greater than a single grid point, creating significant discrepancies between software and field results. Thus, the field luminance measurements do not reflect the luminance values for individual grid points but rather the average luminance value for a stretch of the road that was approximately 360 ft long.

Since the luminance values of individual grid points were not measured in the field, no statement or inference is made about the luminance uniformity ratios (i.e., max/min and avg/min) obtained from the field data. However, the average field luminance values for each luminaire cycle would be close to the true average luminance of all grid points in a luminaire cycle. This is because the luminance readings are expected to repeat from one cycle to the next and the area measured by the device is close to two complete luminaire cycles (about 24 grid points); therefore, the average luminance obtained in the field is also expected to be similar to the average obtained using data from each grid point.

7.1 HPS

The field data and software results for the HPS are compared with the IDOT luminance design criteria in Table 7-1. According to the results given in Table 7-1:

- The field data show that HPS satisfied the average maintained luminance design criterion for major roads.
- Likewise, according to the software results, the HPS met all luminance design criteria for major roads.

Table 7-1. Comparison of the IDOT Luminance Requirements with the Field Data and Software Results for the HPS

		FIELD DATA	SOFTWARE RESULTS		IDOT REQ.		
			AGi32 calculations	Roadway Optimizer	Major road, high pedestrian conflict	Major road, medium pedestrian conflict	Major road, low pedestrian conflict
Luminaire cycle 1	Average[1]	2.51	1.59	1.59	1.20	0.90	0.60
	Maximum[2]	3.05*	2.57	2.57			
	Minimum[3]	1.94*	0.92	0.92			
	Avg/Min[4]	1.29*	1.73	1.73	Max. 3.0	Max. 3.0	Max. 3.5
	Max/Min[5]	1.58*	2.79	2.79	Max. 5.0	Max. 5.0	Max. 6.0
	Max/Avg[6]	1.22*	1.61	1.62			
Luminaire cycle 2	Average[1]	2.43	1.59	1.59	1.20	0.90	0.60
	Maximum[2]	2.92*	2.57	2.57			
	Minimum[3]	1.90*	0.92	0.92			
	Avg/Min[4]	1.28*	1.73	1.73	Max. 3.0	Max. 3.0	Max. 3.5
	Max/Min[5]	1.53*	2.79	2.79	Max. 5.0	Max. 5.0	Max. 6.0
	Max/Avg[6]	1.20*	1.61	1.62			
Luminaire cycle 3	Average[1]	2.20	1.59	1.59	1.20	0.90	0.60
	Maximum[2]	2.87*	2.57	2.57			
	Minimum[3]	1.35*	0.92	0.92			
	Avg/Min[4]	1.63*	1.73	1.73	Max. 3.0	Max. 3.0	Max. 3.5
	Max/Min[5]	2.12*	2.79	2.79	Max. 5.0	Max. 5.0	Max. 6.0
	Max/Avg[6]	1.30*	1.61	1.62			

[1]Average maintained luminance in cd/m^2.
[2]Maximum maintained luminance in cd/m^2.
[3]Minimum maintained luminance in cd/m^2.
[4]The ratio of the average maintained luminance to the minimum maintained luminance.
[5]The ratio of the maximum maintained luminance to the minimum maintained luminance.
[6]The ratio of the maximum maintained luminance to the average maintained luminance.
**These field luminance measurements are not for individual grid points, but rather for a stretch of the road that was approximately 360 ft long. Hence, these values are not compared to the corresponding IDOT luminance design criteria.*

7.2 LED#1

The field data and software results for LED#1 are compared with the IDOT luminance design criteria in Table 7-2. According to the results given in Table 7-2:

- The field data show that LED#1 satisfied the average luminance design criterion for major roads (except in fixture cycles 1 and 3, where it did not meet average maintained luminance value for major roads/high pedestrian).
- According to the software results, LED#1 met all luminance design criteria for major/medium and major/low. However, it did not meet the average maintained luminance criterion for major roads/high pedestrian.

Table 7-2. Comparison of the IDOT Luminance Requirements with the Field Data and Software Results for LED#1

		FIELD DATA	SOFTWARE RESULTS		IDOT REQ.		
			AGi32 calculations	Roadway Optimizer	Major road, high pedestrian conflict	Major road, medium pedestrian conflict	Major road, low pedestrian conflict
Luminaire cycle 1	Average¹	1.01	0.94	0.94	1.20	0.90	0.60
	Maximum²	1.25*	1.51	1.51			
	Minimum³	0.73*	0.51	0.51			
	Avg/Min⁴	1.38*	1.84	1.84	Max. 3.0	Max. 3.0	Max. 3.5
	Max/Min⁵	1.72*	2.96	2.96	Max. 5.0	Max. 5.0	Max. 6.0
	Max/Avg⁶	1.25*	1.61	1.61			
Luminaire cycle 2	Average¹	1.26	0.94	0.94	1.20	0.90	0.60
	Maximum²	1.45*	1.51	1.51			
	Minimum³	1.07*	0.51	0.51			
	Avg/Min⁴	1.19*	1.84	1.84	Max. 3.0	Max. 3.0	Max. 3.5
	Max/Min⁵	1.36*	2.96	2.96	Max. 5.0	Max. 5.0	Max. 6.0
	Max/Avg⁶	1.15	1.61	1.61			
Luminaire cycle 3	Average¹	1.17	0.94	0.94	1.20	0.90	0.60
	Maximum²	1.36*	1.51	1.51			
	Minimum³	0.89*	0.51	0.51			
	Avg/Min⁴	1.32*	1.84	1.84	Max. 3.0	Max. 3.0	Max. 3.5
	Max/Min⁵	1.54*	2.96	2.96	Max. 5.0	Max. 5.0	Max. 6.0
	Max/Avg⁶	1.17*	1.61	1.61			

¹Average maintained luminance in cd/m².
²Maximum maintained luminance in cd/m².
³Minimum maintained luminance in cd/m².
⁴The ratio of the average maintained luminance to the minimum maintained luminance.
⁵The ratio of the maximum maintained luminance to the minimum maintained luminance.
⁶The ratio of the maximum maintained luminance to the average maintained luminance.
**These field luminance measurements are not for individual grid points, but rather for a stretch of the road that was approximately 360 ft long. Hence, these values are not compared to the corresponding IDOT luminance design criteria.*

7.3 LED#2

The field data and software results for LED#2 are compared with the IDOT luminance design criteria in Table 7-3. According to the results given in Table 7-3:

- The field data show that LED#2 satisfied the average maintained luminance design criterion for major roads
- According to the software results, LED#2 also satisfied the average maintained luminance design criterion, but it did not meet one of the uniformity criteria since the ratio of “Max/Min” exceeded 6.0.

Table 7-3. Comparison of the IDOT Luminance Requirements with the Field Data and Software Results for LED#2

		FIELD DATA	SOFTWARE RESULTS		IDOT REQ.		
			Agi32 calculations	Roadway Optimizer	Major road, high pedestrian conflict	Major road, medium pedestrian conflict	Major road, low pedestrian conflict
Luminaire cycle 1	Average[1]	2.07	2.18	2.18	1.20	0.90	0.60
	Maximum[2]	2.60*	5.20	5.20			
	Minimum[3]	1.30*	0.81	0.81			
	Avg/Min[4]	1.60*	2.69	2.69	Max. 3.0	Max. 3.0	Max. 3.5
	Max/Min[5]	2.00*	6.42	6.42	Max. 5.0	Max. 5.0	Max. 6.0
	Max/Avg[6]	1.25*	2.39	2.39			
Luminaire cycle 2	Average[1]	2.17	2.18	2.18	1.20	0.90	0.60
	Maximum[2]	2.70*	5.20	5.20			
	Minimum[3]	1.51*	0.81	0.81			
	Avg/Min[4]	1.44*	2.69	2.69	Max. 3.0	Max. 3.0	Max. 3.5
	Max/Min[5]	1.79*	6.42	6.42	Max. 5.0	Max. 5.0	Max. 6.0
	Max/Avg[6]	1.24*	2.39	2.39			
Luminaire cycle 3	Average[1]	1.96	2.18	2.18	1.20	0.90	0.60
	Maximum[2]	2.64*	5.20	5.20			
	Minimum[3]	1.16*	0.81	0.81			
	Avg/Min[4]	1.69*	2.69	2.69	Max. 3.0	Max. 3.0	Max. 3.5
	Max/Min[5]	2.27*	6.42	6.42	Max. 5.0	Max. 5.0	Max. 6.0
	Max/Avg[6]	1.34*	2.39	2.39			

[1]Average maintained luminance in cd/m^2.
[2]Maximum maintained luminance in cd/m^2.
[3]Minimum maintained luminance in cd/m^2.
[4]The ratio of the average maintained luminance to the minimum maintained luminance.
[5]The ratio of the maximum maintained luminance to the minimum maintained luminance.
[6]The ratio of the maximum maintained luminance to the average maintained luminance.
**These field luminance measurements are not for individual grid points, but rather for a stretch of the road that was approximately 360 ft long. Hence, these values are not compared to the corresponding IDOT luminance design criteria.*

7.4 LED#3

The field data and software results for LED#3 are compared with the IDOT luminance design criteria in Table 7-4. According to the results given in Table 7-4:

- The field data indicate that LED#3 satisfied the average maintained luminance design criterion for major roads.
- According to the software results, the average maintained luminance design criterion for LED#3 met the IDOT requirements, but it did exceeded one of uniformity criteria since the ratio of Max/Min exceeded 6.0.

Table 7-4. Comparison of the IDOT Luminance Requirements with the Field Data And software Results for LED#3

		FIELD DATA	SOFTWARE RESULTS		IDOT REQ.		
			AGi32 calculations	Roadway Optimizer	Major road, high pedestrian conflict	Major road, medium pedestrian conflict	Major road, low pedestrian conflict
Luminaire cycle 1	Average[1]	1.57	1.88	1.88	1.20	0.90	0.60
	Maximum[2]	2.13*	4.93	4.93			
	Minimum[3]	1.02*	0.78	0.79			
	Avg/Min[4]	1.54*	2.40	2.38	Max. 3.0	Max. 3.0	Max. 3.5
	Max/Min[5]	2.10*	6.32	6.24	Max. 5.0	Max. 5.0	Max. 6.0
	Max/Avg[6]	1.36*	2.63	2.62			
Luminaire cycle 2	Average[1]	1.66	1.88	1.88	1.20	0.90	0.60
	Maximum[2]	2.18*	4.93	4.93			
	Minimum[3]	1.18*	0.79	0.79			
	Avg/Min[4]	1.41*	2.38	2.38	Max. 3.0	Max. 3.0	Max. 3.5
	Max/Min[5]	1.86*	6.24	6.24	Max. 5.0	Max. 5.0	Max. 6.0
	Max/Avg[6]	1.31*	2.63	2.62			
Luminaire cycle 3	Average[1]	1.54	1.87	1.88	1.20	0.90	0.60
	Maximum[2]	2.24*	4.93	4.93			
	Minimum[3]	1.06*	0.79	0.79			
	Avg/Min[4]	1.46*	2.37	2.38	Max. 3.0	Max. 3.0	Max. 3.5
	Max/Min[5]	2.11*	6.24	6.24	Max. 5.0	Max. 5.0	Max. 6.0
	Max/Avg[6]	1.45*	2.63	2.62			

[1]Average maintained luminance in cd/m^2.
[2]Maximum maintained luminance in cd/m^2.
[3]Minimum maintained luminance in cd/m^2.
[4]The ratio of the average maintained luminance to the minimum maintained luminance.
[5]The ratio of the maximum maintained luminance to the minimum maintained luminance.
[6]The ratio of the maximum maintained luminance to the average maintained luminance.
**These field luminance measurements are not for individual grid points, but rather for a stretch of the road that was approximately 360 ft long. Hence, these values are not compared to the corresponding IDOT luminance design criteria.*

CHAPTER 8 LIFE-CYCLE COST AND INDUSTRY INPUT

Economic analysis of lighting provides a framework for making a selection among competing lighting designs. The lighting designer can make decisions and gauge the profitability of a capital investment in a lighting system through an economic analysis. In general, there are two basic methods for running an economic analysis: first-level methods and second-level methods.

First-level methods are relatively simple and include Cost of Light, Simple Payback, and Simple Rate of Return; however, they may lead to significant errors for long payback periods. On the other hand, second-level methods include Life-Cycle Cost/Benefit Analysis, Savings Investment Ratio, Internal Rate of Return, and Net Present Value. In contrast to the first-level analysis methods, the second-level analysis methods consider time value of money. Among the second-level analysis methods, IESNA recommends the use of life-cycle cost-benefit analysis (LCCBA) for economic analysis of lighting design. LCCBA is a robust method that is widely accepted by experts in managerial economics from all industries (IESNA Lighting Economics Committee 1996). In the next phase of this study, the economic analysis will include the computation and comparison of the life-cycle costs of the selected roadway luminaires applying the LCCA method.

In the LCCA method, an analysis period is specified, and it determines the length of time chosen for consideration of cost (AASHTO 1993). Then, the analyst converts all types of costs that occur in the analysis period into their present value. The costs include initial cost, maintenance cost, energy cost, and salvage value. When those costs are converted into their present value, the principle of time equivalence of money is used (IESNA Lighting Economics Committee 1996). The time equivalence of money can be explained by the following example: When government spends a particular amount of money for roadway lighting, it loses the chance of investing this money elsewhere. The rate at which that money could be invested elsewhere is called opportunity rate of capital or, more simply, the opportunity rate. The opportunity rate is also sometimes referred to as discount rate or interest rate (AASHTO 1993; IESNA Lighting Economics Committee 1996). For instance, if $100,000 is invested elsewhere at that rate and becomes $110,000 one year later, the opportunity rate is 10%. Thus, having $100,000 today is equivalent to having $110,000 one year from now. These two values are called time equivalents of money.

In LCCA, all maintenance costs, energy costs, and salvage value that occur during the analysis period are discounted to their present values using the opportunity rate of capital. The total present value of each lighting design is then computed by adding the present values of all maintenance costs, energy costs, and salvage value to the initial cost. Finally, the total present values of different lighting design alternatives are compared to each other (IESNA Lighting Economics Committee 1996). Appendix I presents detailed procedure for the computation of life-cycle costs for roadway luminaires.

A proposed second phase of this study involves detailed life-cycle cost analysis of the tested luminaires. The comparison of the life-cycle costs of the selected LED luminaires with the life-cycle costs of the HPS luminaire will provide an accurate economic comparison of the tested roadway luminaires and will help better identify their suitability for roadway applications. To conduct an accurate life-cycle cost analysis of the selected luminaires, several items such as initial cost, luminaire lifetime, etc., need to be known. Hence, as part of this study, the manufacturers of the luminaires (i.e., GE, Relume, and Cooper Lighting) were invited to give a presentation at IDOT Central Offices in Springfield on March 29, 2011. The main purpose of these presentations was for the companies to provide information on technical issues and product performance, as well as quality control and future directions regarding the production of LED luminaires for roadway lighting.

Following the presentations, a questionnaire was prepared and submitted to the companies. Among technical questions about the product performance and warranties, the questionnaire included questions relevant to the required input data for a detailed life-cycle cost analysis. A copy of the questionnaire is included in Appendix J.

Results with the feedback received from the companies will be used to conduct a comprehensive life-cycle cost analysis as part of the second phase of the study.

CHAPTER 9 LED ROADWAY LIGHTING AT IDOT

The research team conducted interviews with members of IDOT's Central Office Electrical Unit and some of the districts in order to identify the main steps that are followed for the development of a lighting design project. The main objectives of these interviews were to clearly establish the procedures currently in practice for this type of project, determine potential differences between such practice and the procedures described in Chapter 56 of the *Bureau of Design and Environment Manual* (BDE manual), and generate specific ideas for improvements.

The main steps of the procedure are briefly described as follows, as a summary of the complete text contained in Chapter 56, Section 4 of the BDE manual:

1. Initial need for the new lighting or the need to upgrade/replace existing lighting is identified by the district.
2. Decision is made to use a lighting consultant or Central Office Electrical Unit to design the system. This decision should be made based on a discussion between the district and the Central Office Electrical Unit.
3. The district, in conjunction with the Central Office Electrical Unit, gives guidance to the lighting designer regarding project-specific lighting parameters and configurations to be used.
4. If the lighting design is done by a consultant, several submittals are made to the district and reviews are done by the Central Office Electrical Unit. Lighting design calculations using AGi32 software and the lighting layout must be submitted for review and approved before the rest of the documents (plans, estimates, and special provisions) are prepared. Submittals are then made for the review of preliminary and final lighting plans and project documents.
5. If the lighting is designed by the Central Office Electrical Unit, design issues are coordinated between the Central Office Electrical Unit and the district. The lighting design package is prepared and sent to the district for processing or a consultant for drafting and inclusion into the plan set.

This procedure applies to all districts except for District 1, which is directly in charge of the lighting design. Central Office Electrical Unit and District 1 are the only ones that regularly use lighting design software for the projects, which is currently standardized to be AGi32.

After the contract is bid and awarded, the contractor prepares all drawings in a shop-drawing submittal package and sends them to Central Office Electrical Unit and districts for approval. It is noted that the contractor provides in this package a list of all materials, including luminaires and all hardware to be used in the project. The contractor is notified if items not approved—for example, if the luminaires are not expected to meet the minimum design luminance and illuminance levels—and the process continues until all items pass the requirements. This terminates the design, awarding, and review process and the final selection of luminaires.

The first interview in this study was conducted at the IDOT Central Office in Springfield, with the participation of Mark Seppelt, IDOT Electrical Unit Chief; and IDOT consultant Vilmantas Gurskas. A questionnaire related to development of a lighting project and other related topics was provided during the interview to the participants. The questionnaire can be found in a separate document that accompanies this summary.

After the process in Chapter 56 was described, the research team inquired about any differences with actual practices in the development of a lighting project. The participants stated that the current practice procedures do follow Chapter 56 in its current form and that changes for projects involving LED luminaires compared to current ones using HPS would be required primarily in the design stages. Current design is based on performance of at least three different products that are representative of the market for a specific type of luminaire (e.g., HPS), and the generation of minimum requirements is done such that all three products meet them. For LEDs, a similar number of products will have to be used to determine the required pole location, spacing, and height.

It was also mentioned that, in general, the current procedure for selecting and acquiring luminaires for a new project is flexible enough not only to accommodate current HPS-based luminaires but also newer models using LEDs.

Other topics were also discussed as part of the interviews. Related to maintenance and luminaire replacement, it was noted that the current IDOT re-lamping policy was to replace luminaires one at a time after a failure is reported, instead of a pre-scheduled systemwide re-lamping. It was mentioned that keeping track of failure rates and performance of specific products could be beneficial for future contracts and will allow for the development of a rating scale for each product used in the past that is exclusively based on performance. However, such a database is not currently maintained.

Field data verification was also said to have potential benefits to determine differences between expected design performance and field measurements. In addition, data on actual dirt depreciation factors from luminaires being replaced could provide valuable data to improve design policies.

Even though the initiatives described above could result in improved future designs, they may require significant efforts to be implemented and establishing new procedures for their continuous execution.

A second interview was conducted in District 4 offices in Peoria with the participation of Randy Laninga and Eric Howald, IDOT engineers. The same questionnaire presented to participants from the Central Office Electrical Unit was also discussed in this interview to determine whether the development of a lighting project was done precisely according to the procedure in Chapter 56 of the DBE manual.

The interviewees explained that typical lighting projects involving the installation of new luminaires and poles are sent to the Central Office Electrical Unit, as stated in the manual, and that very small luminaire jobs are done in-house. These mainly include single luminaires at intersections, which normally use combination poles (holding luminaires and traffic signals).

In addition, the re-lamping process was described as being similar to how it is done in the Central Office Electrical Unit. Thus, luminaires that have failed are replaced upon notification to the district, and this service is contracted out to a private company in the area. It was also noted that all luminaires in the district currently use HPS lamps.

A suggestion proposed by the participants to improve the current process was to establish pre-approved drawings for poles at typical locations, since the revisions and the back-and-forth dynamic between IDOT and contractors can be very time consuming for simple installations. In addition, the current re-lamping policy is in question, given the high cost of labor and because in some cases these costs are incurred for a single or only a few HPS lamps when a crew is called out.

A summary of the interviews with personnel at IDOT's Central Office Electrical Unit and District 4 (mentioned above) was sent to Districts 1 and 8 to determine potential differences in the procedures. District 1 provided the research team with a copy of the document "District 1 – General Guidelines for Lighting Design," dated November 2011, where, among general requirements for submittals, design, plans, etc., detailed descriptions are included of the requirements of specific projects (e.g., beacon lighting, ornamental lighting, and landscape and flood lighting).

In the section "General Requirements for the State-Owned and Maintained System," a step-by-step procedure is described for completing the design. The steps include a meeting with the Bureau of Traffic Operations Electrical Design Section, to establish the scope and goals of the project, followed by a review of the contractor's proposed design by the same office (different submittal stages are detailed). Then, contact with the electric utility is required, as well as a field inspection. Plans and calculations of photometric performance, following District 1 standards, are required to be submitted. Final delivery includes a comprehensive set of documentation, following specific rules for the submission. It is noted that this procedure is similar to that used by the Central Office in Springfield.

Additionally, electronic communications were exchanged with Districts 1 and 8 regarding their interest in and current use of LED luminaires. Mark Jenkins from District 1 mentioned that the current IDOT procedure is flexible enough and would allow the purchase and installation of LED luminaires if the district is interested on them. This is similar to the opinion received from the Central Office Electrical Unit. District 8, through Michael Preston, mentioned that Chapter 56 of the BDE manual currently states that LED lights have become a popular light source due to their long life and low electric energy usage, but they have not yet become effective for most roadway applications. Based on this, Mr. Preston stated that further comments regarding the use of LED lighting in the district will be withheld until effective LED lights are identified and they are requested with drafts of Chapter 56 of the DBE manual. Similarly, District 8, through David Walker, said that at this point there is no interest in using LED luminaires for IDOT-maintained roads given that current products are more suitable for other applications such as decorative lighting.

CHAPTER 10 CONCLUSIONS AND RECOMMENDATIONS

This study examined the field performance of three LED roadway luminaires and compared them with that of a selected HPS roadway luminaire. The mounting height was 30 ft, luminaire spacing was 150 ft., and the pavement type was R3 at the test site. The luminaires lit two lanes, each 11 ft. wide. The roadway classification of the test site was assumed as major road with medium pedestrian conflict (major/medium). Two sets of illuminance and luminance data were collected for each type of roadway luminaire. The field data were then compared with the Agi32 results to check how well the software results matched the field data for each type of roadway luminaire. Moreover, both the field data and software results were compared with the IDOT lighting design criteria for major roads with medium pedestrian conflict.

In general, there were significant discrepancies between field measurements and results from AGi32, and some of the IDOT criteria were not met, depending on the luminaire. The performance of the tested luminaires varied significantly among each other. This suggests that a case-by-case analysis is necessary to determine the suitability of a specific luminaire for any given installation, and generalizations about the performance of the luminaires based on their technical specifications are not straightforward. For each LED luminaire, adjustment factors were proposed to estimate the field luminance and illuminance values based on the software-computed values.

Luminance field measurements were conducted using a meter that had an acceptance angle greater than that specified by LM-50-99; thus, software and field results are not directly comparable because the measured area for each luminance reading is different. This device does not have the acceptance angle to provide point-by-point readings using the grid from LM-50-99. Therefore, individual values for each point are not comparable, but measurements for average luminance were accurate and are emphasized over maximum and minimum values.

The following sections summarize the results for each tested roadway luminaire in terms of the field measurements and software results, and also compared to the IDOT lighting design criteria.

10.1 HPS

- There was close agreement between the field measured illuminance data and Agi32 software results, except at the grid points in the immediate vicinity of the light poles. At those points, the field data returned considerably higher illuminance levels than the software results. Thus, the field data for the HPS did not satisfy the IDOT illuminance uniformity criterion (i.e., average/minimum) for the roadway classification major/medium; however, the Agi32 software results satisfied all illuminance design criteria for the roadway classification major/medium.
- The field data show that the HPS luminaires satisfied the average luminance design criterion for major roads.
- Software results for the HPS luminaires satisfied all luminance design criteria at the study site for major roads.

10.2 LED#1

- In the illuminance results, there was very close agreement between the field data and AGi32 results.
- According to both the field data and software results, LED#1 did not satisfy the average illuminance criterion at the study site for the roadway classification major/medium.

- The field data show that LED#1 satisfied the average luminance design criterion for major roads except in fixture cycles 1 and 3, where it did not meet the average maintained luminance value the for roadway classification major/high.
- According to the software results, LED#1 met all luminance design criteria for major/medium and major/low. However, it did not meet the average maintained luminance criterion for the roadway classification major/high.

10.3 LED#2

- In the illuminance results, there were significant discrepancies between the field data and Agi32 results at the grid points in the immediate vicinity of the light poles. At those points, the software results returned considerably higher illuminance levels than the field data.
- Both the field data and software results for LED#2 satisfied all illuminance design criteria at the study site for major roads with medium pedestrian conflict.
- The field luminance data for LED#2 show that it satisfied the average maintained luminance criterion at the test site for major roads. The software luminance results for LED#2 did not satisfy one of the uniformity criteria (i.e., maximum/minimum).

10.4 LED#3

- In the illuminance results, there were considerable discrepancies between the field data and AGi32 results. At all grid points, the software results returned considerably higher illuminance levels than the field data.
- Both the field data and software results for LED#3 satisfied all illuminance design criteria at the study site for major roads with medium pedestrian conflict.
- The field luminance data for LED#3 satisfied the average maintained luminance design criterion at the test site for major roads.
- The software luminance results for LED#3 did not satisfy one of the uniformity ratio criteria (i.e., maximum/minimum).

10.5 RECOMMENDATIONS

In light of the results, a second phase of this study is proposed. The second phase should involve various tasks such as determining appropriate light loss factors for LED roadway luminaires; providing the required information for new IDOT specifications; examining the suitability of other technologies such as ceramic metal halide, plasma, and induction; and performing detailed life-cycle cost analysis for the roadway luminaires.

Appendix K includes a preliminary list of some suggested items for new specifications. Some of the suggestions are formed based on current LED roadway lighting specifications of other institutions. In the proposed second phase of the study, further detailed information should be provided to build appropriate LED roadway specifications for IDOT. Moreover, a detailed economic analysis should provide accurate economic comparison of the selected roadway luminaires and should help better identify their suitability for roadway applications.

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APPENDIX A LED ROADWAY LUMINAIRE SURVEY

This Appendix includes the LED roadway luminaire survey and the complete list of the LED companies that the LED roadway luminaire survey was sent to. The survey questions are given in Table A-1. Table A-2 gives the complete list of the LED companies contacted for the LED roadway luminaire survey and also indicates whether the companies returned the survey or not.

Table A-1 LED Roadway Luminaire Survey

1. Company Name:
6. Please provide the following information for your commercially available LED roadway luminaires designed to be mounted at 30 ft. or above:
7. Are all the products listed above Energy Star qualified? (Yes or No):
8. Do you have a written binning policy for all the products listed above? (Yes or No):
9. If Yes to Question 4, please briefly describe the main criteria you consider in your binning policy:
10. Do you have a written end-of-life-policy for all the products listed above? (Yes or No):
11. What is the recommended lumen maintenance – as a percentage of the initial lumen – to determine the life of your products listed above?
    70% of the original lumen output (Yes or No):
    50% of the original lumen output (Yes or No):
    Other Criteria (Please describe):
12. Would the company make spare units available for purchase for the 5 years following the installation of your luminaires? (Yes or No):
13. Please indicate if the warranty covers the following items, and if yes, the number of years covered:
    a) Solid state lighting (SSL) components: (Yes or No):
    if yes, number of years covered:
    b) Heat management components: (Yes or No):
    if yes, number of years covered:
    c) Power supply components: (Yes or No):
    if yes, number of years covered:
    d) Housing components: (Yes or No):
    if yes, number of years covered:
    Other Additional information:
    number of years covered:
14. Please provide the names and contact information of up to 3 of your main costumers, whom we may contact for further information about their experience using your LED roadway luminaires:
15. Please list any factors you believe set your LED roadway luminaires apart from the rest of the market?
16. How interested is your company in loaning/donating 4 luminaires to be evaluated in this research project? (Please select from the options below)
    a) Very Interested
    b) Interested
    c) Somewhat interested
    d) Not interested
    e) Do not know at this point

Table A-1 *(cont'd)* LED Roadway Luminaire Survey

17. Please attach to this survey (or give the link for downloading) the IES LM-79-08 photometric report, if available, for each product listed in Question 2.
18. Please attach to this survey (or give the link for downloading) the brochure/technical data sheets, if available, of the products listed in Question 2.
19. Please provide your contact information:

Table A-2 List of the LED companies contacted for the LED roadway luminaire survey

Company Name	Returned the survey?
1. Act One Communications, Inc.	√
2. American Electric Lighting	
3. Archibald & Meek (Commercial Representative of Hadco Lighting)	√
4. Beacon Products (a division of Hubbell Lighting, Inc.)	√
5. Beta LED	
6. Borealis Lighting	
7. Bright Energy Group	
8. Brown Traffic Products, Inc. by Dialight Street Lights	√
9. Carmanah	
10. Clean Light Green Light Solid State Lighting Solutions	√
11. Cooper Lighting Products	√
12. Crescent – Stonco	
13. CSS-LED	
14. Digital Light	
15. Downey + Rippe LED & Induction Lighting Systems	√
16. Echelon Corporation	
17. EdisonLED Products by Fiberdyne Energy	
18. ElectraLED, Inc.	
19. ESCO Lighting, Inc.	√
20. EvoLucia Next Generation LED Lighting (Same as Sunovia Energy Technologies, Inc.)	
21. GE Lumination	
22. General LED	
23. Go Green Lighting LED	
24. Guth Lighting by Philips	√
25. Guth Lighting by Philips – Illinois Representative	
26. Howard Lighting	
27. IQLED	
28. Keyseen LED Lighting Technology Co. Ltd.	
29. LED Roadway Lighting Ltd.	√
30. LED Waves	
31. LEDAlux	
32. LEDLight	
33. Ledtronics, Inc.	

Table A-2 *(cont'd)* List of the LED companies contacted for the LED roadway luminaire survey

Company Name	Returned the Survey?
34. Leotek	√
35. Lighting Science Group Corp.	
36. Lumecon	
37. Lumex	
38. Lumileds by Philips Lighting Company	
39. Lumitrak	√
40. Midwest Circuits	
41. NEPTUN Light, Inc.	√
42. Nexxus Lighting (Formerly Advanced Lighting Systems)	
43. Niland Company	
44. North Star Lighting	
45. Rabbit LED Lighting Technology	
46. Relume Technologies	
47. Safeco Ind.	
48. Schreder Lighting	
49. Spring City Electrical Manufacturing Co. Inc.	√
50. Sternberg Lighting	
51. Temple, Inc.	
52. Tersen Lighting	
53. The Will Group- Lighting Solutions of Illinois	
54. Unilumin Group Co., Ltd.	
55. Universal Electronic Solutions (Same as Uniray)	
56. USA LED Solutions (formerly Golden Ocean Electronics)	√
57. Visionaire Lighting	

Selected roadway luminaires:

- HPS: M-400 by GE,
- LED#1: Evolve/ 454239 by GE,
- LED#2: Vue/ 320-HE by Relume Technologies,
- LED#3: Ventus/ VSTA08 by Cooper Lighting, Inc.

APPENDIX B CLOSE-UP PHOTOS OF THE PAVEMENT SURFACE

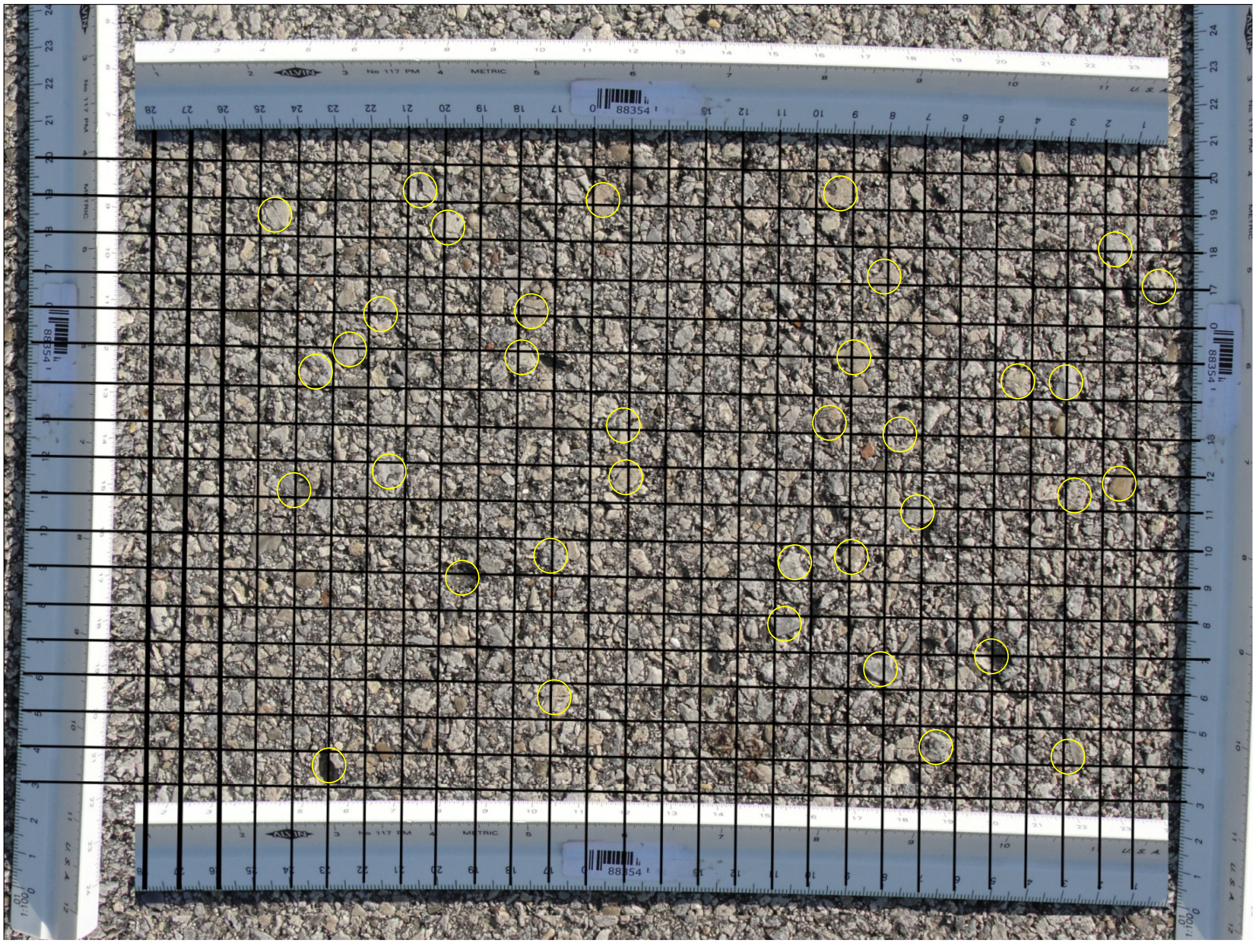


Figure B-1 Close-up photo of the pavement surface from span 1 at the study site

- Grid area = 27 x 17 = 459 in^2
- Aggregate size greater than 1" in the observed plane = 36
- Aggregate size greater than 1" = 36 * 3 = 108 (assuming the same distribution on other axes)
- Estimated percentage of aggregate size greater than 1" = 108/ 459 = 24%

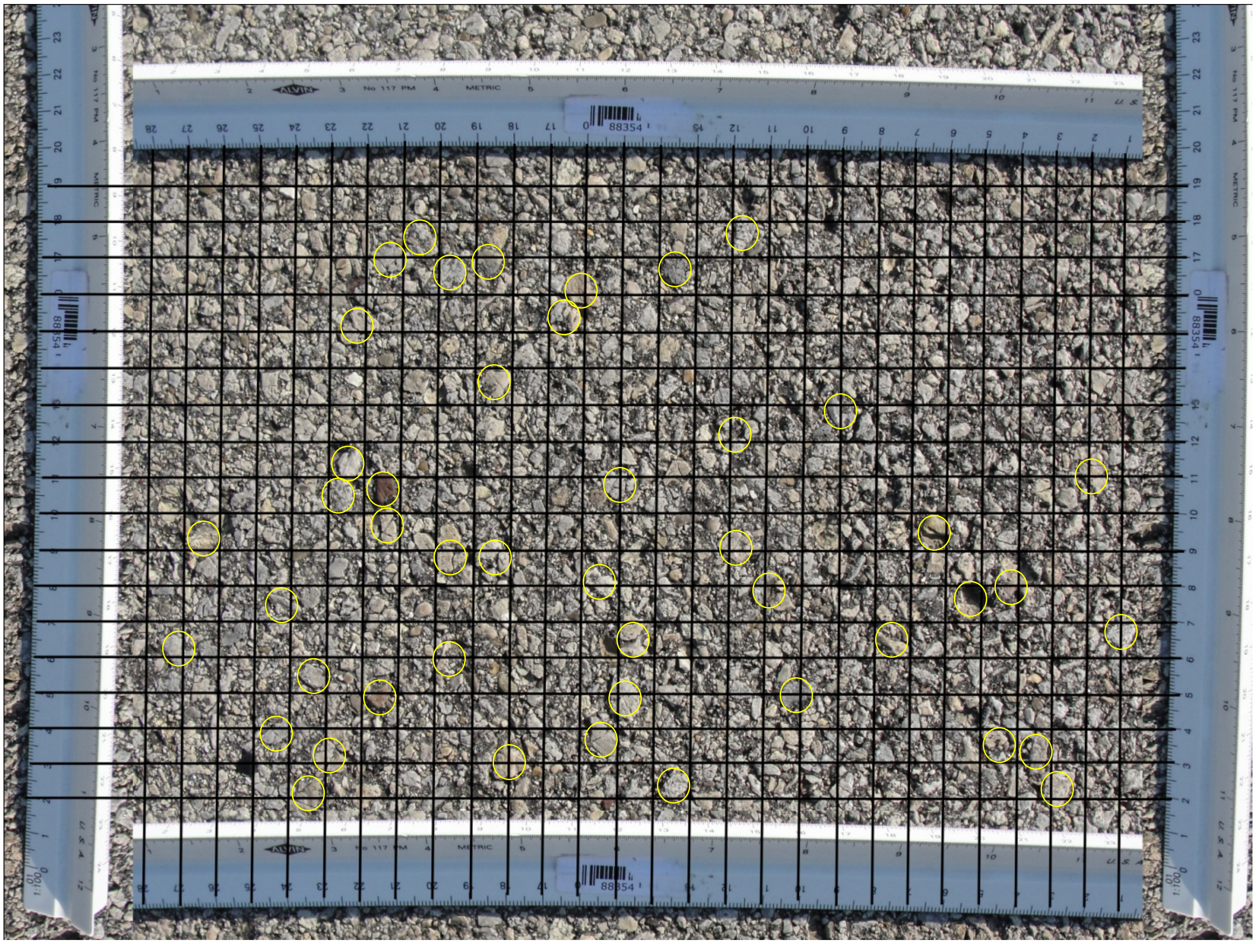


Figure B-2 Close-up photo of the pavement surface from span 2 at the study site

- Grid area = 27 x 17 = 459 in^2
- Aggregate size greater than 1” in the observed plane = 46
- Aggregate size greater than 1” = 46 * 3 = 138 *(assuming the same distribution on other axes)*
- Estimated percentage of aggregate size greater than 1” = 138/ 459 = 30%

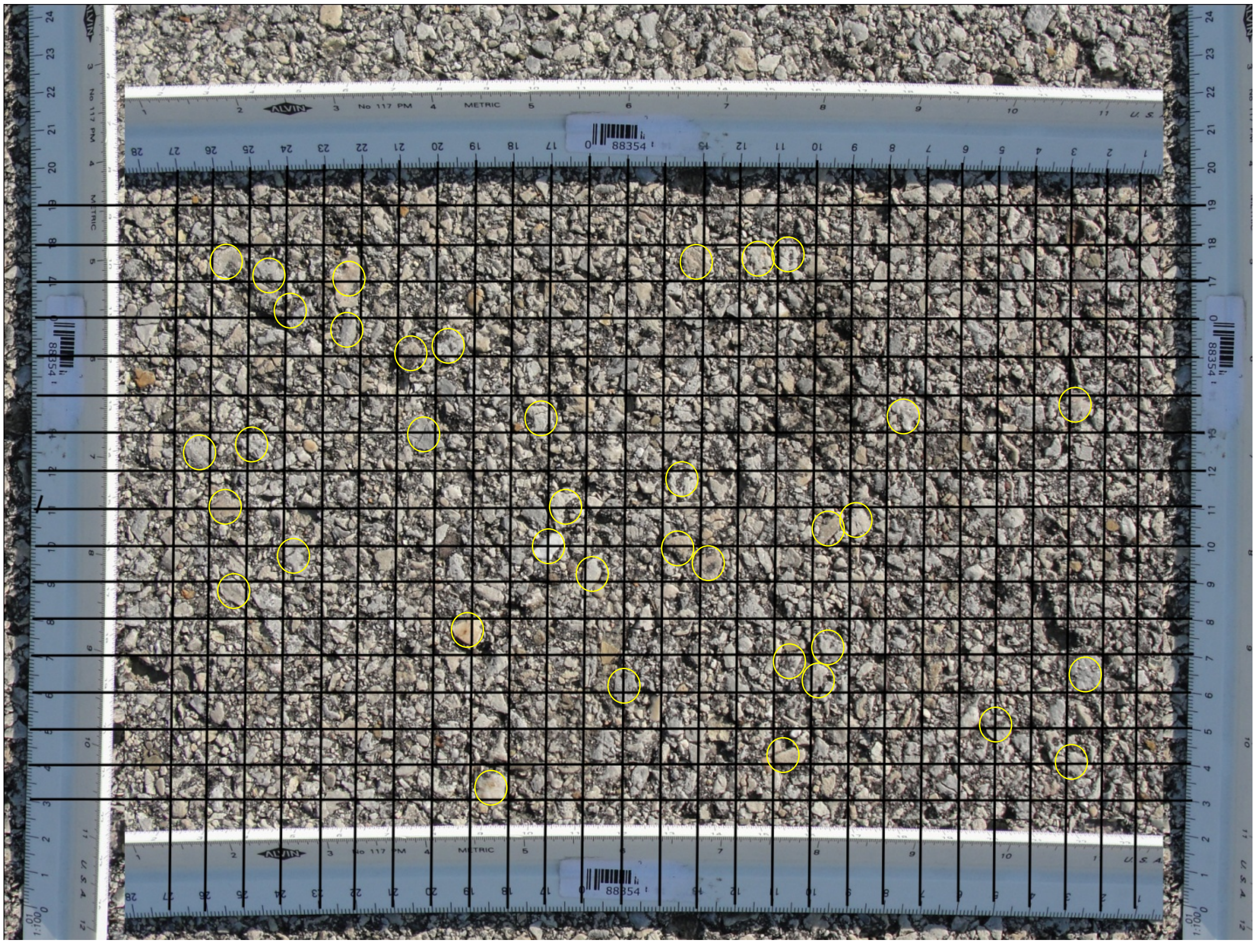


Figure B-3 Close-up photo of the pavement surface from span 3 at the study site

- Grid area = 26 x 16 = 416 in^2
- Aggregate size greater than 1" in the observed plane = 37
- Aggregate size greater than 1" = 37 * 3 = 111 *(assuming the same distribution on other axes)*
- Estimated percentage of aggregate size greater than 1" = 111/ 416 = 27%

APPENDIX C SOFTWARE COMPARISON OF ROADWAY CROSS-SECTIONS

This Appendix compares the estimated light levels (from the software) produced by the four types of luminaires on various roadway cross sections. In Section C.1, the light levels produced on roadways with different widths are estimated. Section C.2 presents the estimated light levels achieved by each type of luminaire at different mounting heights. Moreover, Section C.3 investigates the limitations of the selected luminaires in satisfying the IDOT lighting design requirements for major road, high pedestrian conflict.

The results presented in this chapter were found using the AGi32 software, and no field data is used. For a given roadway cross section and mounting height, the average illuminance and average luminance produced by each luminaire were estimated using the AGi32 software. Both the average illuminance and average luminance were estimated in accordance with the IESNA LM-50-99, Guide for Photometric Measurement of Roadway Lighting Installations. Then the average illuminance and luminance levels produced by each type of luminaire were compared with the corresponding IDOT lighting design criteria for major roads. Table C-1 gives the IDOT lighting design requirements regarding the average illuminance and luminance levels for major roads.

It should be noted that there are other IDOT lighting design requirements such as uniformity ratio and maximum veiling luminance ratio, which are not considered in this chapter. Hence, consideration of the average illuminance and luminance levels alone may not adequately estimate the overall performance of the selected roadway luminaires on various road cross sections. A more comprehensive approach would be to compute the largest pole spacing at which a particular luminaire satisfies all the IDOT lighting design requirements for a given roadway cross section, roadway type and mounting height. This approach is planned to be included in a future phase of the study.

Table C-1 IDOT lighting design requirements regarding average illuminance and luminance levels for major roads (IDOT, 2010)

Road type	Pedestrian conflict area	Min. required average illuminance (ft-cd)	Min. required average luminance (cd/m^2)
Major	High	1.7	1.2
	Medium	1.3	0.9
	Low	0.9	0.6

C.1 RESTRICTIONS ON ROADWAY WIDTH

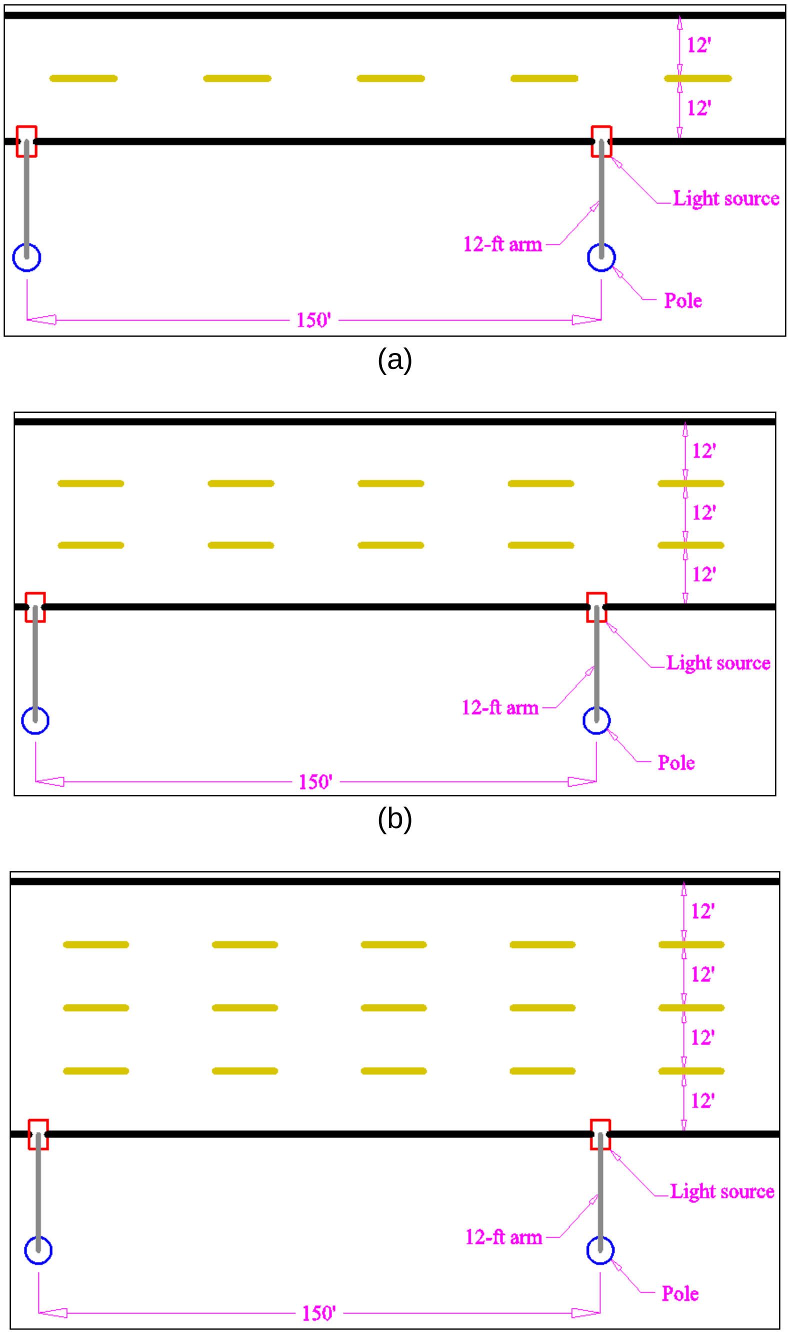
The purpose of this section is to determine the roadway widths where the estimated average illuminance and luminance levels produced by the selected luminaires may be adequate. Three types of roadway cross section are considered in this section:

1. Two lanes per direction with 12-ft lane width;
2. Three lanes per direction with 12-ft lane width;
3. Four lanes per direction with 12-ft lane width.

The roadway cross sections were defined in AGi32 software. For each roadway cross section, the light poles were assumed to have a 12-ft setback from the outer edge of the rightmost lane. The arm length was assumed to be 12 ft so that the center of the light sources projected onto the outer edge of the rightmost lane. Figure C-1 illustrates detailed layout of the three roadway cross sections. The mounting height was taken as 30 ft, which is generally the minimum mounting height for IDOT lighting applications (IDOT, 2010). The minimum mounting height was selected for AGi32 software analysis because the average illuminance and luminance levels decrease with increasing mounting height. Moreover, the pole spacing was set at 150 ft, which was the same as at the test site. After the roadway cross sections were defined in AGi32 software, the average illuminance and luminance levels produced by each luminaire were computed for each roadway cross section.

The average illuminance results obtained from the AGi32 software are shown in Figure C-2. According to the results shown in Figure C-2:

- For all three roadway cross sections, the software models for the HPS and LED#3 satisfied the average illuminance requirement for major road with low or medium pedestrian conflict.
- For the roadway cross sections with two and three lanes per direction, the software model for LED#2 satisfied the average illuminance requirement for major road with low or medium pedestrian conflict. For the roadway cross section with four lanes per direction, the software model for LED#2 satisfied the average illuminance requirement for major road with only low pedestrian conflict.
- For the road cross sections with two and three lanes per direction, the software model for LED#1 satisfied the average illuminance requirement for major road with only low pedestrian conflict. For the roadway cross section with four lanes per direction, the software model for LED#1 did not satisfy the average illuminance requirement for any pedestrian conflict level.



(a)

(b)

(c)

Figure C-1 Assumed roadway and luminaire layouts (for single direction) for AGi32 analysis of the lighting restrictions on roadway width: (a) Two lanes per direction, (b) three lanes per direction, (c) four lanes per direction.

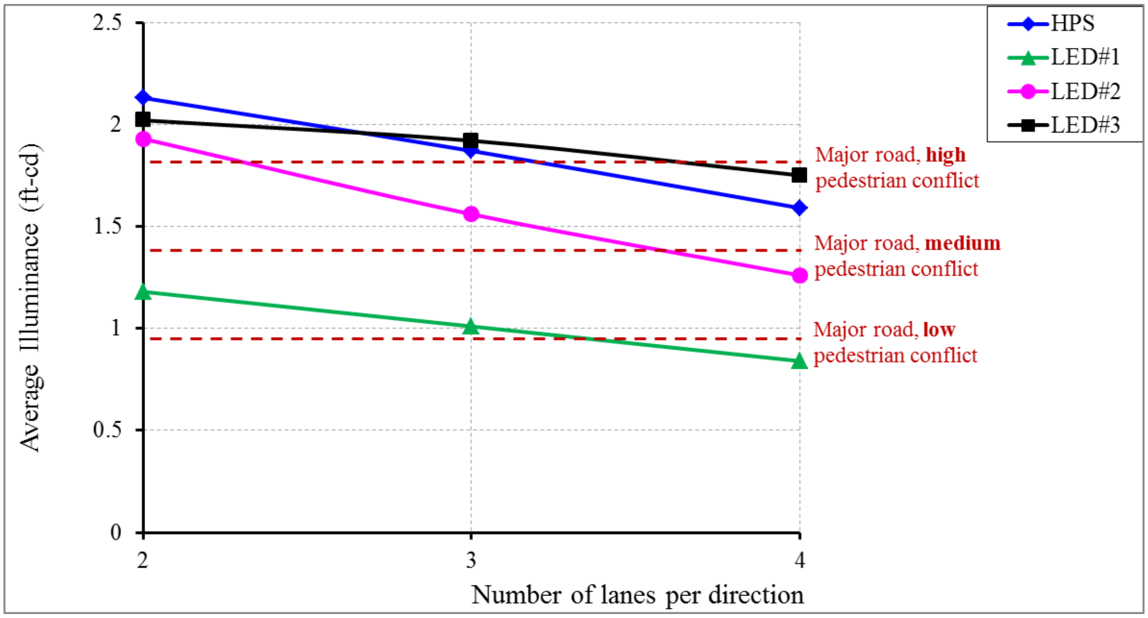


Figure C-2 Average illuminance vs. the number of lanes lit for 150-ft luminaire spacing, 30-ft mounting height, and 12-ft lane width

Next, the software results for average luminance levels are shown in Figure C-3. According to Figure C-3:

- For all three roadway cross sections, the software models for LED#2 and LED#3 satisfied the average luminance requirement for major roads with low, medium or high pedestrian conflict.
- For the roadway cross sections with two and three lanes per direction, the software model for the HPS satisfied the average luminance requirement for major road with low or medium pedestrian conflict. For the road cross section with four lanes per direction, the software model for the HPS satisfied the average luminance requirement for major road with only low pedestrian conflict.
- For the roadway cross section with two lanes per direction, the software model for LED#1 satisfied the average luminance requirement for major road with low or medium pedestrian conflict. For the roadway cross sections with three and four lanes per direction, the software model for LED#1 satisfied the average luminance requirement for major road with only low pedestrian conflict.

Based on the results shown in Figure C-2 and Figure C-3, the satisfaction of the IDOT average illuminance and luminance criteria is summarized in Table C-2. According to Table C-2, it would be appropriate to test the LED luminaires on a roadway with either two lanes or three lanes per direction. If the number of lanes per direction is greater than three, LED#1 may not achieve the required illuminance and luminance levels for major roads with any level of pedestrian conflict.

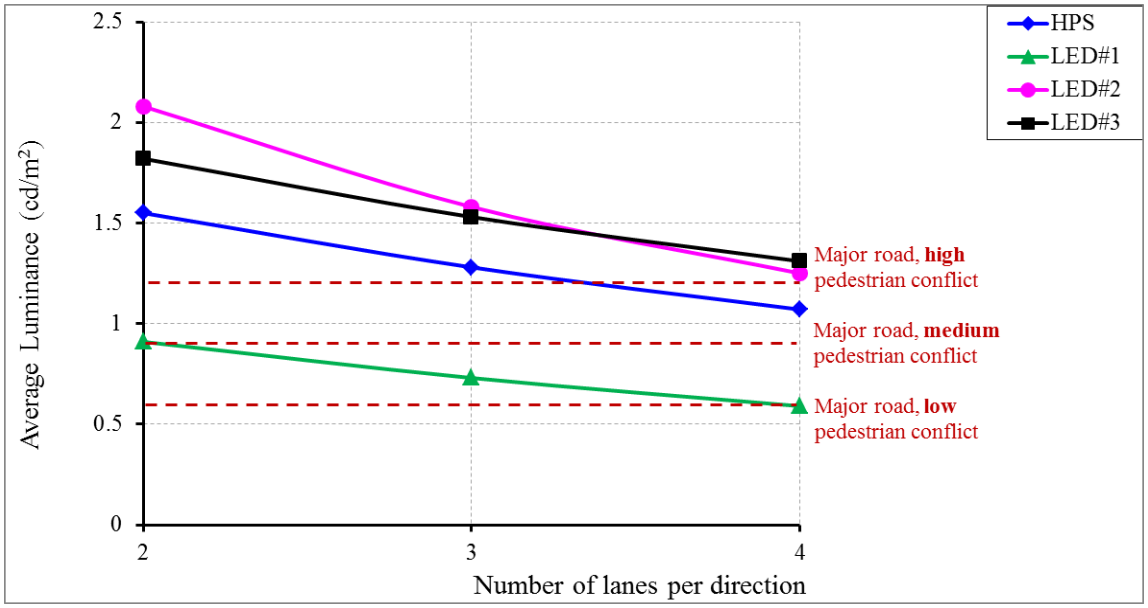


Figure C-3 Average luminance vs. the number of lanes lit for 150-ft luminaire spacing, 30-ft mounting height, and 12-ft lane width

Table C-2 Number of lanes per direction the selected luminaires satisfies the IDOT average illuminance and luminance criteria at 150-ft luminaire spacing, 30-ft mounting height, and 12-ft lane width with (a) medium pedestrian conflict, (b) low pedestrian conflict

(a)

	No. of lanes lit		
	2	3	4
HPS	√	√	√
LED#1			
LED#2	√	√	
LED#3	√	√	√

(b)

	No. of lanes lit		
	2	3	4
HPS	√	√	√
LED#1	√	√	
LED#2	√	√	√
LED#3	√	√	√

C.2 RESTRICTIONS ON MOUNTING HEIGHT

Mounting height is defined as the *"vertical distance between the roadway surface and the center of the light source in the luminaire"* (IDOT, 2010). The higher the mounting height is, the lower the average illuminance and luminance level is produced by roadway luminaires. The purpose of this section is to estimate the mounting heights for which the estimated average illuminance and luminance levels produced by the selected luminaires is adequate. AGi32 lighting software was used to determine those mounting heights.

Luminaire mounting heights generally range from 30 ft to 65 ft for conventional highway lighting applications (IDOT, 2010). Hence, mounting heights of 30, 35, 40, 45, 50, 55, 60 and 65 ft are considered. In the AGi32 software analysis, three roadway layouts as shown in Figure C-1 were defined. Then for each roadway layout, the average illuminance and luminance levels produced by each roadway luminaire were computed at the aforementioned mounting heights.

C.2.1 Major Roadway with Two Lanes

Figure C-4 illustrates the AGi32 results for average illuminance levels produced by the selected luminaires at various mounting heights on a road with two lanes per direction. The roadway layout and the location of the luminaires are the same as shown in Figure C-1a. According to the results illustrated in Figure C-4:

- At a mounting height of 30 ft, the software models for both LED#2 and LED#3 satisfied the average illuminance requirement for major roads with all three levels of pedestrian conflict. At the mounting heights of 35, 40, and 45 ft, their software models satisfied the average illuminance requirement for major road with low or medium pedestrian conflict. At the other mounting heights, their software models satisfied the average illuminance requirement for major road with only low pedestrian conflict.
- At all considered mounting heights, the software model for the HPS produced the highest illuminance levels compared to the other selected luminaires. At the mounting heights of 30 and 35 ft, its software model satisfied the average illuminance requirement for major road with all three levels of pedestrian conflict. At the mounting heights of 40 and 45 ft, its software model satisfied the average illuminance requirement for major road with low or medium pedestrian conflict. At the other mounting heights, its software model satisfied the average illuminance requirement for major road with only low pedestrian conflict.
- On the other hand, the estimated average illuminance levels produced by LED#1 are lower than those produced by the other three luminaires. At the mounting heights of 30 and 35 ft, the software model for LED#1 satisfied the average illuminance requirement for major road with only low pedestrian conflict. At the other mounting heights, the AGi32 model for LED#1 did not satisfy the average illuminance requirement for major roadways with any level of pedestrian conflict.

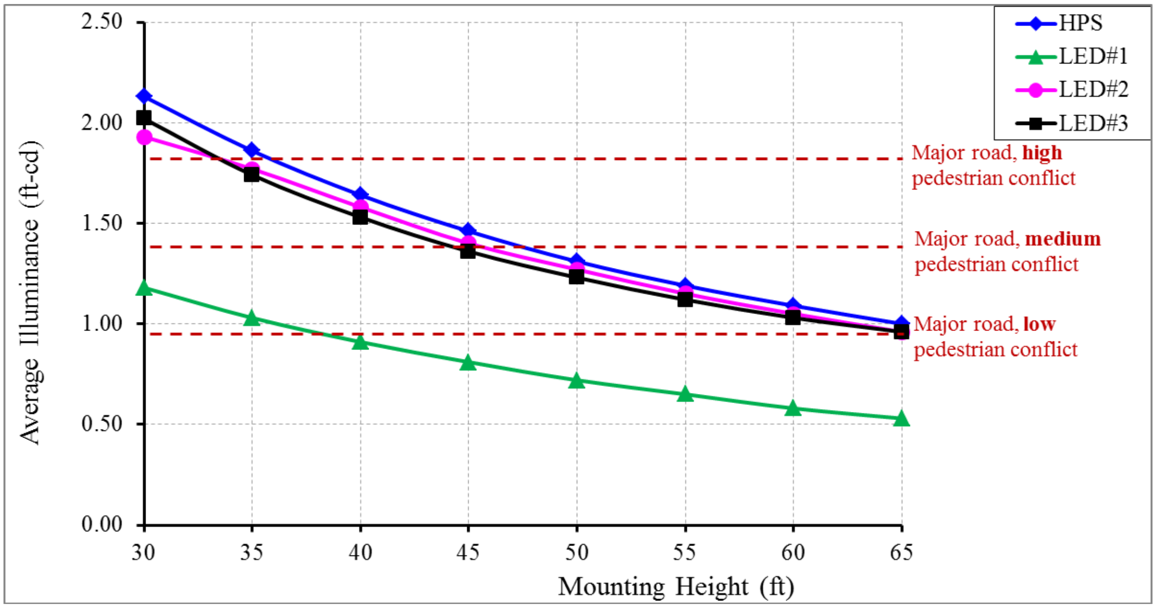


Figure C-4 Average illuminance vs. mounting height for 150-ft luminaire spacing, two lanes, and 12-ft lane width

Furthermore, Figure C-5 illustrates the AGi32 results for average luminance levels produced by the selected luminaires at various mounting heights on a road with two lanes which has the same layout as illustrated in Figure C-1a. According to the results shown in Figure C-5:

- At all considered mounting heights, the software model for LED#2 produced the highest average luminance levels compared to the other selected roadway luminaires. At all considered mounting heights, the software model for LED#2 satisfied the average luminance requirement for major road with all three levels of pedestrian conflict.
- Up to a mounting height of 55 ft, the software model for LED#3 satisfied the average luminance requirement for major road with all three levels of pedestrian conflict. At the mounting heights of 60 and 65 ft, it satisfied the average luminance requirement for major road with low or medium pedestrian conflict.
- At the mounting heights of 30, 35, and 40 ft, the software model for the HPS satisfied the average luminance requirement for major road with all three levels of pedestrian conflict. At the mounting heights from 45 to 60 ft, it satisfied the average luminance requirement for major road with low or medium pedestrian conflict. At the mounting height of 65 ft, it satisfied the average luminance requirement for major road with only low pedestrian conflict.
- The software model for LED#1 produced the lowest average luminance levels at all mounting heights. At the mounting height of 30 ft, it satisfied the average luminance requirement for major road with low or medium pedestrian conflict. At the mounting heights from 35 to 55 ft, it satisfied the average luminance requirement for major road with only low pedestrian conflict.

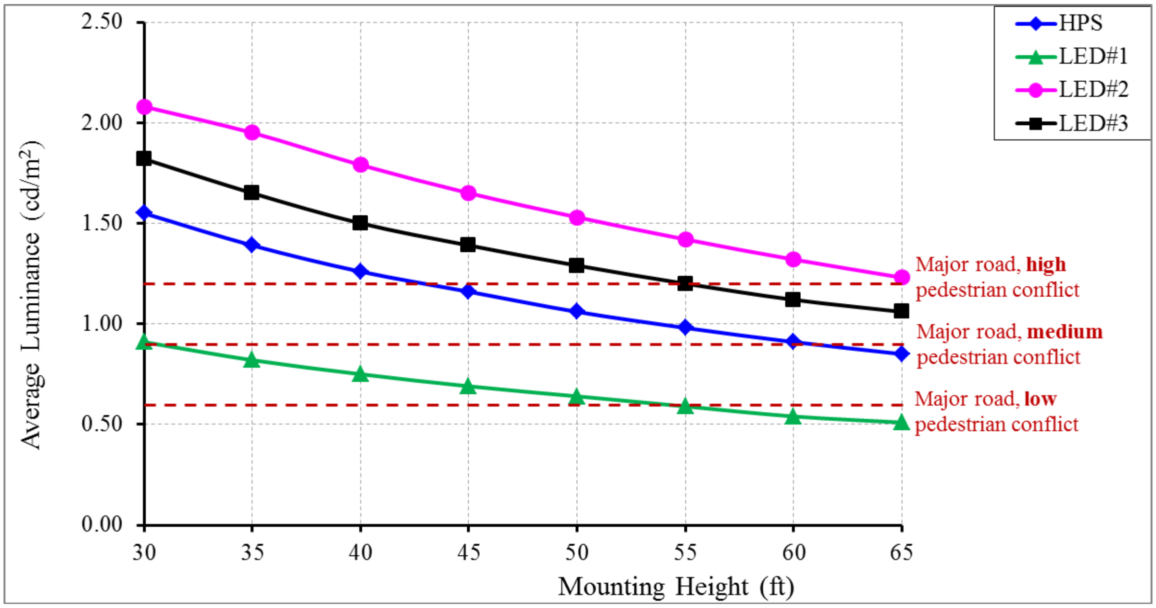


Figure C-5 Average luminance vs. mounting height for 150-ft luminaire spacing, two lanes, and 12-ft lane width

Based on the results given in Figure C-4 and Figure C-5, the satisfaction of the IDOT average illuminance and luminance criteria are summarized with respect to mounting height in Table C-3. Table C-3a shows at what mounting heights the AGi32 models of the selected luminaires satisfy the IDOT average illuminance and luminance criteria for a two-lane, 24-ft wide major road with medium pedestrian conflict. Likewise, Table C-3b shows at what mounting heights the AGi32 models of the selected luminaires satisfy the IDOT average illuminance and luminance criteria for a two-lane, 24-ft wide major road with low pedestrian conflict. According to Table C-3a, when the mounting height is equal to or greater than 50 ft, none of the computer models of the selected luminaires satisfied the IDOT average illuminance and luminance criteria for a major roadway with two lanes per direction and medium pedestrian conflict. So it would be appropriate to use a mounting height lower than 50 ft for field-testing since the study site includes a major roadway with two lanes per direction and medium pedestrian conflict.

Table C-3 Mounting heights of the selected luminaires that satisfy the IDOT average illuminance and luminance criteria for two-lane, 24-ft wide major roads with (a) medium pedestrian conflict, (b) low pedestrian conflict

(a)

	Mounting Height (ft)*							
	30	35	40	45	50	55	60	65
HPS	√	√	√	√				
LED#1								
LED#2	√	√	√	√				
LED#3	√	√	√					

(b)

	Mounting Height (ft)*							
	30	35	40	45	50	55	60	65
HPS	√	√	√	√	√	√	√	√
LED#1	√	√						
LED#2	√	√	√	√	√	√	√	√
LED#3	√	√	√	√	√	√	√	√

**:Pole spacing= 150 ft.*

C.2.2 Major Roadway with Three Lanes

Figure C-6 shows the AGi32 results for average illuminance levels produced by the selected luminaires at various mounting heights on a road with three lanes as illustrated in Figure C-1b. According to the results illustrated in Figure C-6:

- At a mounting height of 30 ft, the software models for LED#3 and the HPS satisfied the average illuminance requirement for major road with all three levels of pedestrian conflict. At the mounting heights of 35 and 40 ft, the software models for LED#3 and the HPS satisfied the average illuminance requirement for major road with low or medium pedestrian conflict. At the other mounting heights, they both satisfied the average illuminance requirement for major road with only low pedestrian conflict.
- At the mounting heights of 30, 35, and 40 ft, the software model for LED#2 satisfied the average illuminance requirement for major road with low or medium pedestrian conflict,. At the other mounting heights, it satisfied the average illuminance requirement for major road with only low pedestrian conflict.
- On the other hand, the estimated average illuminance levels produced by LED#1 are lower than those produced by the other three luminaires. At the mounting heights of 30 and 35 ft, the software model for LED#1 satisfied the average illuminance requirement for major road with only low pedestrian conflict.

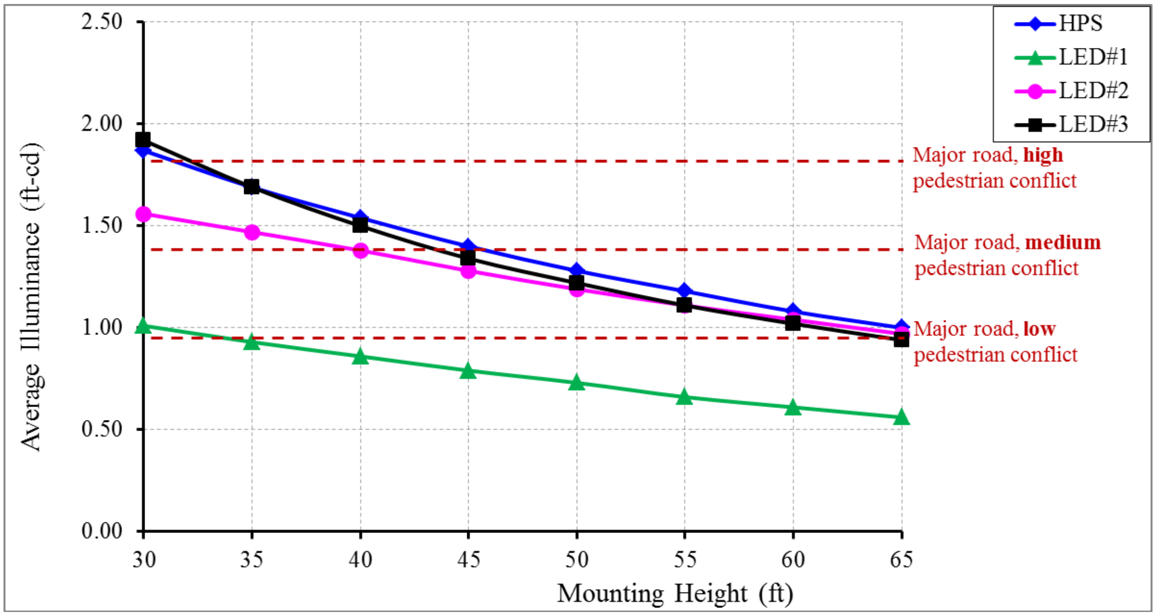


Figure C-6 Average illuminance vs. mounting height for 150-ft luminaire spacing, three lanes, and 12-ft lane width

Next, Figure C-7 illustrates the AGi32 results for average luminance levels produced by the selected luminaires at various mounting heights on a road with three lanes per direction. According to the results shown in Figure C-7:

- The software model for LED#2 produced the highest luminance levels at all mounting heights. At the all mounting heights but 65 ft, it satisfied the average luminance requirement for major road with all three levels of pedestrian conflict.
- At the mounting heights less than or equal to 45 ft, the software model for LED#3 satisfied the average luminance requirement for major road with all three levels of pedestrian conflict. At the mounting heights of 60 and 65 ft, the software model for LED#3 satisfied the average illuminance requirement for major road with low or medium pedestrian conflict.
- At the mounting height of 30 ft, the software model for the HPS satisfied the average luminance requirement for major road with all three levels of pedestrian conflict. At the mounting heights from 35 to 55 ft, the software model for the HPS satisfied the average luminance requirement for major road with low or medium pedestrian conflict. At the other mounting heights, it satisfied the average luminance requirement for major road with only low pedestrian conflict.
- At the mounting heights of less than or equal to 45 ft, the software model for LED#1 satisfied the average luminance requirement for major road with only low pedestrian conflict.

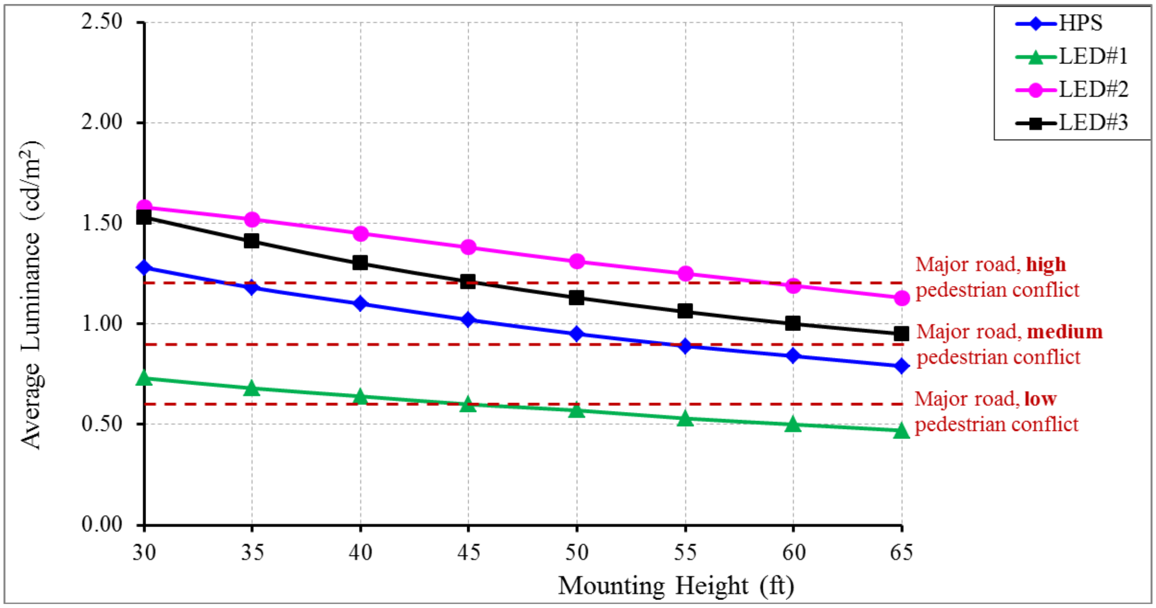


Figure C-7 Average luminance vs. mounting height for 150-ft luminaire spacing, three lanes, and 12-ft lane width

Based on the results given in Figure C-6 and Figure C-7, the satisfaction of the IDOT average illuminance and luminance criteria for major roads are summarized in Table C-4. Table C-4a shows at what mounting heights the AGi32 models of the selected luminaires satisfy the IDOT average illuminance and luminance criteria for a two-lane, 24-ft wide major road with medium pedestrian conflict. Likewise, Table C-4b shows at what mounting heights the AGi32 models of the selected luminaires satisfy the IDOT average illuminance and luminance criteria for a three-lane, 36-ft wide major road with only pedestrian conflict. According to Table C-4a, when the mounting height is equal to or greater than 45 ft, none of computer models of the selected LEDs satisfied the IDOT average illuminance and luminance criteria for major roads with three lanes per direction and medium pedestrian conflict. Therefore, it would be appropriate to test the selected luminaires at mounting heights less than 45 ft if the luminaires were to be tested on a major road with three lanes per direction and medium pedestrian conflict.

Table C-4 Mounting heights of the selected luminaires that satisfy the IDOT average illuminance and luminance criteria for three-lane, 36-ft wide major roads with (a) medium pedestrian conflict, (b) low pedestrian conflict

(a)

	Mounting Height (ft)*							
	30	35	40	45	50	55	60	65
HPS	√	√	√	√				
LED#1								
LED#2	√	√	√					
LED#3	√	√	√					

(b)

	Mounting Height (ft)*							
	30	35	40	45	50	55	60	65
HPS	√	√	√	√	√	√	√	√
LED#1	√							
LED#2	√	√	√	√	√	√	√	√
LED#3	√	√	√	√	√	√	√	√

**:Pole spacing= 150 ft.*

C.2.3 Major Roadway with Four Lanes

Figure C-8 illustrates the AGi32 results for average illuminance levels produced by the selected luminaires at various mounting heights on a road with four lanes as illustrated in Figure C-1c. According to the results shown in Figure C-8:

- At the mounting heights of 30, 35, and 40 ft, the software models for the HPS and LED#3 satisfied the average illuminance requirement for major road with low or medium pedestrian conflict. At the other mounting heights, their software models satisfied the average illuminance requirement for major road with only low pedestrian conflict.
- At all the mounting heights but 65 ft, the software model for LED#2 satisfied the average illuminance requirement for major road with only low pedestrian conflict.
- At all the mounting heights, the software model for LED#1 did not satisfy the average illuminance requirement for major road with any level of pedestrian conflict.

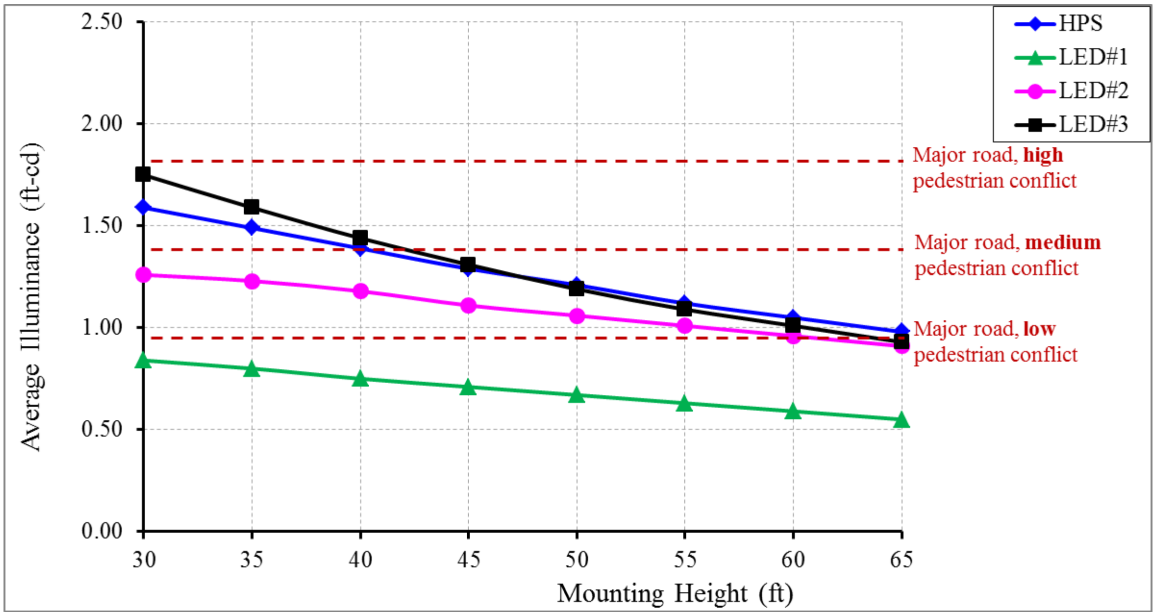


Figure C-8 Average illuminance vs. mounting height for 150-ft luminaire spacing, four lanes, and 12-ft lane width

Next, Figure C-9 illustrates the AGi32 results for average luminance levels produced by the selected luminaires at various mounting heights on a road with four lanes per direction. According to the results shown in Figure C-9:

- At the mounting heights of 30 and 35 ft, the software models for LED#2 and LED#3 satisfied the average luminance requirement for major road with all three levels of pedestrian conflict. At the other mounting heights, the software model for LED#3 satisfied the average luminance requirement for major road with low or medium pedestrian conflict. Moreover, at the other mounting heights but 65 ft., the software model for LED#2 satisfied the average luminance requirement for major road with low and medium pedestrian conflict.
- At the mounting height less than or equal to 45 ft, the software model for the HPS satisfied the average luminance requirement for major road with low or medium level of pedestrian conflict. At the other mounting heights, the software model for the HPS satisfied the average luminance requirement for major road with only low pedestrian conflict.
- At all the mounting heights, the software model for LED#1 did not satisfy the average luminance requirement for major road with any level of pedestrian conflict.

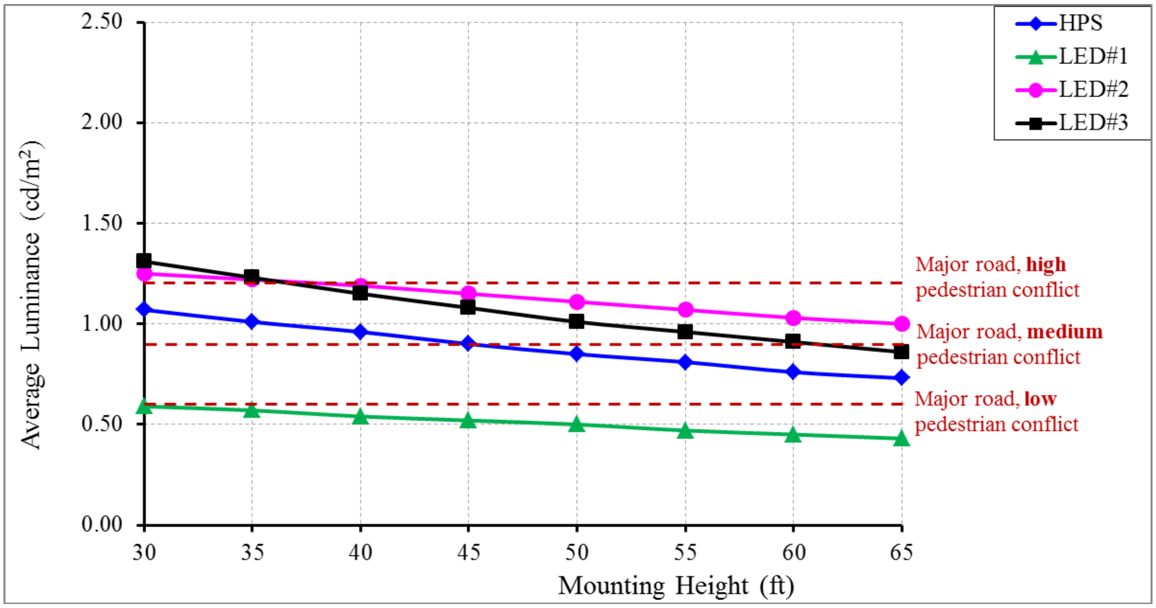


Figure C-9 Average luminance vs. mounting height for 150-ft luminaire spacing, four lanes, and 12-ft lane width

Based on the results given in Figure C-8 and Figure C-9, the satisfaction of the IDOT average illuminance and luminance criteria for major roads are summarized in Table C-5. Table C-5a shows at what mounting heights the AGi32 models of the selected luminaires satisfy the IDOT average illuminance and luminance criteria for a four-lane, 48-ft wide major road with medium pedestrian conflict. Likewise, Table C-5b shows at what mounting heights the AGi32 models of the selected luminaires satisfy the IDOT average illuminance and luminance criteria for a four-lane, 48-ft wide major road with low pedestrian conflict. According to Table C-5a, when the mounting height is greater than or equal to 45 ft, none of the computer models of the selected luminaires satisfied the IDOT average illuminance and luminance criteria for major roads with medium pedestrian conflict. Thus, it would be appropriate to test the selected luminaires at mounting heights less than 45 ft if the luminaires were to be tested on a major road with four lanes per direction and medium pedestrian conflict.

Table C-5 Mounting heights of the selected luminaires that satisfy the IDOT average illuminance and luminance criteria for four-lane, 48-ft wide major roads with (a) medium pedestrian conflict, (b) low pedestrian conflict

(a)

	Mounting Height (ft)*							
	30	35	40	45	50	55	60	65
HPS	√	√	√					
LED#1								
LED#2								
LED#3	√	√	√					

(b)

	Mounting Height (ft)*							
	30	35	40	45	50	55	60	65
HPS	√	√	√	√	√	√	√	√
LED#1								
LED#2	√	√	√	√	√	√	√	
LED#3	√	√	√	√	√	√	√	√

**:Pole spacing= 150 ft.*

C.3 LIMITATIONS ON HIGH PEDESTRIAN CONFLICT CLASSIFICATION

According to Table C-1, the minimum required average illuminance is 1.7 ft-cd for major roads with high pedestrian conflict. Likewise, the minimum required average luminance is 1.2 cd/m^2 for major roads with high pedestrian conflict. Based on the given IDOT design criteria, AGi32 software was run using different lane configurations to check whether the selected luminaires satisfy the IDOT average illuminance and luminance design criteria for major roads with high pedestrian conflict. There were three lane configurations used. For those three lane configurations, the roadway layout and the arrangement of the luminaires were the same as shown in Figure C-1. All AGi32 runs were made assuming a pole spacing of 150 ft and mounting height of 30 ft. The results of the AGi32 runs are summarized in Table C-6. The following are concluded from the results:

- Table C-6a shows that at a mounting height of 30 ft, the AGi32 models of the HPS, LED#2 and LED#3 were able to satisfy the abovementioned IDOT criteria for a two-lane, 24-ft wide major road with high pedestrian conflict. At a mounting height of 35 ft, only the HPS was able to satisfy the abovementioned IDOT criteria for a two-lane, 24-ft wide major road with high pedestrian conflict. For the other lighting design configurations, the abovementioned IDOT criteria were not satisfied for a two-lane, 24-ft wide major road.
- Table C-6b shows that at a mounting height of 30 ft, only the HPS and LED#3 were able to satisfy the abovementioned IDOT criteria for a three-lane, 36-ft wide major road with high pedestrian conflict. For the other lighting design configurations, the abovementioned IDOT criteria were not satisfied for a three-lane, 36-ft wide major road.
- Table C-6c shows that none of the lighting design configurations was able to satisfy the abovementioned IDOT criteria for a four-lane, 48-ft wide major road with high pedestrian conflict.
- The AGi32 results show that the use of the selected roadway luminaires would be rather limited for a major road with high pedestrian conflict.

Table C-6 Mounting heights of the selected luminaires that satisfy the IDOT average illuminance and luminance criteria for (a) two-lane, 24-ft wide major roads with high pedestrian conflict, (b) three-lane, 36-ft wide major roads with high pedestrian conflict, (c) four-lane, 48-ft wide major roads with high pedestrian conflict

(a)

	Mounting Height (ft)*							
	30	35	40	45	50	55	60	65
HPS	√	√						
LED#1								
LED#2	√							
LED#3	√							

(b)

	Mounting Height (ft)*							
	30	35	40	45	50	55	60	65
HPS	√							
LED#1								
LED#2								
LED#3	√							

(c)

	Mounting Height (ft)*							
	30	35	40	45	50	55	60	65
HPS								
LED#1								
LED#2								
LED#3								

**:Pole spacing= 150 ft.*

APPENDIX D ILLUMINANCE MEASUREMENTS

D.1 AVERAGE FIELD DATA

Table D-1 Average field illuminance data for the HPS

Point Number	FIELD DATA			
	NE LANE		SW LANE	
	Outer	Center	Center	Outer
1	5.66	5.68	5.43	4.48
2	3.01	3.16	3.15	2.79
3	1.50	1.54	1.75	1.84
4	0.87	0.93	1.00	1.05
5	0.73	0.76	0.76	0.76
6	0.66	0.72	0.71	0.75
7	0.77	0.81	0.81	0.90
8	1.31	1.38	1.38	1.73
9	2.78	2.84	2.77	2.50
10	5.38	5.65	5.30	4.96
11	5.68	5.82	5.25	4.23
12	3.10	3.24	3.07	2.60
13	1.55	1.70	2.12	2.06
14	0.91	0.96	1.14	1.15
15	0.84	0.87	0.98	1.07
16	0.68	0.74	0.79	0.90
17	0.74	0.82	0.82	0.94
18	1.42	1.54	1.54	1.83
19	2.96	3.11	3.03	2.67
20	5.89	5.97	5.54	5.02
21	6.01	6.00	5.49	4.28
22	3.22	3.37	3.29	2.84
23	1.54	1.63	1.85	1.90
24	0.89	0.95	1.07	1.18
25	0.73	0.76	0.81	0.86
26	0.75	0.81	0.85	0.93
27	0.97	1.08	1.16	1.21
28	1.68	1.94	1.95	2.01
29	3.26	3.38	3.37	2.90
30	5.55	5.48	5.04	4.12

Table D-2 Average field illuminance data for LED#1

Point Number	FIELD DATA			
	NE LANE		SW LANE	
	Outer	Center	Center	Outer
1	1.04	1.56	1.56	1.41
2	0.62	0.82	0.82	0.92
3	0.35	0.43	0.42	0.49
4	0.29	0.32	0.32	0.37
5	0.34	0.35	0.34	0.37
6	0.41	0.37	0.40	0.41
7	0.49	0.52	0.55	0.58
8	0.57	0.60	0.67	0.71
9	1.17	1.40	1.31	1.45
10	1.91	2.50	2.66	2.39
11	2.03	2.79	2.85	2.59
12	1.18	1.61	1.65	1.67
13	0.70	0.80	0.80	0.87
14	0.51	0.64	0.59	0.66
15	0.40	0.44	0.41	0.46
16	0.42	0.46	0.44	0.48
17	0.48	0.54	0.55	0.60
18	0.67	0.72	0.76	0.82
19	1.26	1.55	1.60	1.66
20	2.01	2.79	2.96	2.62
21	2.09	2.88	2.88	2.75
22	1.23	1.63	1.68	1.73
23	0.65	0.80	0.78	0.89
24	0.50	0.62	0.59	0.66
25	0.51	0.55	0.54	0.56
26	0.54	0.54	0.55	0.56
27	0.61	0.62	0.62	0.63
28	0.83	0.81	0.93	0.89
29	1.25	1.57	1.87	1.74
30	2.23	2.98	2.96	2.81

Table D-3 Average field illuminance data for LED#2

Point Number	FIELD DATA			
	NE LANE		SW LANE	
	Outer	Center	Center	Outer
1	2.37	2.63	2.25	2.15
2	0.84	0.94	0.87	0.84
3	0.87	1.55	1.05	0.64
4	0.97	1.54	1.62	1.25
5	1.01	1.56	1.61	1.57
6	0.89	1.29	1.54	1.50
7	0.77	1.10	1.35	1.08
8	0.73	1.20	1.07	0.71
9	0.98	1.13	1.27	1.29
10	2.82	3.23	2.53	2.14
11	2.67	3.28	2.63	1.54
12	0.96	1.16	1.20	1.20
13	1.17	1.36	0.81	0.61
14	1.41	1.65	1.32	0.91
15	1.41	1.82	1.59	1.40
16	1.21	1.62	1.69	1.52
17	1.01	1.43	1.49	1.11
18	0.92	1.43	1.13	0.69
19	0.87	1.03	1.19	1.23
20	2.36	2.77	2.33	1.84
21	3.23	4.05	3.27	1.81
22	0.93	1.19	1.22	1.14
23	1.02	1.24	0.86	0.70
24	1.28	1.58	1.32	0.91
25	1.57	1.94	1.66	1.35
26	1.85	1.95	1.69	1.33
27	1.87	1.57	1.19	0.84
28	1.61	1.24	0.77	0.60
29	1.31	1.83	2.12	1.70
30	4.20	4.72	3.26	1.62

Table D-4 Average field illuminance data for LED#3

Point Number	FIELD DATA			
	NE LANE			
	Outer		Center	
1	2.22	2.00	1.56	1.39
2	1.69	1.57	1.35	1.27
3	1.19	1.28	0.94	1.10
4	0.81	0.84	0.82	0.80
5	0.74	0.78	0.70	0.76
6	0.90	0.84	0.80	0.81
7	1.05	0.87	0.95	0.83
8	1.39	1.26	1.13	1.16
9	1.90	1.66	1.53	1.36
10	2.42	2.14	1.86	1.74
11	2.49	2.19	1.83	1.69
12	1.86	1.65	1.66	1.62
13	1.26	1.33	1.12	1.27
14	0.73	0.81	0.86	0.87
15	0.71	0.81	0.74	0.85
16	0.89	0.82	0.78	0.84
17	1.21	0.95	1.08	0.92
18	1.46	1.31	1.19	1.24
19	2.02	1.76	1.60	1.41
20	2.41	2.14	1.83	1.65
21	2.42	2.16	1.77	1.57
22	1.79	1.59	1.54	1.46
23	1.29	1.34	1.14	1.28
24	0.89	0.95	0.97	0.99
25	0.85	0.88	0.85	0.94
26	0.96	0.92	0.93	1.01
27	1.06	0.90	0.99	0.89
28	1.45	1.25	1.16	1.17
29	1.85	1.45	1.39	1.21
30	2.32	2.06	1.68	1.39

D.2 SOFTWARE RESULTS

Table D-5 AGi32 illuminance results for the HPS

Point Number	SOFTWARE			
	NE LANE		SW LANE	
	Outer	Center	Center	Outer
1	4.35	4.53	4.11	3.24
2	2.81	3.05	3.10	2.78
3	1.52	1.78	1.92	1.87
4	0.98	1.08	1.20	1.22
5	0.82	0.86	0.94	1.04
6	0.82	0.86	0.94	1.04
7	0.98	1.08	1.20	1.22
8	1.52	1.78	1.93	1.87
9	2.81	3.05	3.10	2.78
10	4.35	4.54	4.11	3.25
11	4.35	4.54	4.11	3.25
12	2.81	3.05	3.10	2.78
13	1.52	1.78	1.93	1.87
14	0.98	1.08	1.20	1.22
15	0.82	0.86	0.94	1.04
16	0.82	0.86	0.94	1.04
17	0.98	1.08	1.20	1.22
18	1.52	1.78	1.93	1.87
19	2.81	3.05	3.10	2.78
20	4.35	4.54	4.11	3.25
21	4.35	4.54	4.11	3.25
22	2.81	3.05	3.10	2.78
23	1.52	1.78	1.93	1.87
24	0.98	1.08	1.20	1.22
25	0.82	0.86	0.94	1.04
26	0.82	0.86	0.94	1.04
27	0.98	1.08	1.20	1.22
28	1.52	1.78	1.92	1.87
29	2.81	3.05	3.10	2.78
30	4.35	4.53	4.11	3.24

Table D-6 AGi32 illuminance results for LED#1

Point Number	SOFTWARE			
	NE LANE		SW LANE	
	Outer	Center	Center	Outer
1	2.16	2.81	3.10	2.44
2	1.22	1.48	1.70	1.47
3	0.69	0.81	0.90	0.86
4	0.52	0.56	0.60	0.58
5	0.47	0.51	0.53	0.52
6	0.47	0.51	0.53	0.52
7	0.52	0.56	0.60	0.59
8	0.70	0.81	0.91	0.86
9	1.23	1.48	1.71	1.48
10	2.17	2.82	3.11	2.45
11	2.17	2.82	3.11	2.45
12	1.23	1.48	1.71	1.48
13	0.70	0.81	0.91	0.86
14	0.52	0.56	0.60	0.59
15	0.48	0.51	0.53	0.52
16	0.48	0.51	0.53	0.52
17	0.52	0.56	0.60	0.59
18	0.70	0.81	0.91	0.86
19	1.23	1.48	1.71	1.48
20	2.17	2.82	3.11	2.45
21	2.17	2.82	3.11	2.45
22	1.23	1.48	1.71	1.48
23	0.70	0.81	0.91	0.86
24	0.52	0.56	0.60	0.59
25	0.47	0.51	0.53	0.52
26	0.47	0.51	0.53	0.52
27	0.52	0.56	0.60	0.58
28	0.69	0.81	0.90	0.86
29	1.22	1.48	1.70	1.47
30	2.16	2.81	3.10	2.44

Table D-7 AGi32 illuminance results for LED#2

Point Number	SOFTWARE			
	NE LANE		SW LANE	
	Outer	Center	Center	Outer
1	4.18	4.99	3.90	2.19
2	1.48	2.15	2.36	1.84
3	0.91	1.08	1.06	0.95
4	1.20	1.59	1.42	1.08
5	1.60	2.09	1.99	1.58
6	1.60	2.09	1.99	1.58
7	1.20	1.59	1.43	1.09
8	0.92	1.09	1.06	0.96
9	1.49	2.16	2.37	1.86
10	4.20	5.01	3.93	2.23
11	4.20	5.01	3.93	2.23
12	1.49	2.16	2.37	1.86
13	0.92	1.09	1.07	0.96
14	1.20	1.59	1.43	1.09
15	1.60	2.09	1.99	1.59
16	1.60	2.09	1.99	1.59
17	1.20	1.59	1.43	1.09
18	0.92	1.09	1.07	0.96
19	1.49	2.16	2.37	1.86
20	4.20	5.01	3.93	2.23
21	4.20	5.01	3.93	2.23
22	1.49	2.16	2.37	1.86
23	0.92	1.09	1.06	0.96
24	1.20	1.59	1.43	1.09
25	1.60	2.09	1.99	1.58
26	1.60	2.09	1.99	1.58
27	1.20	1.59	1.42	1.08
28	0.91	1.08	1.06	0.95
29	1.48	2.15	2.36	1.84
30	4.18	4.99	3.90	2.19

Table D-8 AGi32 illuminance results for LED#3

Point Number	SOFTWARE			
	NE LANE		SW LANE	
	Outer	Center	Center	Outer
1	2.91	2.55	2.36	2.30
2	2.59	2.29	2.29	2.29
3	2.11	1.99	2.02	1.98
4	1.69	1.69	1.74	1.78
5	1.49	1.45	1.49	1.51
6	1.49	1.45	1.49	1.51
7	1.69	1.70	1.74	1.78
8	2.11	2.00	2.02	1.98
9	2.59	2.29	2.29	2.29
10	2.91	2.55	2.37	2.30
11	2.92	2.55	2.37	2.30
12	2.59	2.29	2.29	2.29
13	2.11	2.00	2.02	1.98
14	1.69	1.70	1.74	1.78
15	1.49	1.45	1.49	1.51
16	1.49	1.45	1.49	1.51
17	1.69	1.70	1.74	1.78
18	2.11	2.00	2.02	1.98
19	2.59	2.29	2.29	2.29
20	2.92	2.55	2.37	2.30
21	2.91	2.55	2.37	2.30
22	2.59	2.29	2.29	2.29
23	2.11	2.00	2.02	1.98
24	1.69	1.70	1.74	1.78
25	1.49	1.45	1.49	1.51
26	1.49	1.45	1.49	1.51
27	1.69	1.69	1.74	1.78
28	2.11	1.99	2.02	1.98
29	2.59	2.29	2.29	2.29
30	2.91	2.55	2.36	2.30

APPENDIX E COMPARISON OF THE ILLUMINANCE RESULTS FOR HPS VS. LEDS

E.1 HPS VS. LED#1

E.1.1 Based on the Field Data

The average field illuminance data for the HPS are graphically compared with the average field illuminance data for LED#1 in Figures E-1, E-2, E-3 and E-4 for the NE lane outer row, NE lane center row, SW lane center row and SW lane outer row, respectively. According to the results:

- Both types of luminaires display the same illuminance distribution pattern. For both types of luminaires, the maximum illuminance level in a particular row is attained at the grid points adjacent to the light poles, and the minimum illuminance level in a particular row occurs at the midpoints between the light poles.
- For any given row, the average field illuminance levels produced by the HPS are always greater than the average field illuminance levels produced by the LED#1. For any given row, the biggest differences between the illuminance levels produced by the HPS and LED#1 are observed at the grid points adjacent to the light poles.
- The field illuminance level produced by the HPS is found to go above the field illuminance level produced by the LED#1 by 0.21 – 4.62 ft-cd in the NE lane outer row, 0.21 – 4.11 ft-cd in the NE lane center row, 0.26 – 3.87 ft-cd in the SW lane center row, and 0.30 – 3.07 ft-cd in the SW lane outer row.
- On average, the field illuminance level for the HPS is found to exceed the field illuminance level for LED#1 by 1.46 ft-cd in the NE lane outer row, 1.31 ft-cd in the NE lane center row, 1.24 ft-cd in the SW lane center row, and 1.06 ft-cd in the SW lane outer row.

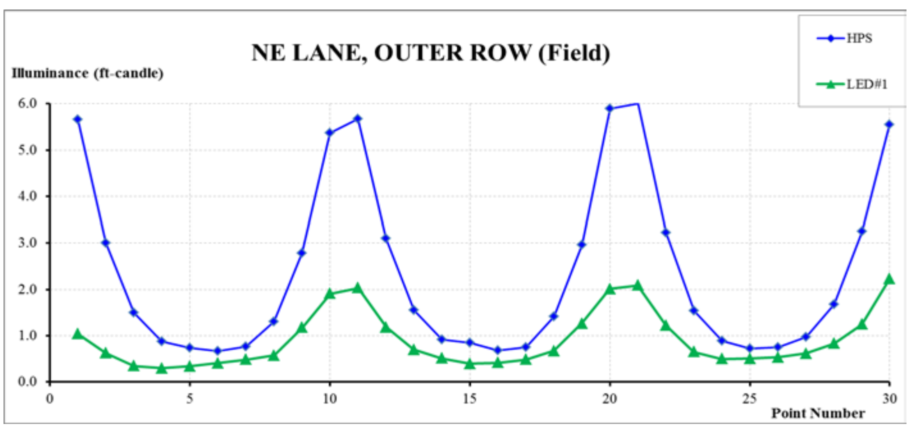


Figure E-1 Comparison of the field illuminance data for HPS vs. LED#1 (NE lane, outer row)

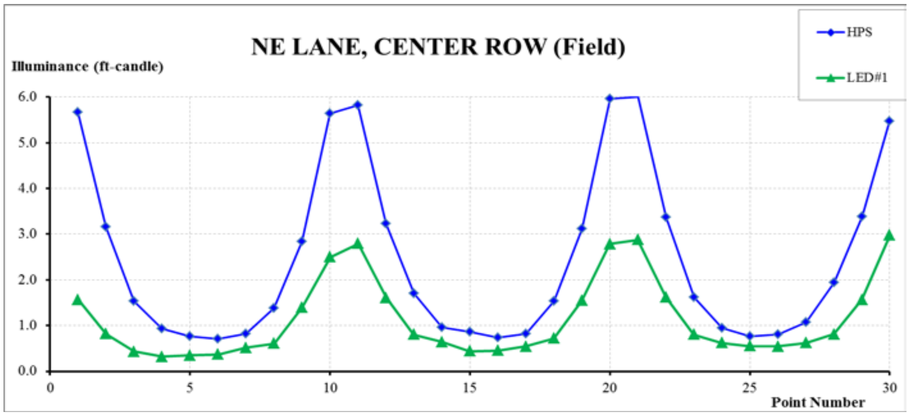


Figure E-2 Comparison of the field illuminance data for HPS vs. LED#1 (NE lane, center row)

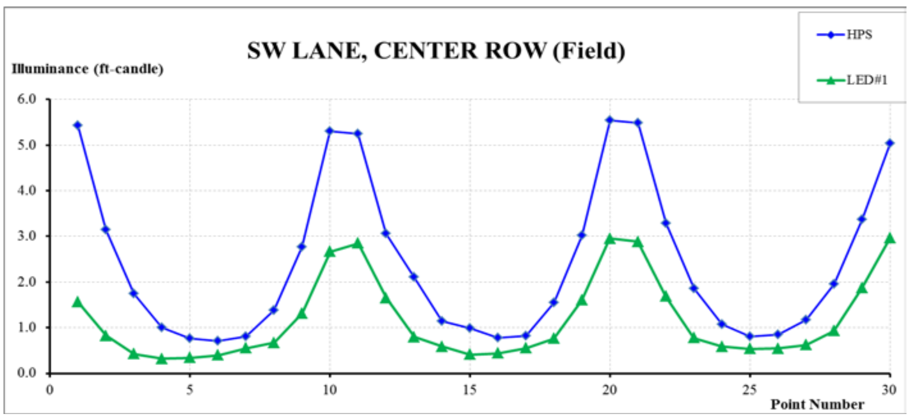


Figure E-3 Comparison of the field illuminance data for HPS vs. LED#1 (SW lane, center row)

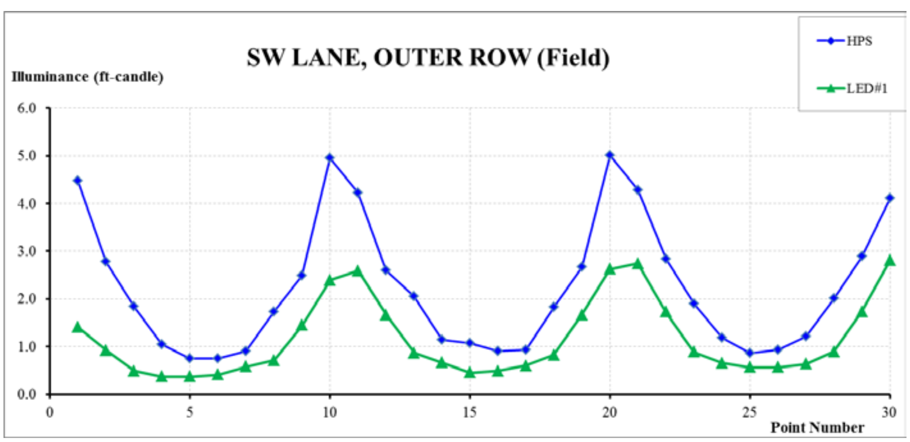


Figure E-4 Comparison of the field illuminance data for HPS vs. LED#1 (SW lane, outer row)

E.1.2 Based on the Software Results

Figures E-5, E-6, E-7 and E-8 graphically compare the AGi32 illuminance results for the HPS vs. LED#1 for the NE lane outer row, NE lane center row, SW lane center row and SW lane outer row, respectively. According to the results:

- Both types of luminaires display the same illuminance distribution pattern. For both types of luminaires, the maximum illuminance level in a particular row is attained at the grid points adjacent to the light poles, and the minimum illuminance level in a particular row occurs at the midpoints between the light poles.
- For a given row, the average field illuminance levels produced by the HPS are always greater than the average field illuminance levels produced by the LED#1. For a given row, the biggest differences between the illuminance levels produced by the HPS and LED#1 are observed at the grid points adjacent to the light poles.
- The AGi32 illuminance results for the HPS is found to exceed the AGi32 illuminance results for LED#1 by 0.34 – 2.19 ft-cd in the NE lane outer row, 0.35 – 1.72 ft-cd in the NE lane center row, 0.41 – 1.40 ft-cd in the SW lane center row, and 0.52 – 1.31 ft-cd in the SW lane outer row.

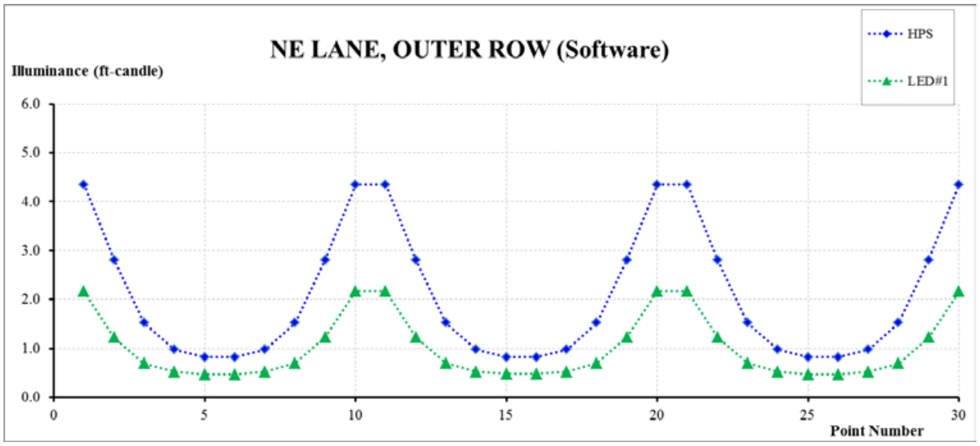


Figure E-5 Comparison of the software illuminance results for HPS vs. LED#1 (NE lane, outer row)

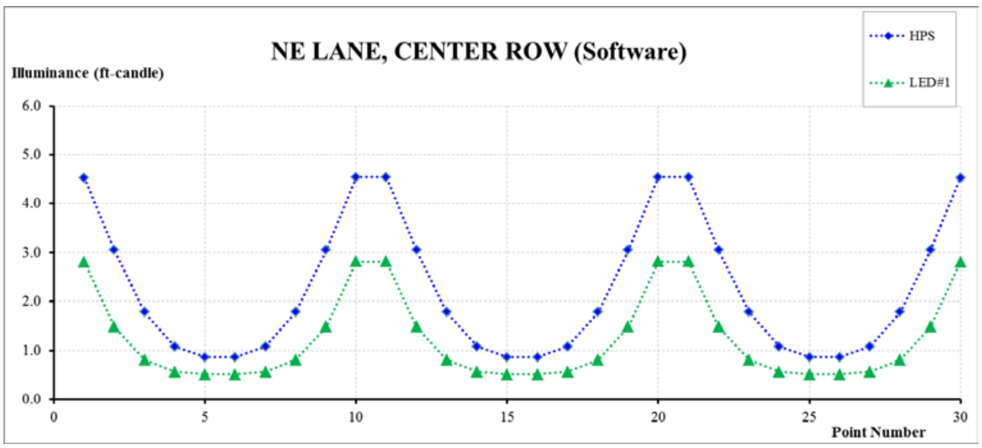


Figure E-6 Comparison of the software illuminance results for HPS vs. LED#1 (NE lane, center row)

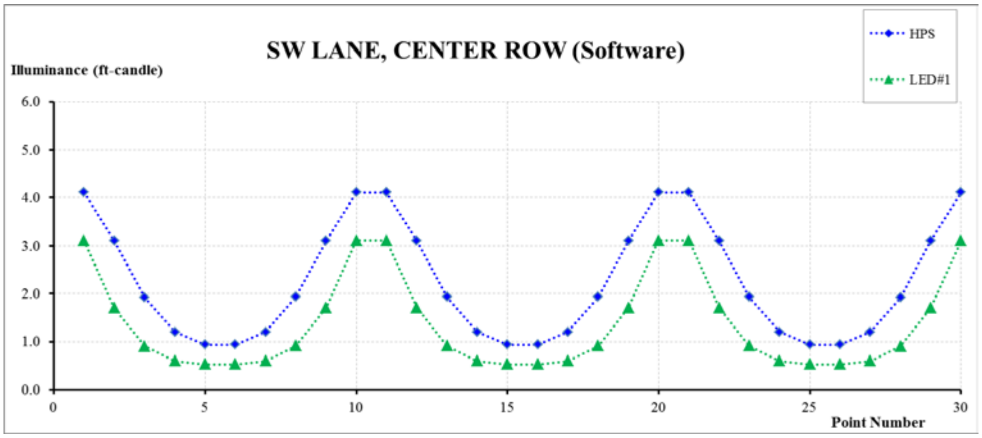


Figure E-7 Comparison of the software illuminance results for HPS vs. LED#1 (SW lane, center row)

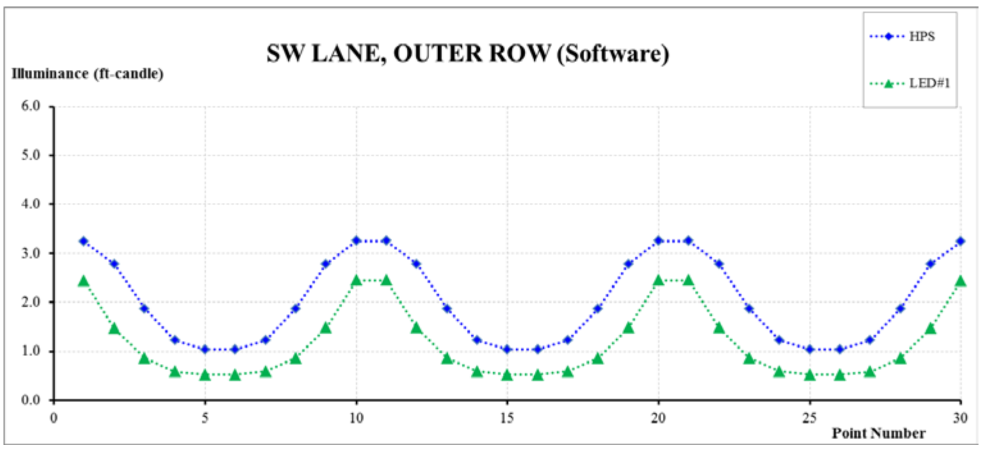


Figure E-8 Comparison of the software illuminance results for HPS vs. LED#1 (SW lane, outer row)

- On average, the AGi32 illuminance results for the HPS are found to exceed the AGi32 illuminance results for LED#1 by 1.08 ft-cd in the NE lane outer row, 1.03 ft-cd in the NE lane center row, 0.89 ft-cd in the SW lane center row, and 0.85 ft-cd in the SW lane outer row.

E.2 HPS VS. LED#2

E.2.1 Based on the Field Data

The average field illuminance data for the HPS are graphically compared with the average field illuminance data for LED#2 in Figures E-9, E-10, E-11 and E-12 for the NE lane outer row, NE lane center row, SW lane center row and SW lane outer row, respectively. According to the results:

- The two types of luminaires do not display the same illuminance distribution pattern. For the HPS, the maximum illuminance level in a particular row is attained at the grid points adjacent to the light poles, and the minimum illuminance level in a particular row occurs at the midpoints between the light poles. On the other hand, for LED#2, the minimum illuminance level in a particular row is usually attained at the second grid point on either side of the light poles.

- For all four rows, the field illuminance levels for the HPS are greater than the field illuminance for LED#2 in the vicinity of the light poles. The field illuminance levels for the HPS is found to exceed the field illuminance levels for LED#2 in the vicinity of the light poles by up to 3.53 ft-cd in the NE lane outer row, 3.20 ft-cd in the NE lane center row, 3.21 ft-cd in the SW lane center row, and 3.17 ft-cd in the SW lane outer row.
- On the contrary, the field illuminance levels for LED#2 exceed the field illuminance levels for the HPS usually at the three or four of the mid grid points between the light poles. At those points, the field illuminance levels for LED#2 is found to exceed the field illuminance levels for the HPS by up to 1.10 ft-cd in the NE lane outer row, 1.18 ft-cd in the NE lane center row, 0.90 ft-cd in the SW lane center row, and 0.81 ft-cd in the SW lane outer row.

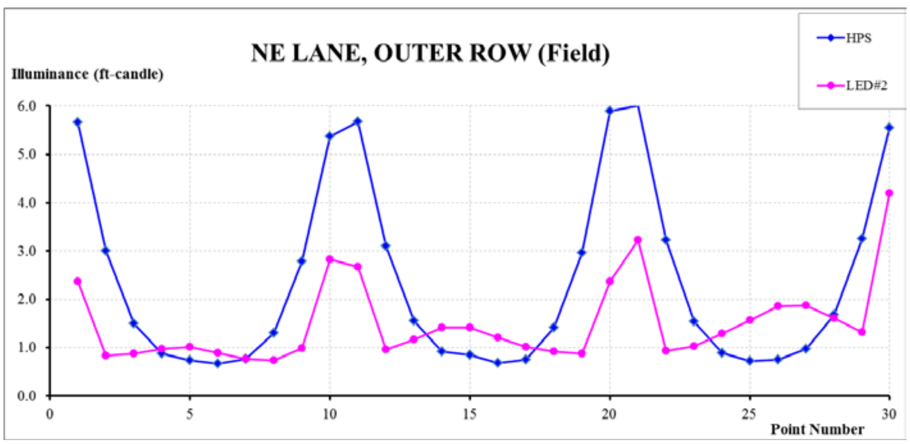


Figure E-9 Comparison of the field illuminance data for HPS vs. LED#2 (NE lane, outer row)

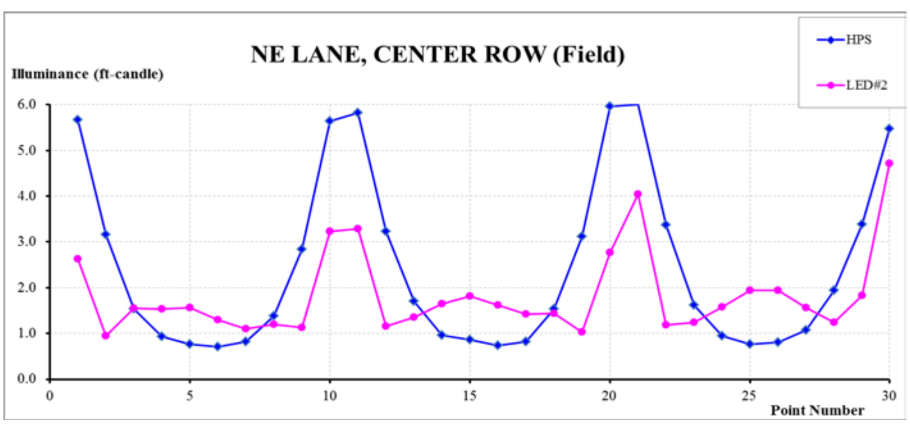


Figure E-10 Comparison of the field illuminance data for HPS vs. LED#2 (NE lane, center row)

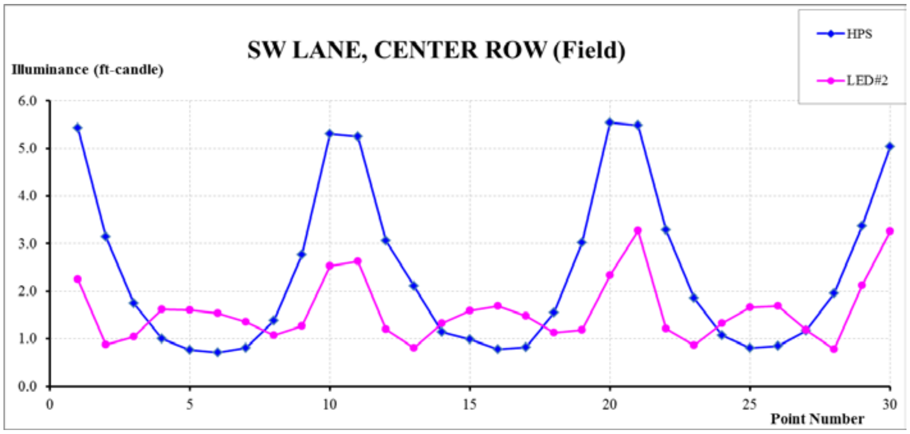


Figure E-11 Comparison of the field illuminance data for HPS vs. LED#2 (SW lane, center row)

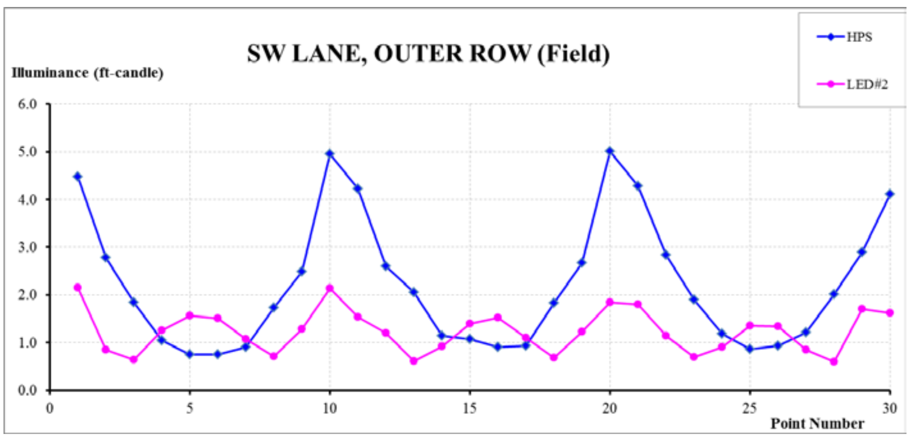


Figure E-12 Comparison of the field illuminance data for HPS vs. LED#2 (SW lane, outer row)

E.2.2 Based on the Software Results

Figures E-13, E-14, E-15 and E-16 graphically compare the AGi32 illuminance results for the HPS vs. LED#2 for the NE lane outer row, NE lane center row, SW lane center row and SW lane outer row, respectively. According to the results:

- The two types of luminaires do not display the same illuminance distribution pattern. For the HPS, the maximum illuminance level in a particular row is attained at the grid points adjacent to the light poles, and the minimum illuminance level in a particular row occurs at the midpoints between the light poles. On the other hand, for LED#2, the minimum illuminance level in a particular row is usually attained at the third grid point on either side of the light poles.
- For all four rows but the SW lane outer row, the AGi32 illuminance results for LED#2 exceed the AGi32 illuminance results for the HPS at four of the mid grid points between the light poles. For the SW lane outer row, which was the furthest from the light poles, the AGi32 illuminance results for LED#2 exceed the AGi32 illuminance results for the HPS at two of the mid grid points between the light poles.
- For the SW lane outer row, the AGi32 illuminance results for the HPS are considerably greater than those for LED#2 in the vicinity of the light poles. For the NE lane center row, the peak illuminance levels for LED#2 are greater than those for the HPS. On the other

hand, for both the NE lane outer row and SW lane center row, the peak illuminance levels for LED#2 and the HPS are almost equal.

- At the mid grid points between the light poles, the AGi32 illuminance results for LED#2 are found to exceed the AGi32 illuminance results for the HPS by up to 0.78 ft-cd in the NE lane outer row, 1.23 ft-cd in the NE lane center row, and 1.05 ft-cd in the SW lane center row. In the SW lane outer row, the AGi32 illuminance results for the HPS are found to exceed the AGi32 illuminance results for LED#2 by up to 1.05 ft-cd in the vicinity of the light poles

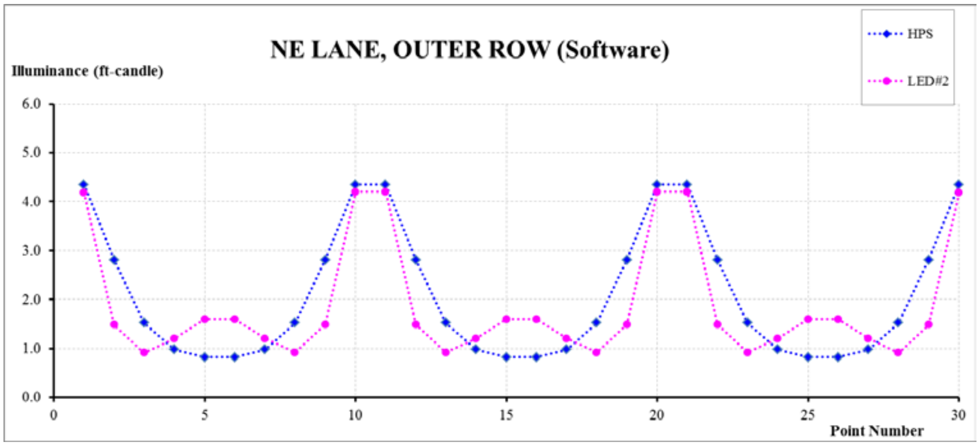


Figure E-13 Comparison of the software illuminance results for HPS vs. LED#2 (NE lane, outer row)

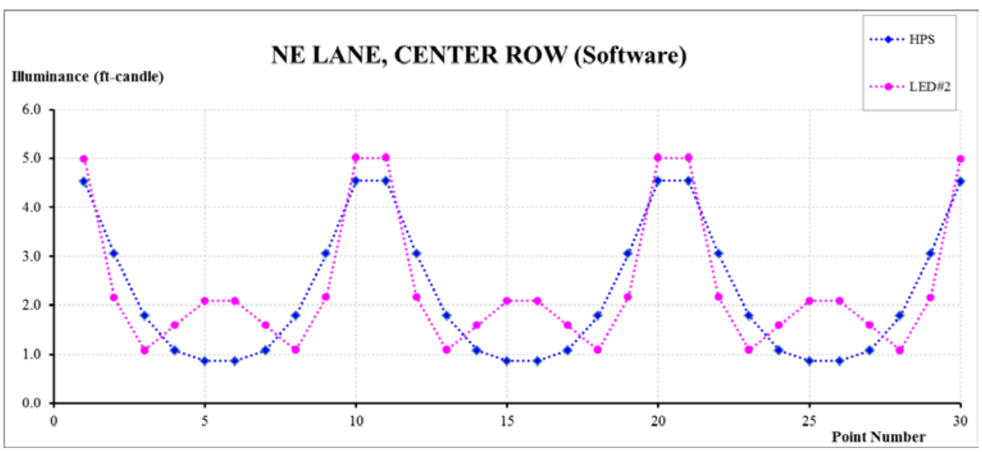


Figure E-14 Comparison of the software illuminance results for HPS vs. LED#2 (NE lane, center row)

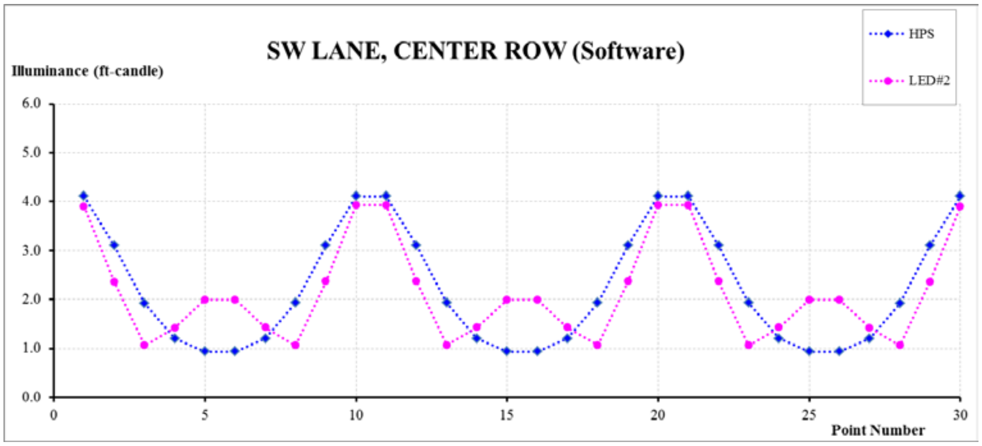


Figure E-15 Comparison of the software illuminance results for HPS vs. LED#2 (SW lane, center row)

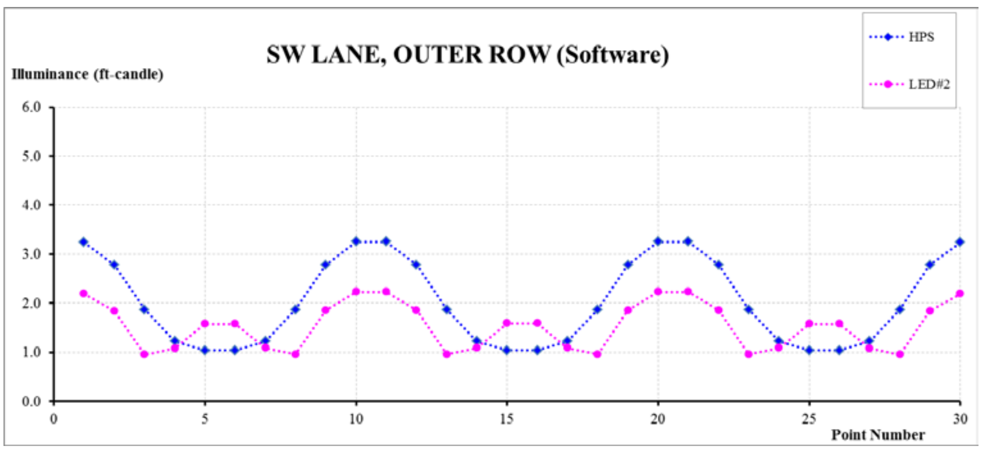


Figure E-16 Comparison of the software illuminance results for HPS vs. LED#2 (SW lane, outer row)

E.3 HPS VS. LED#3

E.3.1 Based on the Field Data

The average field illuminance data for the HPS are graphically compared with the average field illuminance data for LED#3 in Figures E-17, E-18, E-19 and E-20 for the NE lane outer row, NE lane center row, SW lane center row and SW lane outer row, respectively. According to the results:

- Both types of luminaires display the same illuminance distribution pattern. For both types of luminaires, the maximum illuminance level in a particular row is attained at the grid points adjacent to the light poles, and the minimum illuminance level in a particular row occurs at the midpoints between the light poles.
- For all four rows, the biggest differences between the illuminance levels produced by the HPS and LED#3 are observed at the grid points adjacent to the light poles. On the other hand, the illuminance levels produced by both luminaires are nearly equal in the midpoints between the light poles.
- The field illuminance levels for the HPS is found to exceed the field illuminance levels for LED#2 in the vicinity of the light poles by up to 3.55 ft-cd in the NE lane outer row, 3.83

ft-cd in the NE lane center row, 3.85 ft-cd in the SW lane center row, and 3.39 ft-cd in the SW lane outer row.

- In a given row, LED#3 produced lower average illuminance levels than the HPS. However, LED#3 produced more uniform illuminance distribution in a given row than the HPS.

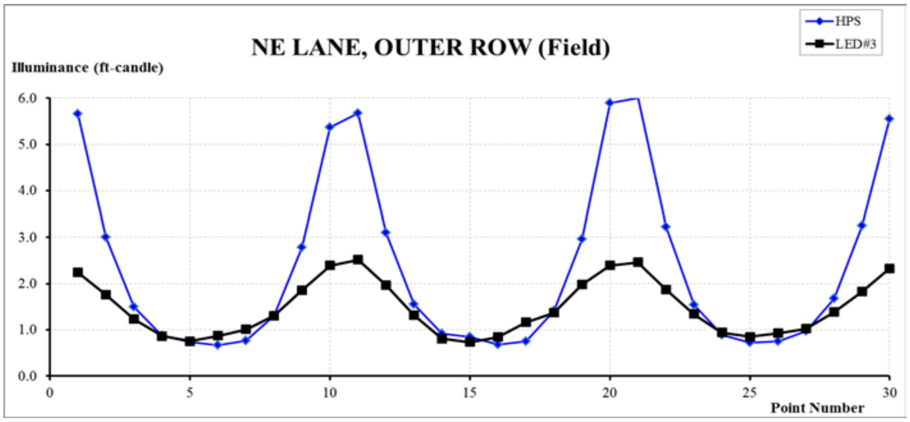


Figure E-17 Comparison of the field illuminance data for HPS vs. LED#3 (NE lane, outer row)

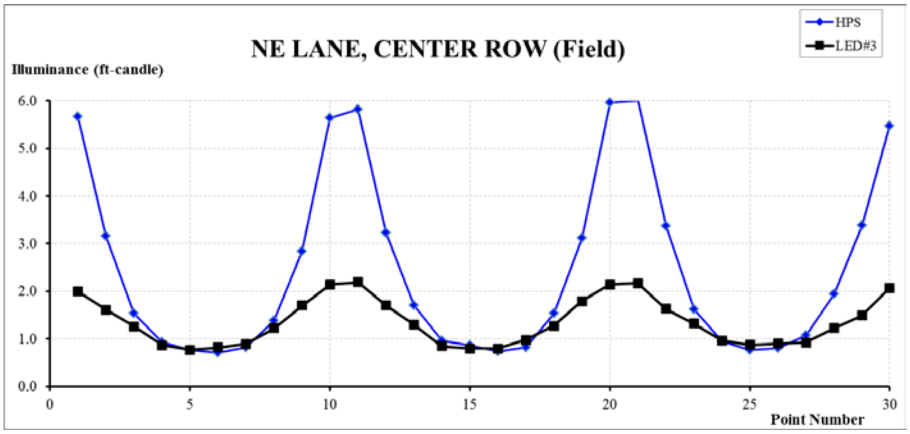


Figure E-18 Comparison of the field illuminance data for HPS vs. LED#3 (NE lane, center row)

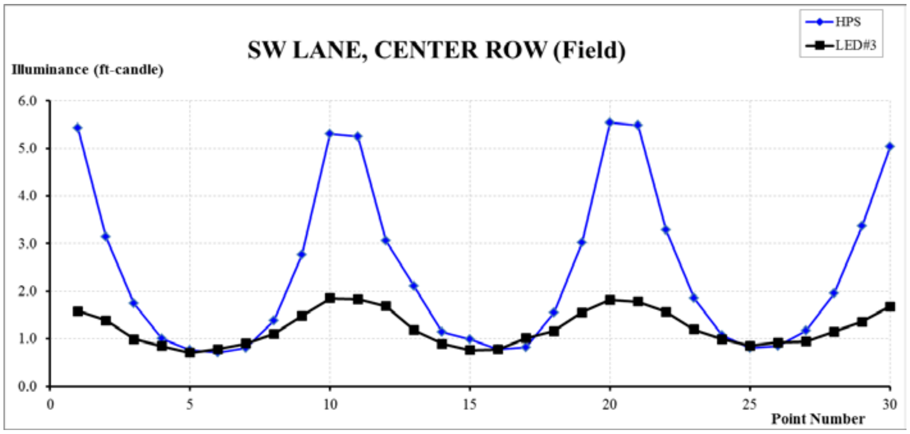


Figure E-19 Comparison of the field illuminance data for HPS vs. LED#3 (SW lane, center row)

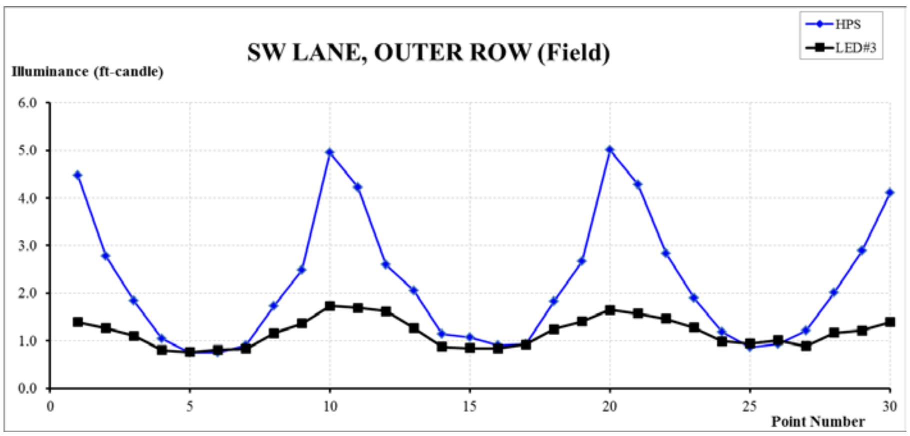


Figure E-20 Comparison of the field illuminance data for HPS vs. LED#3 (SW lane, outer row)

E.3.2 Based on the Software Results

Figures E-21, E-22, E-23 and E-24 graphically compare the AGi32 illuminance results for the HPS vs. LED#3 for the NE lane outer row, NE lane center row, SW lane center row and SW lane outer row, respectively. According to the results:

- Both types of luminaires display the same illuminance distribution pattern. For both types of luminaires, the maximum illuminance level in a particular row is attained at the grid points adjacent to the light poles, and the minimum illuminance level in a particular row occurs at the midpoints between the light poles.
- For all four rows, the peak illuminance levels produced by the HPS are considerably greater than those produced by LED#3. On the other hand, for all four rows, LED#3 produced higher illuminance levels at the mid grid points between the light poles than the HPS. Hence, LED#3 provided more uniform illuminance distribution in each row than the HPS.
- In the vicinity of the light poles, the AGi32 illuminance results for the HPS exceed the AGi32 illuminance results for LED#3 by up to 1.44 ft-cd in the NE lane outer row, 1.99 ft-cd in the NE lane center row, 1.75 ft-cd in the SW lane center row, and 0.95 ft-cd in the SW lane outer row.

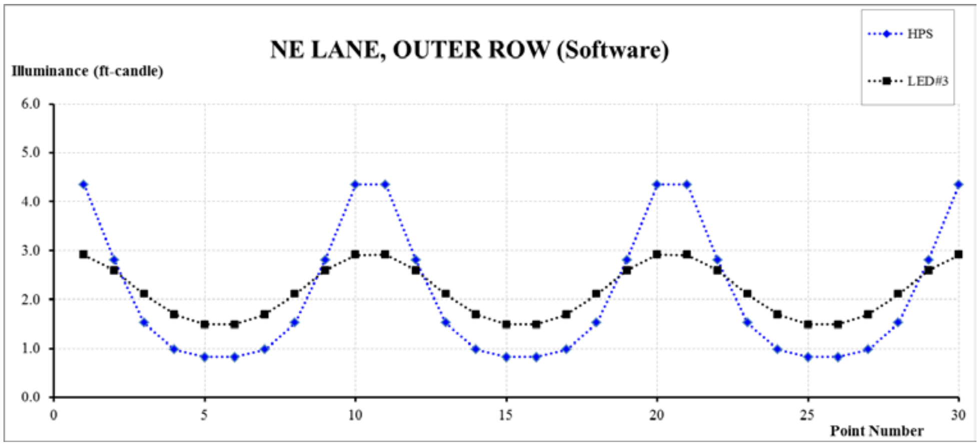


Figure E-21 Comparison of the software illuminance results for HPS vs. LED#3 (NE lane, outer row)

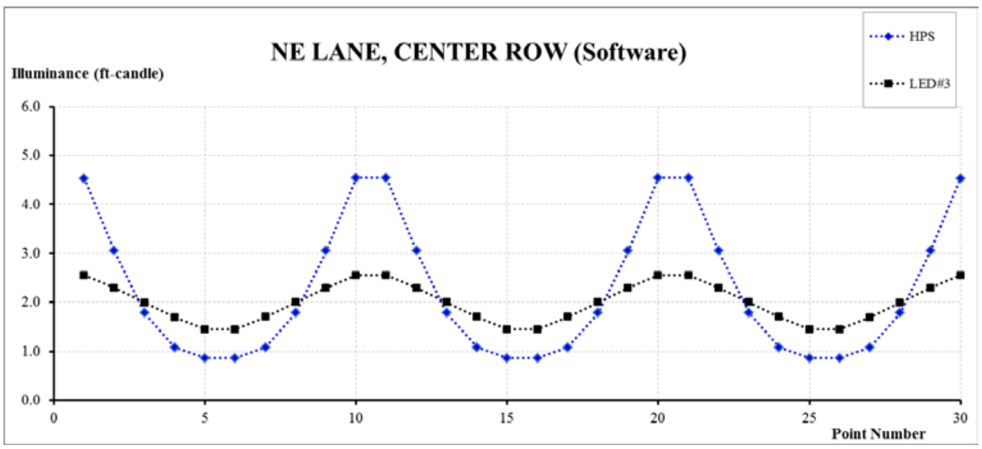


Figure E-22 Comparison of the software illuminance results for HPS vs. LED#3 (NE lane, center row)

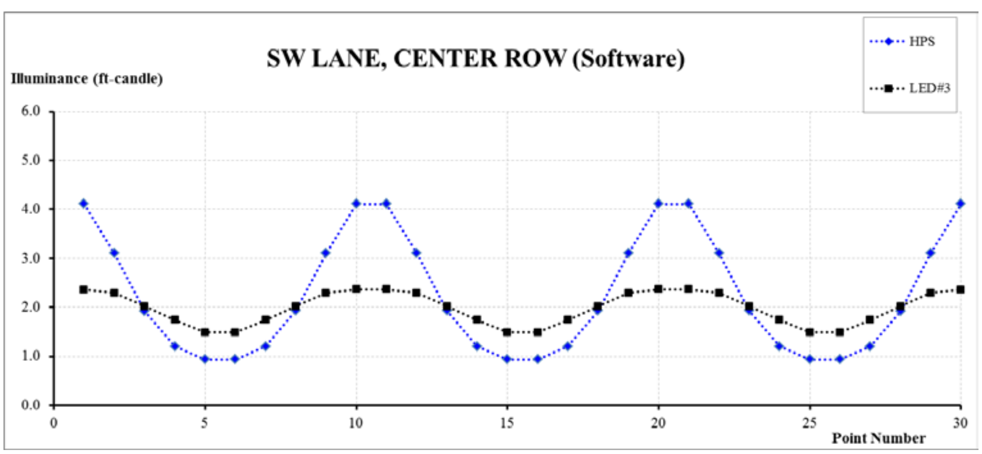


Figure E-23 Comparison of the software illuminance results for HPS vs. LED#3 (SW lane, center row)

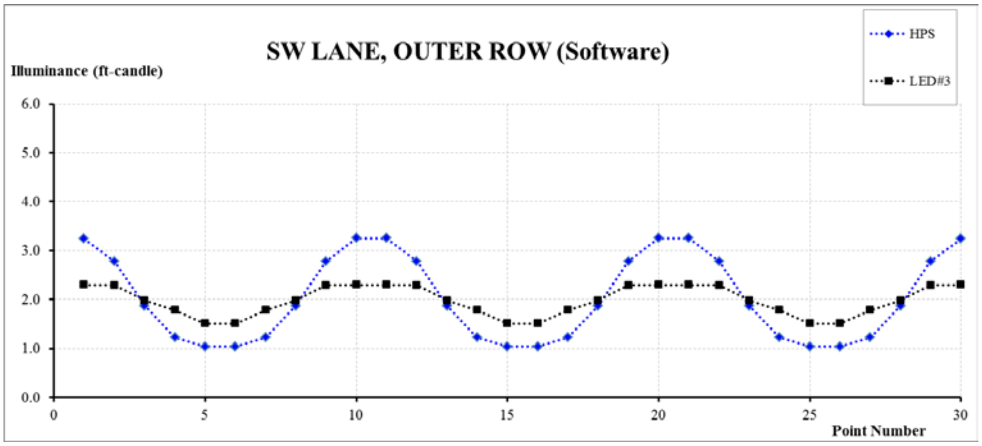


Figure E-24 Comparison of the software illuminance results for HPS vs. LED#3 (SW lane, outer row)

- At the mid grid points between the light poles, the AGi32 illuminance results for LED#3 are found to go above the AGi32 illuminance results for the HPS by up to 0.71 ft-cd in the NE lane outer row, 0.62 ft-cd in the NE lane center row, 0.55 ft-cd in the SW lane center row, and 0.56 ft-cd and in the SW lane outer row.

APPENDIX F LUMINANCE MEASUREMENTS

F.1 AVERAGE FIELD DATA

Table F-1 Average field luminance data for the HPS

Point Number	FIELD DATA			
	NE LANE			
	Outer		Center	
1	2.82	2.54	2.43	1.96
2	2.94	2.72	2.53	2.13
3	2.97	2.77	2.63	2.26
4	3.04	2.85	2.66	2.30
5	3.05	2.88	2.66	2.28
6	2.85	2.82	2.44	2.11
7	2.73	2.58	2.43	2.06
8	2.62	2.46	2.25	1.97
9	2.57	2.47	2.23	1.94
10	2.53	2.53	2.27	1.95
11	2.71	2.57	2.26	2.09
12	2.82	2.57	2.41	2.16
13	2.83	2.73	2.55	2.23
14	2.92	2.82	2.63	2.31
15	2.76	2.70	2.60	2.25
16	2.67	2.69	2.48	2.19
17	2.62	2.41	2.44	2.00
18	2.49	2.28	2.20	1.90
19	2.48	2.28	2.14	1.93
20	2.56	2.34	2.16	1.93
21	2.65	2.41	2.22	1.98
22	2.73	2.53	2.34	2.04
23	2.76	2.62	2.42	2.13
24	2.87	2.58	2.45	2.15
25	2.77	2.79	2.43	2.03
26	2.52	2.58	2.32	1.90
27	2.41	2.30	2.21	1.77
28	2.00	1.90	1.96	1.51
29	1.83	1.68	1.91	1.57
30	1.93	1.67	1.84	1.35

Table F-2 Average field luminance data for LED#1

Point Number	FIELD DATA			
	NE LANE			
	Outer		Center	
1	0.91	0.91	0.81	0.73
2	0.98	0.89	0.85	0.75
3	0.98	1.03	0.92	0.77
4	0.76	1.02	0.98	0.90
5	1.06	1.10	1.03	0.96
6	1.14	1.13	1.04	0.95
7	1.20	1.14	1.04	0.95
8	1.18	1.14	1.02	0.98
9	1.20	1.22	1.02	0.95
10	1.20	1.25	1.07	1.02
11	1.24	1.28	1.23	1.12
12	1.31	1.32	1.26	1.15
13	1.33	1.42	1.27	1.17
14	1.33	1.44	1.35	1.22
15	1.36	1.45	1.36	1.24
16	1.36	1.39	1.36	1.24
17	1.24	1.34	1.29	1.16
18	1.26	1.29	1.18	1.07
19	1.23	1.26	1.14	1.07
20	1.27	1.27	1.16	1.10
21	1.19	1.29	1.20	1.10
22	1.28	1.33	1.25	1.17
23	1.27	1.36	1.29	1.22
24	1.29	1.33	1.35	1.25
25	1.30	1.35	1.34	1.18
26	1.22	1.22	1.36	1.20
27	1.10	1.22	1.29	0.96
28	1.03	1.13	1.12	0.94
29	0.96	1.02	1.07	0.92
30	0.89	0.95	0.97	0.89

Table F-3 Average field luminance data for LED#2

Point Number	FIELD DATA			
	NE LANE			
	Outer		Center	
1	2.25	2.34	1.86	1.30
2	2.20	2.33	1.91	1.32
3	2.08	2.30	1.94	1.40
4	2.12	2.34	1.95	1.52
5	2.15	2.40	2.14	1.64
6	2.24	2.47	2.18	1.66
7	2.22	2.44	2.17	1.68
8	2.29	2.49	2.21	1.69
9	2.32	2.57	2.24	1.71
10	2.32	2.60	2.28	1.75
11	2.27	2.54	2.29	1.76
12	2.26	2.52	2.19	1.66
13	2.28	2.51	2.15	1.69
14	2.33	2.52	2.10	1.60
15	2.43	2.59	2.08	1.58
16	2.44	2.63	2.11	1.54
17	2.48	2.58	2.01	1.58
18	2.52	2.63	2.09	1.56
19	2.38	2.70	2.11	1.51
20	2.40	2.57	2.19	1.58
21	2.49	2.64	2.14	1.61
22	2.46	2.47	2.05	1.54
23	2.31	2.48	2.12	1.53
24	2.31	2.35	1.95	1.49
25	2.43	2.37	1.89	1.41
26	2.45	2.41	1.87	1.40
27	2.30	2.39	1.61	1.34
28	2.15	2.11	1.66	1.24
29	1.99	2.19	1.71	1.16
30	1.89	1.97	1.51	1.19

Table F-4 Average field luminance data for LED#3

Point Number	FIELD DATA			
	NE LANE			
	Outer		Center	
1	1.89	1.58	1.31	1.02
2	1.96	1.67	1.29	1.05
3	1.99	1.63	1.30	1.10
4	2.03	1.72	1.35	1.17
5	2.00	1.74	1.34	1.17
6	2.06	1.78	1.37	1.19
7	2.04	1.73	1.38	1.22
8	2.13	1.73	1.40	1.20
9	2.13	1.83	1.41	1.25
10	2.07	1.81	1.43	1.28
11	2.18	1.84	1.45	1.25
12	2.16	1.84	1.46	1.29
13	2.13	1.88	1.55	1.45
14	2.14	1.82	1.62	1.49
15	2.14	1.82	1.57	1.40
16	2.13	1.81	1.38	1.23
17	2.13	1.81	1.33	1.18
18	2.12	1.73	1.34	1.18
19	2.13	1.67	1.28	1.20
20	2.16	1.69	1.32	1.22
21	2.21	1.77	1.41	1.23
22	2.20	1.71	1.40	1.24
23	2.24	1.82	1.49	1.39
24	2.17	1.69	1.48	1.39
25	2.10	1.77	1.39	1.33
26	1.96	1.74	1.33	1.22
27	1.93	1.71	1.21	1.18
28	1.77	1.47	1.20	1.09
29	1.73	1.32	1.07	1.15
30	1.67	1.29	1.06	1.16

F.2 SOFTWARE RESULTS

Table F-5 AGi32 luminance results for the HPS

Point Number	SOFTWARE			
	NE LANE			
	Outer		Center	
1	1.42	1.46	1.31	1.06
2	1.25	1.16	1.09	0.96
3	1.46	1.20	1.04	0.92
4	2.15	1.59	1.26	1.03
5	2.57	1.97	1.47	1.26
6	2.51	1.98	1.54	1.31
7	2.39	2.09	1.73	1.30
8	2.31	2.18	1.87	1.50
9	2.11	2.04	1.82	1.34
10	1.72	1.70	1.49	1.16
11	1.43	1.46	1.31	1.06
12	1.25	1.16	1.09	0.96
13	1.46	1.20	1.04	0.92
14	2.15	1.59	1.26	1.03
15	2.57	1.97	1.47	1.26
16	2.51	1.98	1.54	1.31
17	2.39	2.09	1.73	1.30
18	2.31	2.18	1.87	1.50
19	2.11	2.04	1.81	1.34
20	1.72	1.70	1.49	1.16
21	1.42	1.46	1.31	1.06
22	1.24	1.16	1.09	0.96
23	1.46	1.19	1.04	0.92
24	2.15	1.59	1.25	1.02
25	2.57	1.96	1.47	1.26
26	2.50	1.98	1.54	1.31
27	2.37	2.07	1.72	1.30
28	2.29	2.16	1.86	1.49
29	2.07	2.01	1.80	1.33
30	1.62	1.63	1.45	1.13

Table F-6 AGi32 luminance results for LED#1

Point Number	SOFTWARE			
	NE LANE			
	Outer		Center	
1	0.93	1.05	1.07	0.85
2	0.84	0.75	0.71	0.58
3	0.98	0.76	0.63	0.51
4	1.33	0.96	0.75	0.55
5	1.46	1.12	0.81	0.62
6	1.51	1.21	0.88	0.67
7	1.27	1.08	0.86	0.63
8	1.13	1.04	0.91	0.71
9	1.06	1.09	1.06	0.76
10	1.06	1.18	1.20	0.93
11	0.94	1.05	1.07	0.86
12	0.84	0.75	0.71	0.58
13	0.98	0.76	0.63	0.51
14	1.33	0.96	0.75	0.55
15	1.46	1.12	0.81	0.62
16	1.51	1.21	0.88	0.67
17	1.27	1.08	0.85	0.63
18	1.12	1.04	0.91	0.71
19	1.06	1.09	1.06	0.76
20	1.04	1.18	1.20	0.93
21	0.93	1.05	1.07	0.86
22	0.83	0.74	0.70	0.58
23	0.97	0.75	0.63	0.50
24	1.31	0.95	0.74	0.55
25	1.44	1.11	0.80	0.62
26	1.47	1.19	0.87	0.66
27	1.21	1.03	0.82	0.61
28	1.02	0.97	0.87	0.68
29	0.90	0.98	0.99	0.71
30	0.82	1.02	1.10	0.86

Table F-7 AGi32 luminance results for LED#2

Point Number	SOFTWARE			
	NE LANE			
	Outer		Center	
1	1.91	2.12	1.65	1.04
2	1.69	1.72	1.49	1.11
3	2.32	2.10	1.68	1.16
4	3.72	3.49	2.70	1.67
5	5.20	4.96	3.42	2.13
6	4.82	4.70	3.08	1.87
7	2.69	2.80	1.80	1.03
8	1.37	1.32	1.05	0.81
9	1.30	1.63	1.55	1.05
10	1.97	2.19	1.69	1.03
11	1.92	2.13	1.67	1.06
12	1.69	1.72	1.49	1.11
13	2.32	2.10	1.68	1.16
14	3.72	3.49	2.70	1.67
15	5.20	4.96	3.42	2.13
16	4.82	4.70	3.08	1.87
17	2.69	2.80	1.79	1.03
18	1.37	1.32	1.05	0.80
19	1.29	1.63	1.55	1.05
20	1.96	2.18	1.69	1.03
21	1.91	2.13	1.67	1.05
22	1.68	1.71	1.48	1.11
23	2.31	2.09	1.66	1.15
24	3.70	3.47	2.68	1.66
25	5.18	4.93	3.39	2.12
26	4.78	4.66	3.04	1.85
27	2.63	2.73	1.74	0.99
28	1.27	1.22	0.96	0.73
29	1.10	1.43	1.39	0.92
30	1.58	1.82	1.41	0.80

Table F-8 AGi32 luminance results for LED#3

Point Number	SOFTWARE			
	NE LANE			
	Outer		Center	
1	0.98	0.87	0.79	0.78
2	1.08	0.91	0.85	0.82
3	1.47	1.22	1.09	0.97
4	2.63	1.97	1.59	1.29
5	4.10	2.93	2.11	1.67
6	4.93	3.61	2.60	2.01
7	4.40	3.43	2.58	1.97
8	3.28	2.48	1.99	1.61
9	1.98	1.57	1.37	1.13
10	1.20	1.01	0.90	0.86
11	0.98	0.87	0.80	0.79
12	1.08	0.91	0.85	0.82
13	1.47	1.22	1.09	0.97
14	2.63	1.97	1.59	1.29
15	4.10	2.93	2.11	1.67
16	4.93	3.61	2.60	2.01
17	4.40	3.42	2.57	1.97
18	3.27	2.47	1.98	1.61
19	1.97	1.56	1.37	1.13
20	1.18	1.00	0.89	0.85
21	0.97	0.86	0.79	0.78
22	1.06	0.90	0.84	0.81
23	1.45	1.20	1.08	0.96
24	2.61	1.96	1.58	1.28
25	4.07	2.91	2.10	1.66
26	4.90	3.58	2.58	2.00
27	4.35	3.39	2.55	1.95
28	3.22	2.43	1.95	1.58
29	1.90	1.51	1.33	1.10
30	1.09	0.92	0.84	0.80

APPENDIX G COMPARISON OF THE LUMINANCE RESULTS FOR HPS VS. LEDS

G.1 HPS VS. LED#1

G.1.1 Based on the Field Data

The average field luminance data for the HPS are graphically compared with the average field luminance data for LED#1 in Figures G-1, G-2, G-3 and G-4 for the NE lane outer row, NE lane center row, SW lane center row and SW lane outer row, respectively. According to the results:

- For a given row, the luminance levels produced by either luminaire display little variation with distance.
- For a given row, the average field luminance levels produced by the HPS are always greater than those produced by LED#1. The average field luminance levels for the HPS is found to go above those for LED#1 by 0.87 – 2.28 cd/m^2 in the NE lane outer row, 0.66 – 1.83 cd/m^2 in the NE lane center row, 0.84 – 1.71 cd/m^2 in the SW lane center row, and 0.46 – 1.50 cd/m^2 in the SW lane outer row.
- On average, the average field luminance levels for the HPS are found to exceed those for LED#1 by 1.48 cd/m^2 in the NE lane outer row, 1.29 cd/m^2 in the NE lane center row, 1.20 cd/m^2 in the SW lane center row, and 0.97 cd/m^2 in the SW lane outer row.

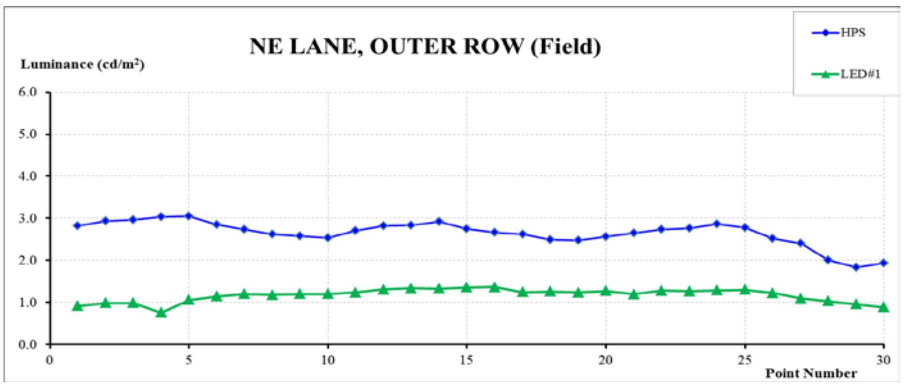


Figure G-1 Comparison of the field luminance data for HPS vs. LED#1 (NE lane, outer row)

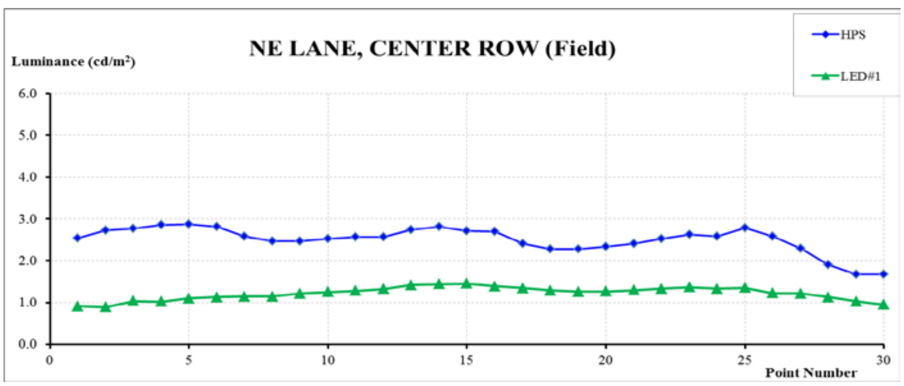


Figure G-2 Comparison of the field luminance data for HPS vs. LED#1 (NE lane, center row)

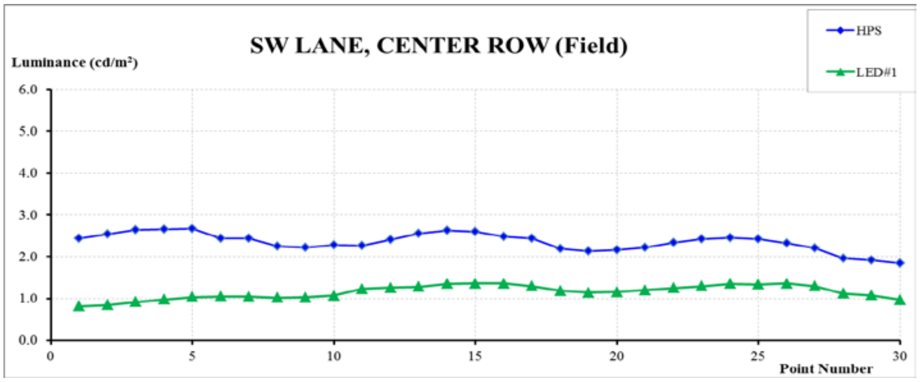


Figure G-3 Comparison of the field luminance data for HPS vs. LED#1 (SW lane, center row)

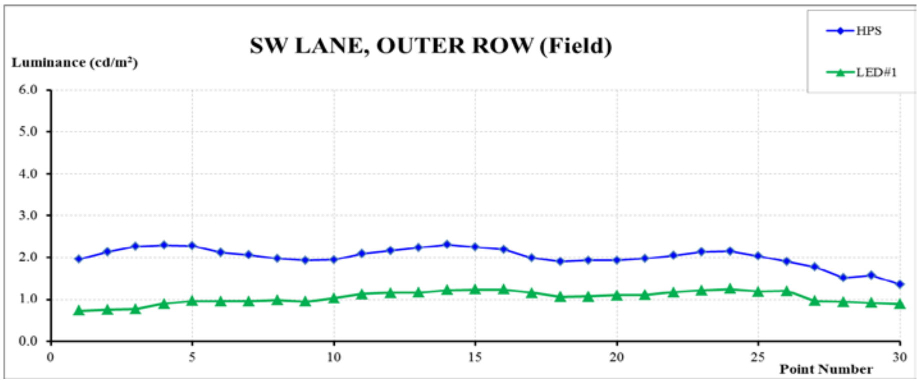


Figure G-4 Comparison of the field luminance data for HPS vs. LED#1 (SW lane, outer row)

G.1.2 Based on the Software Results

Figures G-5, G-6, G-7 and G-8 graphically compare the AGi32 luminance results for the HPS vs. LED#1 for the NE lane outer row, NE lane center row, SW lane center row and SW lane outer row, respectively. According to the results:

- Compared to the HPS, the luminance levels produced by LED#1 display little variation with distance along each row. On the other hand, the HPS exhibits clear peaks and valleys in luminance distribution along each row.
- For all rows, the AGi32 luminance results for the HPS are always greater than those for LED#1. The AGi32 luminance results for the HPS are found to go above those for LED#1 by 0.41 – 1.27 cd/m^2 in the NE lane outer row, 0.41 – 1.19 cd/m^2 in the NE lane center, 0.24 – 0.99 cd/m^2 in the SW lane center row, and 0.20 – 0.81 cd/m^2 in the SW lane outer row.
- On average, the AGi32 luminance results for the HPS are found to exceed those for LED#1 by 0.85 cd/m^2 in the NE lane outer row, 0.72 cd/m^2 in the NE lane center, 0.58 cd/m^2 in the SW lane center row, and 0.51 cd/m^2 in the SW lane outer row.

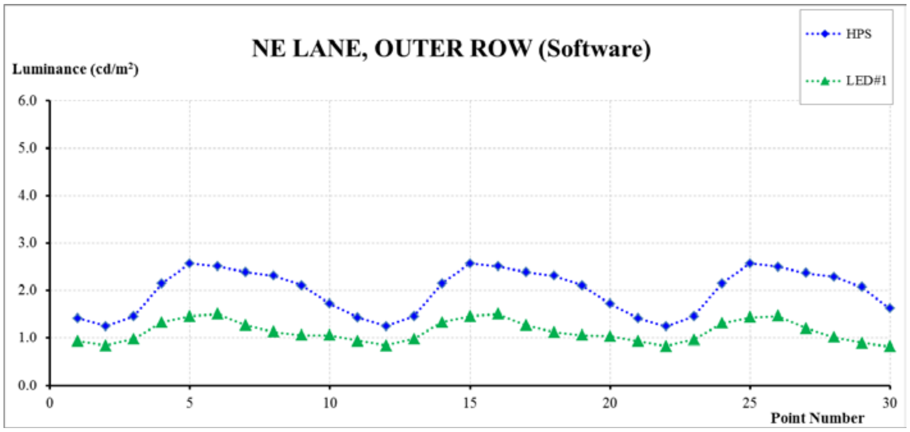


Figure G-5 Comparison of the software luminance results for HPS vs. LED#1 (NE lane, outer row)

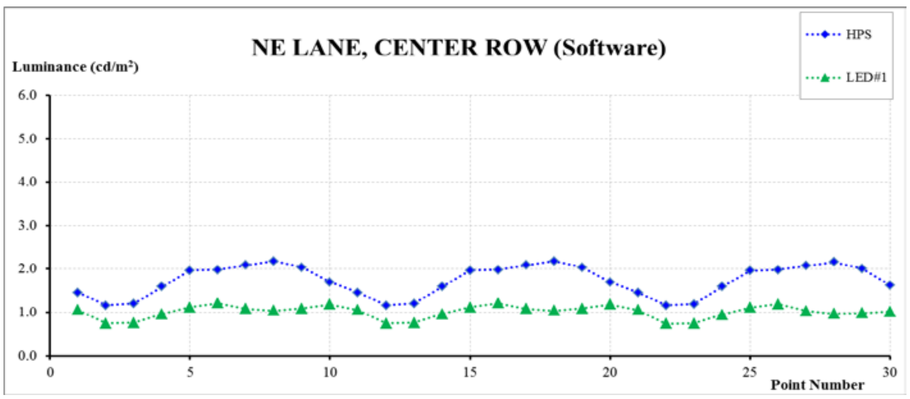


Figure G-6 Comparison of the software luminance results for HPS vs. LED#1 (NE lane, center row)

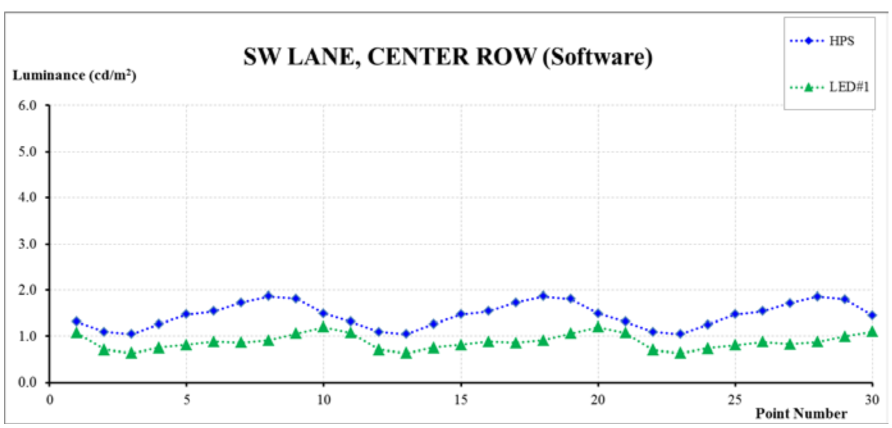


Figure G-7 Comparison of the software luminance results for HPS vs. LED#1 (SW lane, center row)

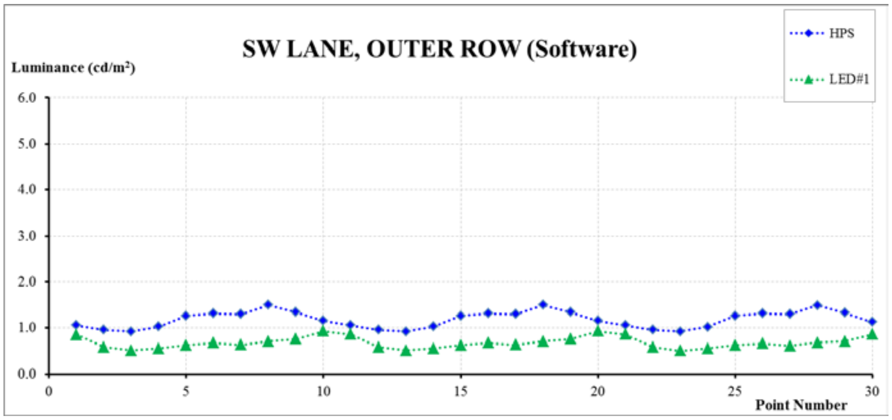


Figure G-8 Comparison of the software luminance results for HPS vs. LED#1 (SW lane, outer row)

G.2 HPS VS. LED#2

G.2.1 Based on the Field Data

The average field luminance data for the HPS are graphically compared with the average field luminance data for LED#2 in Figures G-9, G-10, G-11 and G-12 for the NE lane outer row, NE lane center row, SW lane center row and SW lane outer row, respectively. According to the results:

- For all four rows, the luminance levels produced by either luminaire display little variation with distance
- For all rows but the NE lane center row, the average field luminance levels produced by the HPS are generally greater than those produced by LED#2. However, the differences were rather slight. On average, the average field luminance levels produced by the HPS are found to exceed those produced by LED#2 by 0.41 cd/m^2 in the NE lane outer row, 0.33 cd/m^2 in the SW lane center row, and 0.49 cd/m^2 in the SW lane outer row.

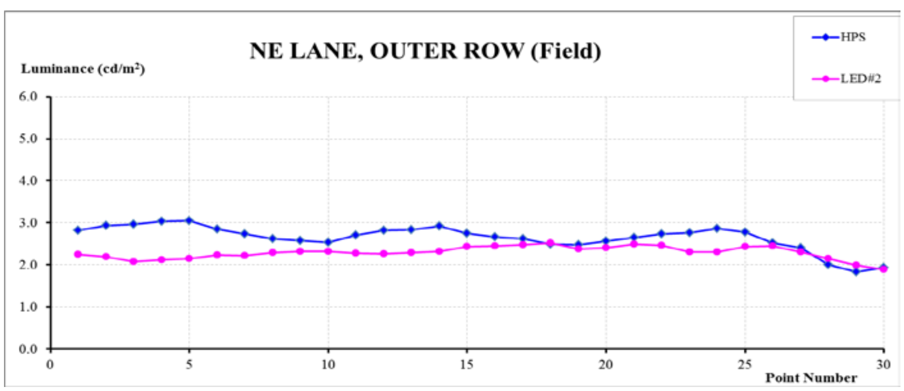


Figure G-9 Comparison of the field luminance data for HPS vs. LED#2 (NE lane, outer row)

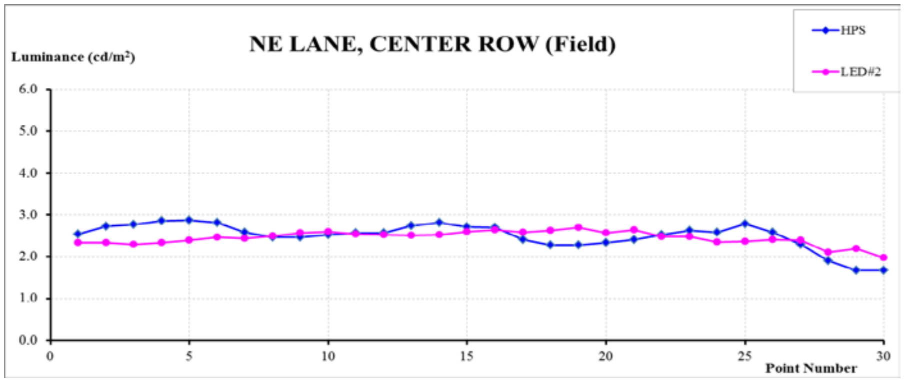


Figure G-10 Comparison of the field luminance data for HPS vs. LED#2 (NE lane, center row)

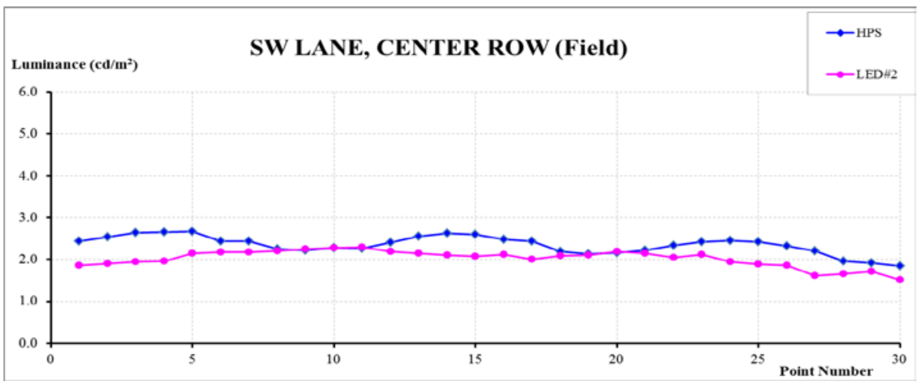


Figure G-11 Comparison of the field luminance data for HPS vs. LED#2 (SW lane, center row)

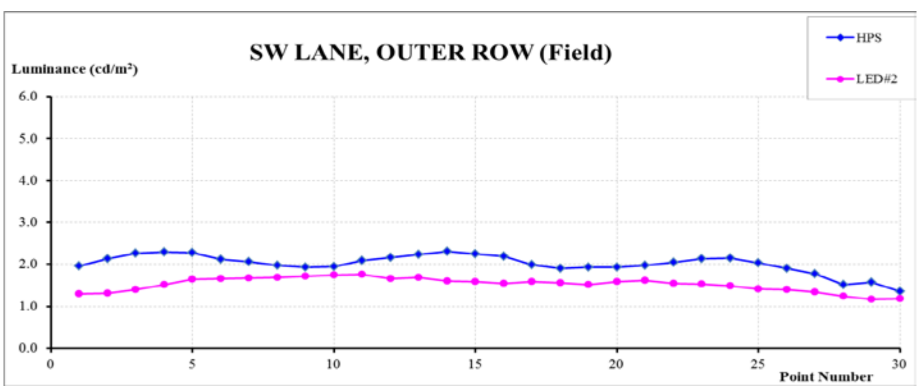


Figure G-12 Comparison of the field luminance data for HPS vs. LED#2 (SW lane, outer row)

G.2.2 Based on the Software Results

The graphical comparison of the AGi32 luminance results for the HPS vs. LED#2 are illustrated in Figures G-13, G-14, G-15 and G-16 for the NE lane outer row, NE lane center row, SW lane center row and SW lane outer row, respectively. According to the results:

- For all four rows, the AGi32 luminance results for both the HPS and LED#2 indicate sharp fluctuations in luminance with distance. However, the magnitude of the fluctuations in luminance levels produced by the HPS is not as high as those produced by LED#2. Thus, the AGi32 results for the HPS point out a more uniform luminance distribution along a given row than the AGi32 results for LED#2.

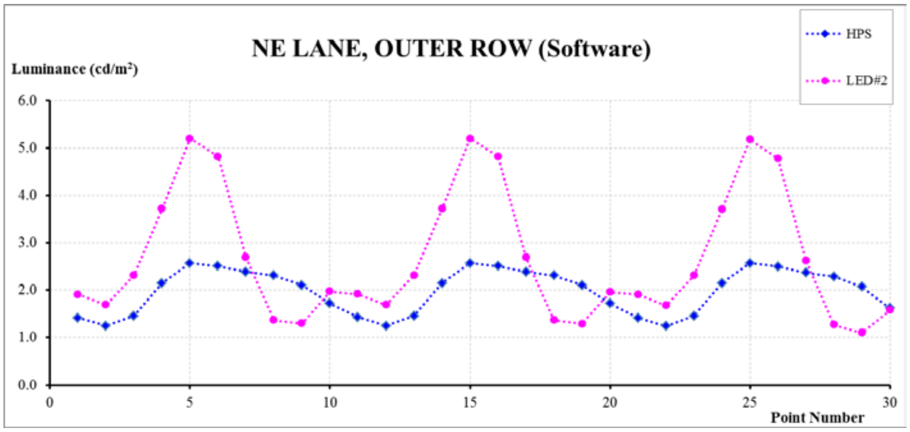


Figure G-13 Comparison of the software luminance results for HPS vs. LED#2 (NE lane, outer row)

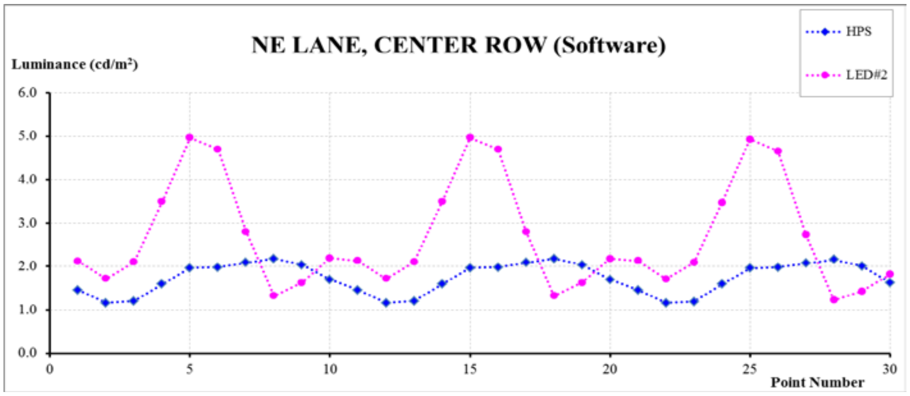


Figure G-14 Comparison of the software luminance results for HPS vs. LED#2 (NE lane, center row)

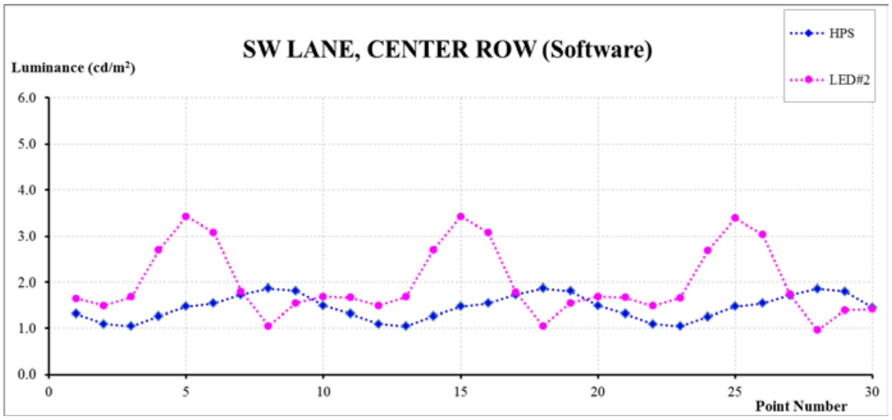


Figure G-15 Comparison of the software luminance results for HPS vs. LED#2 (SW lane, center row)

- At the mid grid points between the light poles, the luminance levels produced by LED#2 are generally considerably greater than those produced by the HPS. At those points, the AGi32 luminance results for LED#2 are found to exceed those for the HPS by up to 2.63 cd/m^2 in the NE lane outer row, 2.99 cd/m^2 in the NE lane center row, 1.95 cd/m^2 in the SW lane center row, and 0.87 cd/m^2 in the SW lane outer row.

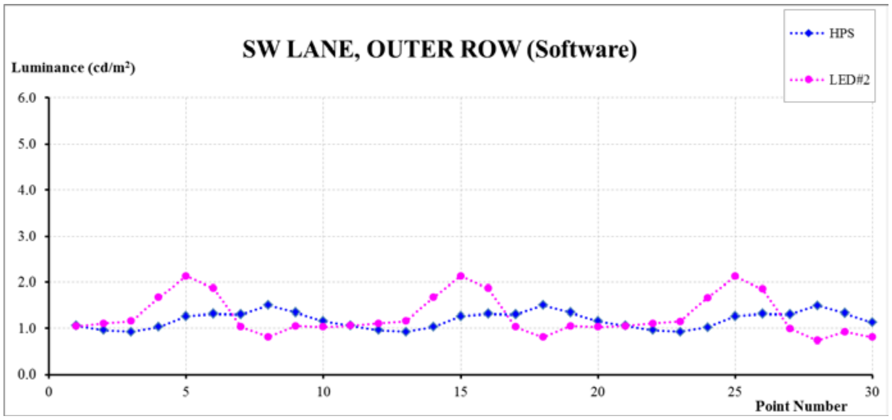


Figure G-16 Comparison of the software luminance results for HPS vs. LED#2 (SW lane, outer row)

G.3 HPS VS. LED#3

G.3.1 Based on the Field Data

The graphical comparison of the average field data for the HPS vs. LED#3 are illustrated in Figures G-17, G-18, G-19 and G-20 for the NE lane outer row, NE lane center row, SW lane center row and SW lane outer row, respectively. According to the results:

- For all four rows, the luminance levels produced by either luminaire display little variation with distance.
- For all rows, the average field luminance levels produced by the HPS are generally greater than those produced by LED#3.
- On average, the average field luminance levels produced by the HPS are found to exceed those produced by LED#3 by 0.59 cd/m^2 in the NE lane outer row, 0.79 cd/m^2 in the NE lane center row, 0.99 cd/m^2 in the SW lane center row, and 0.78 cd/m^2 in the SW lane outer row.

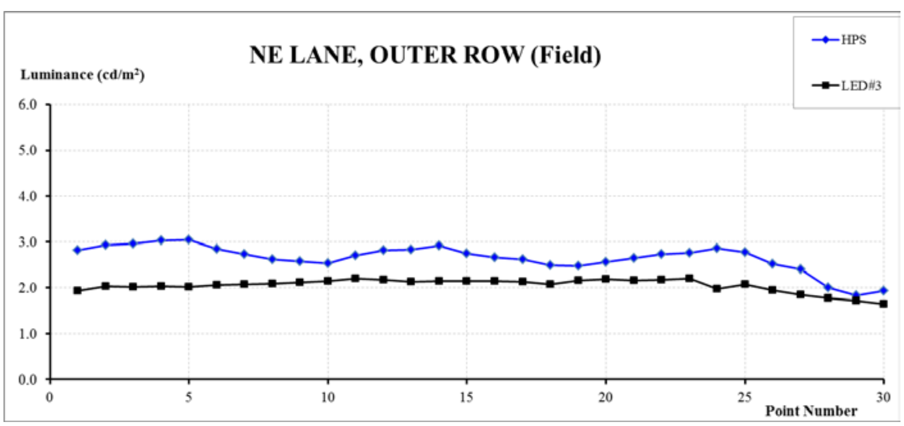


Figure G-17 Comparison of the field luminance data for HPS vs. LED#3 (NE lane, outer row)

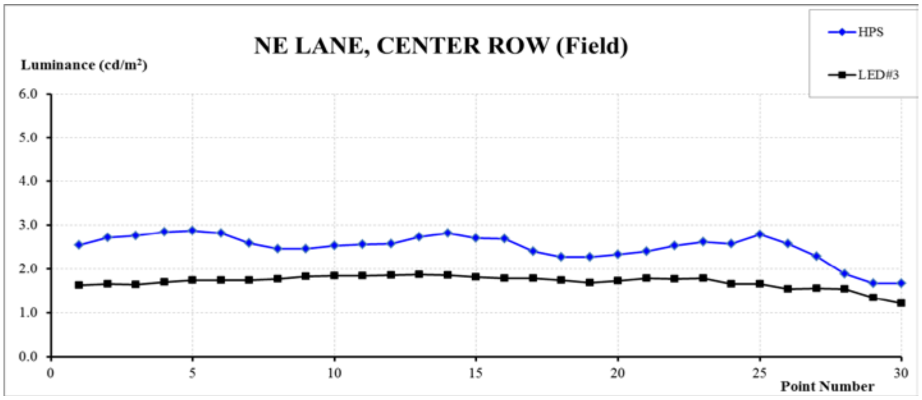


Figure G-18 Comparison of the field luminance data for HPS vs. LED#3 (NE lane, center row)

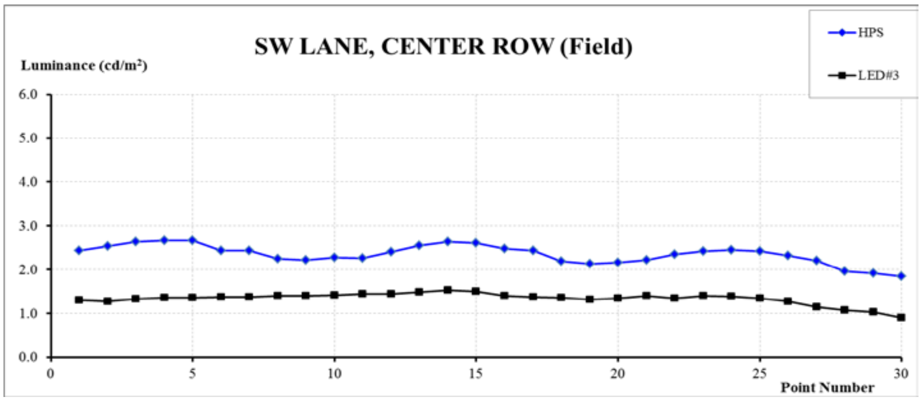


Figure G-19 Comparison of the field luminance data for HPS vs. LED#3 (SW lane, center row)

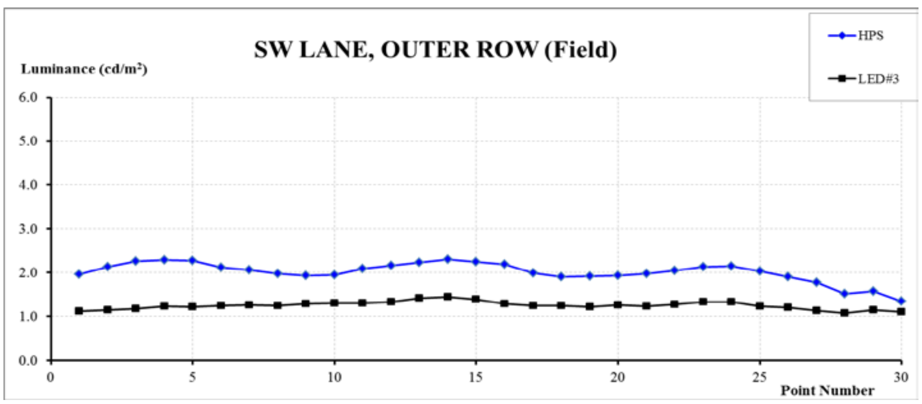


Figure G-20 Comparison of the field luminance data for HPS vs. LED#3 (SW lane, outer row)

G.3.2 Based on the Software Results

The graphical comparison of the AGi32 luminance results for the HPS vs. LED#3 are shown in Figures G-21, G-22, G-23 and G-24 for the NE lane outer row, NE lane center row, SW lane center row and SW lane outer row, respectively. According to the results:

- For a given row, the AGi32 luminance results for both the HPS and LED#3 indicate clear fluctuations in luminance with distance. However, the magnitude of the fluctuations in luminance levels produced by the HPS is not as high as those produced by LED#3. Thus, the AGi32 results for the HPS point out a more uniform luminance distribution along a given row than the AGi32 results for LED#3.
- For a given row, the luminance levels produced by the HPS attain peaks in the close vicinity of the light poles. On the other hand, for a given row, the luminance levels produced by LED#3 attain peaks at the mid grid points between the light poles.
- For a given row, the luminance levels produced by the HPS go somewhat above the luminance levels produced by LED#3 only in the vicinity of the light poles. Otherwise, the luminance levels produced by LED#3 are considerably higher than those produced by the HPS. Indeed, the AGi32 luminance results for LED#3 exceed the AGi32 results for the HPS by up to 2.42 cd/m^2 in the NE lane outer row, 1.63 cd/m^2 in the NE lane center row, 1.06 cd/m^2 in the SW lane center row, and 0.70 cd/m^2 in the SW lane outer row.

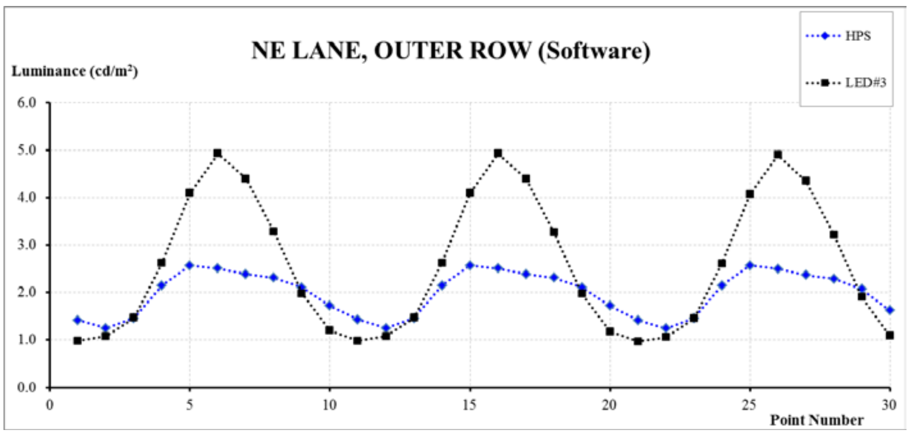


Figure G-21 Comparison of the software luminance results for HPS vs. LED#3 (NE lane, outer row)

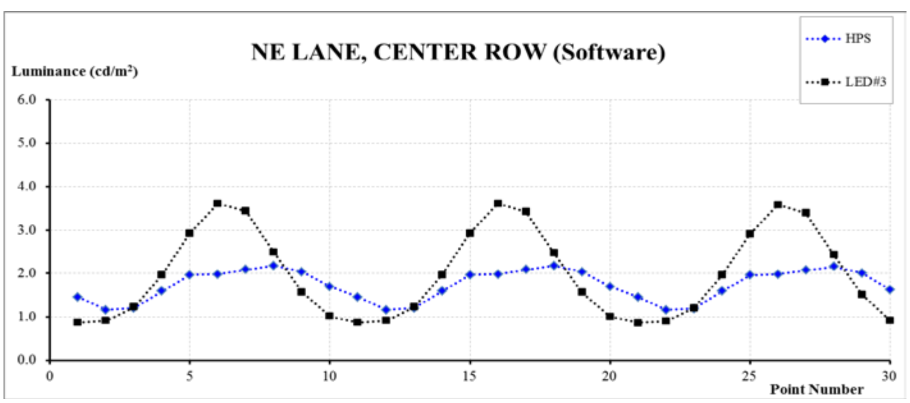


Figure G-22 Comparison of the software luminance results for HPS vs. LED#3 (NE lane, center row)

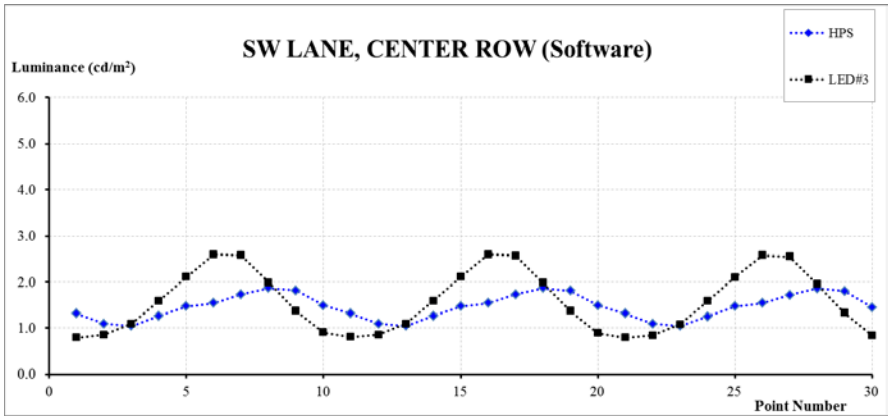


Figure G-23 Comparison of the software luminance results for HPS vs. LED#3 (SW lane, center row)

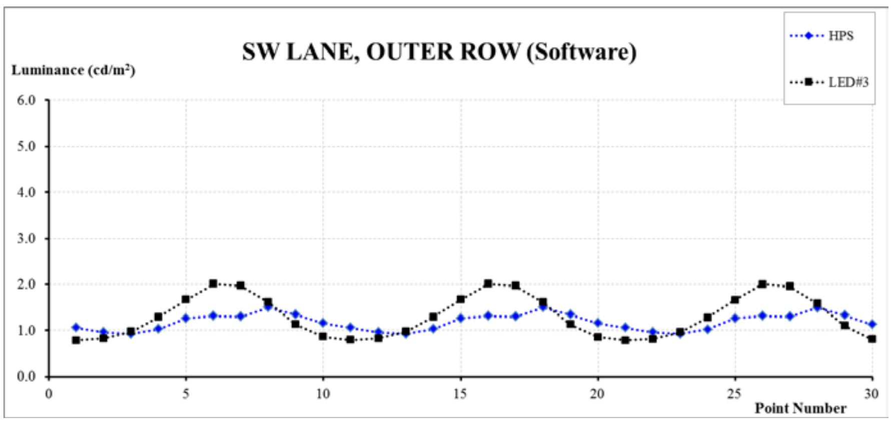


Figure G-24 Comparison of the software luminance results for HPS vs. LED#3

APPENDIX H IDOT DESIGN CRITERIA

Table H-1 IDOT design requirements for illuminance

Roadway Facility Classification	Area Classification (Pedestrian Conflict Area)	Average Maintained Horizontal Illuminance (foot-candle)			Uniformity Ratio (Ave./Min.)
		Pavement Classification			
		R1	R2 & R3	R4	
Freeway	Class A	0.6	0.9	0.8	3:1
	Class B	0.4	0.6	0.5	
Expressway	High	1.0	1.4	1.3	
	Medium	0.8	1.2	1.0	
	Low	0.6	0.9	0.8	
Major	High	1.2	1.7	1.5	
	Medium	0.9	1.3	1.1	
	Low	0.6	0.9	0.8	
Collector	High	0.8	1.2	1.0	4:1
	Medium	0.6	0.9	0.8	
	Low	0.4	0.6	0.5	
Local	High	0.6	0.9	0.8	6:1
	Medium	0.5	0.7	0.6	
	Low	0.3	0.4	0.4	
Alleys	High	0.4	0.6	0.5	
	Medium	0.3	0.4	0.4	
	Low	0.2	0.3	0.3	

Table H-2 IDOT design requirements for luminance

Road and Pedestrian Conflict Area		Average Luminance L_{avg} (cd/m^2)	Uniformity Ratio L_{avg}/L_{min} (cd/m^2) (Maximum Allowed)	Uniformity Ratio L_{max}/L_{min} (cd/m^2) (Maximum Allowed)
Road	Pedestrian Conflict Area			
Freeway	N/A	0.6	3.5	6.0
	N/A	0.4	3.5	6.0
Expressway	High	1.0	3.0	5.0
	Medium	0.8	3.0	5.0
	Low	0.6	3.5	6.0
Major	High	1.2	3.0	5.0
	Medium	0.9	3.0	5.0
	Low	0.6	3.5	6.0
Collector	High	0.8	3.0	5.0
	Medium	0.6	3.5	6.0
	Low	0.4	4.0	8.0
Local	High	0.6	6.0	10.0
	Medium	0.5	6.0	10.0
	Low	0.3	6.0	10.0

APPENDIX I PRELIMINARY ECONOMIC ANALYSIS METHOD

This Appendix presents details on the computation of initial cost, maintenance cost, energy cost and salvage value for life-cycle cost analysis of roadway luminaires as recommended by AASHTO (1993) and IESNA Lighting Economics Committee (1996).

I.1 INITIAL COSTS

The types of initial costs are

- Luminaire cost,
- Foundation cost,
- Breakaway coupling cost,
- Pole cost,
- Labor cost for installation.

Each street light includes one luminaire, one metal and concrete foundation, four breakaway couplings, and an aluminum pole at the given mounting height. All initial costs are presented in today's dollars. Thus, no calculation is required to convert them into present value.

I.2 MAINTENANCE COSTS

The maintenance cost for a particular type of roadway luminaire is the luminaire replacement that occurs at the end of the lifetime of the luminaire. In addition, there is also periodic re-lamping (*and ballast replacement if needed*) cost for HPS luminaires. Unlike LED lamps, HPS lamps may fail catastrophically. Thus, periodic re-lamping of the existing HPS luminaires is performed every four years. Conversely, re-lamping is not performed for the LED roadway luminaires. Instead, the LED luminaires are replaced once the lifetime of the LEDs is over.

If the lifetime of a particular roadway luminaire is greater than the analysis period, it is assumed that there is no maintenance cost for luminaire replacement through the analysis period. For the LED roadway luminaires, luminaire replacement occurs when the LEDs complete their life cycle. The estimated lifetime of the LEDs is 50,000 hours, which corresponds to a lifetime of 13.7 years assuming a daily usage of 10 hours. Thus, the maintenance cost of the LED roadway luminaires includes luminaire replacement cost every 13.7 years. On the other hand, the lifetime of the HPS luminaire is 263,000 hours, which corresponds to: $\frac{263{,}000\ hr}{24hr/day * 365days/year} = 30.02$ years. So if the analysis period is less than or equal to 30.02 years, it is assumed that the HPS luminaire is not replaced within the analysis period. Thus, the maintenance cost of the HPS luminaire involves re-lamping (*and ballast replacement if needed*) every four years if the analysis period is less than or equal to 30 years.

It should be noted a proper lumen depreciation study specifically for LEDs should be conducted for precise determination of life cycle costs, and the time when the LED luminaires should be replaced. This is because approximate dirt depreciation values are not known at this time (given that there will not be any scheduled cleaning of the lenses at any point in time). For LED fixtures L70 (70% of the initial output of the fixture) is typically used to determine the end of service life. As of today, it is difficult to accurately estimate the luminaire maintenance (i.e. light loss) factors without actual data on dirt accumulation and the lumen decay output over time. A second phase of this study is recommended with one of the tasks as accurate estimation of the light loss factors for the LED roadway luminaires.

Both the luminaire replacement costs and re-lamping costs are to occur at some point(s) in the analysis period. Suppose the length of the analysis period is n years, and the lifetime of a particular roadway luminaire is k years where k<n. For the roadway luminaire, the first luminaire replacement cost is to be incurred in year k. The present value of the luminaire replacement

cost incurred in year k is found from Equation (1) (IESNA Lighting Economics Committee, 1996):

$$P_{M,k} = \frac{F_k}{(1+i)^k} \tag{1}$$

where
F_k: Future value of the maintenance cost incurred in year k.
$P_{M,k}$: Present value of the maintenance cost incurred in year k.
i: Annual discount rate (a.k.a. opportunity rate of capital).

If the effects of inflation rate are also considered in computations, AASHTO (1993) recommends the use of inflated maintenance costs as future values (i.e. F_k) and nominal rate of interest including its inflation premium as the discount rate (i.e. i). Alternatively, one can also use non-inflated maintenance costs as future values (i.e. F_k) and real rate of interest that includes the inflation premium as the discount rate (i.e. i). If there is uncertainty associated with predicting future rates of inflation, the analyst can use non-inflated future costs and the real rate of interest in Equation (1). Thereby, the need to speculate about future rate of inflation is eliminated (AASHTO, 1993).

I.3 ENERGY COSTS

The energy costs considered in this study stem from the electricity consumed by the roadway luminaires. For a particular roadway luminaire, the annual cost of energy consumption is computed from Equation (2) as follows:

$$E = \frac{W * c * t_d * 365}{1000} \tag{2}$$

where
E: Annual cost of electricity in today's dollars for the selected roadway luminaire.
W: Luminaire wattage.
c: Price of electricity in today's dollars.
t_d: Average daily usage of the roadway luminaire (assumed to be 10 hours per day).

If the analysis period is n years, the net present value of the total energy cost for a particular roadway luminaire is computed from Equation (3) as follows (IESNA Lighting Economics Committee, 1996):

$$P_E = E\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] \tag{3}$$

where
P_E: Present value of the total energy costs incurred in the analysis period.
E: Annual cost of electricity as of October, 2011 for the selected roadway luminaire.
i: Annual discount rate (a.k.a. opportunity rate of capital).
n: Length of analysis period in years.

If the effects of inflation rate are considered, then the analyst can find the inflated electricity cost for each year, and then discount the individual inflated electricity costs for each future year to the present value using Equation (1). In this case, the discount rate used in Equation (1) should be the nominal rate of interest including its inflation premium. Alternatively, the analyst can use non-inflated electricity costs and compute the present value of total energy cost using Equation (3) (AASHTO, 1993).

I.4 SALVAGE VALUE

Salvage value is defined as the value of reusable materials at the end of the analysis period. Suppose there is a roadway luminaire with a lifetime of 15 years, and the analysis period is 20 years. At the end of year 15, the roadway luminaire needs to be replaced with a new one. By the end of the analysis period, the new roadway luminaire will have been used by only five years, which corresponds to one-third of its lifetime. Therefore, “two-thirds” of the new roadway luminaire will still be reusable at the end of the analysis period. If the luminaire replacement cost is, say, \$3,000 for the luminaire, the salvage value equals $\frac{2}{3} * \$3{,}000 = \$2{,}000$. However, this salvage value is incurred at the end of the analysis period, and it should be discounted to the present value. If the analysis period is n years, salvage value is converted to the present value using Equation (4) as follows (IESNA Lighting Economics Committee, 1996):

$$P_S = \frac{S}{(1+i)^n} \tag{4}$$

where
P_S: Present value of the salvage value at the end of year n.
S: Salvage value at the end of year n.
i: Annual discount rate (a.k.a. opportunity rate of capital).
n: Length of analysis period in years.

I.5 PRESENT VALUE OF LIFE-CYCLE COSTS

After all maintenance costs, energy costs and salvage value for a particular roadway luminaire are converted into their present value, the total present value for the luminaire is found from Equation (5) (IESNA Lighting Economics Committee, 1996):

$$PV = P_i + P_M + P_E - P_S \tag{5}$$

where
PV: Present value of the life-cycle costs incurred in the analysis period.
P_i: Total initial costs.
P_M: Present value of the total maintenance costs incurred in the analysis period.
P_E: Present value of the total energy costs incurred in the analysis period.
P_S: Present value of the salvage value at the end of the analysis period.

I.6 EQUIVALENT UNIFORM ANNUAL VALUE OF LIFE-CYCLE COSTS

In addition to the present value of life cycle costs, one can also present the “Equivalent Uniform Annual Value” (EUAV) of life cycle costs. EUAV is defined as a uniform annual cost that is:

- Spread over the entire analysis period, and
- The equivalent of the total life-cycle cost.

In other words, the total life-cycle cost over the analysis period is equivalent to uniform annual payments of EUAV spread over the analysis period. Given the present value of life cycle costs, the EUAV is computed using Equation (6) (IESNA Lighting Economics Committee, 1996):

$$EUAV = PV\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \quad (6)$$

where
PV: Present value of the life-cycle costs incurred in the analysis period.
EUAV: Equivalent uniform annual value of the life-cycle costs incurred in the analysis period.
i: Annual discount rate (a.k.a. opportunity rate of capital).
n: Length of analysis period in years.

1.7 EXAMPLE CALCULATION OF LIFE-CYCLE COSTS FOR AN HPS STREET LIGHT

In this section, the life-cycle costs for an assumed 250W HPS street light are computed for per-mile segment of an assumed roadway. For the assumed HPS street light, the mounting height is 45 ft, and the pole spacing is 218 ft. The life cycle costs are computed for a period of 30 years.

I.7.1 Initial Costs

The initial costs (P_i) include the installed cost of the luminaire, foundation, four breakaway couplings, and aluminum pole. The initial cost for the assumed HPS street light is found by adding up those costs as follows:

$$P_i = \$500 + \$476 + \$408 + \$2{,}306 = \$3{,}690 \quad (7)$$

where
P_i is the total initial costs for one whole unit of installed HPS streetlight (including the luminaire, pole, foundation and breakaway couplings),
$500 is the installed cost of the HPS luminaire,
$476 is the installed cost of the foundation,
$408 is the installed cost of four breakaway couplings,
$2,306 is the installed cost of the 45-ft pole.

I.7.2 Maintenance Costs

For the HPS roadway luminaire, the maintenance costs include replacement of the roadway luminaire once its lifetime is over as well as periodic re-lamping *(and ballast replacement if needed)* that is performed every four years by IDOT. The expected lifetime of the HPS (GE M-400) luminaire is 263,000 hours, which corresponds to $263{,}000/(24 * 365) = 30.02$ years. Since 30.02 > 30, the roadway luminaire will not be replaced during the 30-year analysis period. However, IDOT performs re-lamping *(and ballast replacement if needed)* every four years, which is assumed to cost $250 including labor and materials. The re-lamping will be performed every four years (i.e. in years 4, 8, 12, …, 24, and 28). Hence, the present value of total re-lamping cost is found as follows:

$$P_{RL} = \sum_k \$250 * \frac{(1+3.12\%)^k}{(1+5.42\%)^k} = \$1{,}248.81 \quad (8)$$

where
P_{RL} is the present value of total re-lamping *(and ballast replacement if needed)* cost in the analysis period.
$k = 4, 8, 12, \ldots, 24, 28.$
3.12% is the assumed annual inflation rate.
5.42% is the assumed annual nominal interest rate.

Since there is no luminaire replacement for the HPS during the 30-year analysis period, the present value of the total maintenance cost is equal to P_{RL}:

$$P_M = P_{RL} = \$1{,}248.81. \tag{9}$$

where
P_M is the total maintenance cost over the analysis period.

I.7.3 Energy Costs

The cost of annual energy usage is found from Equation (2). As of October, 2011, the cost of electricity is \$0.07/ kW-hr. Assuming a daily usage of 10 hours, the annual cost of electricity is found as follows for the assumed HPS luminaire:

$$E = \frac{250 * \$0.07 * 10 * 365}{1000} = \$63.88 \tag{10}$$

where
250 W is the lamp wattage of the HPS.

If the inflation factor is not used in the life-cycle cost analysis, the present value of total energy costs over the analysis period is found from Equation (3). However, an inflation factor of 3.12% is assumed. Thus, the annual energy costs should be individually inflated for each year, and then the inflated annual energy costs should be individually discounted to present value using the assumed nominal interest rate of 5.42%. The present value of the total energy costs for the HPS luminaire is found as follows:

$$P_E = \sum_{k=1}^{30} \left\{ \$63.88 * \frac{(1+3.12\%)^k}{(1+5.42\%)^k} \right\} = \$1{,}386.27 \tag{11}$$

where
P_E is the present value of the total energy costs over the analysis period.
3.12% is the assumed annual inflation rate.
5.42% is the assumed annual nominal interest rate.

I.7.4 Salvage Value

The salvage value accounts for the unused portion of the last installed/ replaced unit at the end of the analysis period. For the HPS roadway luminaire, there are two components whose salvage value should be computed at the end of the analysis period: i) The last installed/ replaced roadway luminaire, ii) the last replaced lamp and ballast.

The lifetime of the HPS roadway luminaire is 30.02 years. The analysis period is 30 years, so by the end of the analysis period: $100\% - \frac{30.02-30}{30.02} * 100 = 0.08\%$ of the HPS luminaire will have been "unused". Although an unused portion of 0.08% is trivial, the corresponding salvage value is computed to illustrate the calculations to the reader.

To find the present value of salvage, one has to find present value of the cost of the unit purchased at the end of the analysis period. If one purchases an HPS luminaire at the end of the analysis period (i.e. in year 30), the inflated cost of the HPS luminaire will be $\$500 * (1 + 3.12\%)^{30} = \$1{,}256.77$ in year 30. In today's dollars, this will correspond to a present value of $\frac{\$1{,}256.77}{(1+5.42\%)^{30}} = \$257.97$. Thus, the present value of the HPS luminaire in year 30 is \$257.97. Since 0.08% of the HPS luminaire will have been "unutilized" in the end of year 30, the present value of salvage is found as:

$$P_{S,Lum.} = 0.08\% * \frac{\$500 * (1 + 3.12\%)^{30}}{(1 + 5.42\%)^{30}} = 0.08\% * \$257.97 = \$0.20 \tag{12}$$

where
$P_{S,Lum.}$ is the present value of salvage derived from the unused portion of the last installed roadway luminaire.

Likewise, the last periodic re-lamping (and ballast replacement if required) is to be performed in the 28th year as shown in Section J.2. Since re-lamping (and ballast replacement if required) is performed every four years, $\frac{30-28}{4} = 50.0\%$ of the last replaced lamp and ballast will have been used by the end of the analysis period. Thus, the salvage value originating from the last replaced lamp (and ballast if required) is computed as follows:

$$P_{S,Lamp} = 50\% * \frac{\$250 * (1 + 3.12\%)^{30}}{(1 + 5.42\%)^{30}} = 50\% * \$128.98 = \$64.49 \tag{13}$$

Hence, the present value of total salvage for the HPS luminaire is found as follows:

$$P_S = P_{S,Lum.} + P_{S,Lamp} = \$0.20 + \$64.49 = \$64.69 \tag{14}$$

It should be noted that IDOT may assume zero salvage at the end of the analysis period and may not include the salvage value in the life-cycle cost analysis.

I.7.5 Present Value of Total Life-Cycle Costs

The present value of total life-cycle costs are found from Equation (5). It is the summation of the initial costs found in Equation (7), maintenance costs found in Equation ((9) and energy costs found in Equation (11) minus the salvage value found in Equation (14):

$$PV = \$3{,}690 + \$1{,}248.81 + \$1{,}386.27 - \$64.69 = \$6{,}260.39$$

where
PV is the present value of the total life-cycle costs for the assumed HPS street light.

To find the life-cycle costs per mile road segment, the life-cycle cost per 10-mile road segment is computed, and then divided by 10. Thereby, rounding error is minimized. Since the pole spacing for the assumed HPS street light is given as 218 ft, the number of luminaires required per 10-mile of road segment is $10 * 5{,}280/218 \approx 243$. Hence, the present value of the total life-cycle costs per ten-mile of road segment will be $243 * \$6{,}260.39 = \$1{,}521{,}274.77$. The present value of the total life-cycle costs per mile of road segment will be $\$1{,}521{,}274.77/10 \approx \$152{,}127$.

I.8 EXAMPLE CALCULATIONS OF LIFE-CYCLE COSTS FOR AN LED STREET LIGHT

In this section, the life-cycle costs for an assumed 150W LED street light are computed for per-mile segment of an assumed roadway. For the assumed LED street light, the mounting height is 45 ft, and the pole spacing is 228 ft. The life cycle costs are computed for a period of 30 years.

I.8.1 Initial Costs

The initial costs (P_i) include the installed cost of the luminaire, foundation, four breakaway couplings, and aluminum pole. The initial cost for the assumed LED street light is found by adding up those costs as follows:

$$P_i = \$1{,}000 + \$476 + \$408 + \$2{,}306 = \$4{,}190 \qquad (15)$$

where
P_i is the total initial cost for one whole unit of the installed LED streetlight (including the luminaire, pole, foundation and breakaway couplings),
\$1,000 is the installed cost of the LED luminaire,
\$476 is the installed cost of the metal and concrete foundation,
\$408 is the installed cost of four breakaway couplings,
\$2,306 is the installed cost of the 45-ft pole.

I.8.2 Maintenance Costs

The maintenance costs for the LED street light include replacement of the roadway luminaire once the lifetime of the LED chips is over. The expected lifetime of the LED is 50,000 hours. Assuming a daily usage of 10 hours, the luminaire is expected to be replaced after $\frac{50{,}000}{10*365} = 13.7$ years. So the roadway luminaire will be replaced twice during the 30-year analysis period. The first replacement will be achieved in the 13th year, and the second replacement will be performed approximately in the 27th year. The current cost for luminaire replacement is \$1,090. To find the present value of luminaire replacement in the 13th year, the inflated cost for the 13th year has to be found. Then the inflated cost for the 13th year is discounted to the present value using the nominal interest rate as follows:

$$P_{LR,13} = \frac{\$1{,}090 * (1 + 3.12\%)^{13}}{(1 + 5.42\%)^{13}} = \$818.25 \qquad (16)$$

where
$P_{LR,13}$ is the present value of the luminaire replacement cost in the 13th year.
3.12% is the assumed annual inflation rate.
5.42% is the assumed annual nominal interest rate.

Likewise, the present value of luminaire replacement in the 27th year is found the same way as follows:

$$P_{LR,27} = \frac{\$1{,}090 * (1 + 3.12\%)^{27}}{(1 + 5.42\%)^{27}} = \$600.85 \qquad (17)$$

where
$P_{LR,27}$ is the present values of the luminaire replacement costs for the 27th year.
3.12% is the assumed annual inflation rate,
5.42% is the assumed annual nominal interest rate.

So the present value of the luminaire replacement cost (P_{LR}) through the 30-year analysis period is found as:

$$P_{LR} = \$818.25 + \$600.85 = \$1{,}419.10 \qquad (18)$$

No periodic re-lamping and ballast replacement is to be performed for the LEDs. However, there may be dirt accumulation in lenses, which may result in additional costs. However, this has not been studied in detail and thus, for the time being, additional maintenance costs that may result from dirt accumulation are not considered in the life-cycle cost analysis. Thus, the present value of the total maintenance cost over the analysis period is equal to the present value of the luminaire replacement cost as follows:

$$P_M = P_{LR} = \$1{,}419.10 \qquad (19)$$

where
P_M is the total maintenance cost over the analysis period.

I.8.3 Energy Costs

The cost of annual energy usage is found from Equation (2). As of October, 2011, the cost of electricity is $0.07/ kW-hr. Assuming a daily usage of 10 hours, the annual cost of electricity is found as follows for the assumed LED:

$$E = \frac{150 * \$0.07 * 10 * 365}{1000} = \$38.33 \qquad (20)$$

where
150 W is the lamp wattage of the assumed LED.

If the inflation factor is not used in the life-cycle cost analysis, the present value of total energy costs for the whole analysis period is found from Equation (3). However, an inflation factor of 3.12% is used in this study. Therefore, the annual energy cost should be individually inflated for each year, and then the inflated annual energy costs should be individually discounted to the present value using the nominal interest rate of 5.42%. The present value of the total energy costs is found as follows for LED#2:

$$P_E = \sum_{k=1}^{30} \left\{ \$38.33 * \frac{(1+3.12\%)^k}{(1+5.42\%)^k} \right\} = \$831.76 \qquad (21)$$

where
P_E is the present value of the total energy costs for the whole analysis period.
3.12% is the annual inflation rate,
5.42% is the annual nominal interest rate.

I.8.4 Salvage Value

The salvage value accounts for the unused portion of the last replaced unit at the end of the analysis period. The lifetime of the assumed LED roadway luminaire is 50,000 hours, which corresponds to 13.7 years assuming a daily usage of 10 hours. The analysis period is 30 years, the roadway luminaire will be replaced twice during the analysis period. So by the end of the analysis period, $100\% - \frac{30-2*13.7}{13.7} * 100 = 81.0\%$ of the last replaced roadway luminaire will remain "unutilized".

To find the present value of salvage, one has to find present value of the cost of the unit purchased at the end of the analysis period. If one purchases one unit of the assumed LED luminaire at the end of the analysis period (i.e. in year 30), the inflated cost of the LED luminaire will be $\$1{,}000 * (1 + 3.12\%)^{30} = \$2{,}513.55$ in year 30. In today's dollars, this will correspond to a present value of $\frac{\$2{,}513.55}{(1+5.42\%)^{30}} = \$515.94$. Thus, the present value of the assumed LED luminaire in year 30 is $515.94. Since 81.0% of the last installed LED luminaire will have been "unutilized" in the end of year 30, the present value of salvage is found as:

$$P_{S,Lum.} = 81.0\% * \frac{\$1{,}000 * (1 + 3.12\%)^{30}}{(1 + 5.42\%)^{30}} = 81.0\% * \$515.94 = \$417.91 \quad (22)$$

where
$P_{S,Lum.}$ is the present value of salvage derived from the unused portion of the last replaced roadway luminaire.

Thus, the present value of total salvage for the assumed LED is found as:

$$P_S = P_{S,Lum} = \$417.91 \quad (23)$$

It should be noted that IDOT may assume zero salvage at the end of the analysis period and may not include the salvage value in the life-cycle cost analysis.

I.8.5 Present Value of Total Life-Cycle Costs

The present value of total life-cycle costs are found from Equation (5). It is the summation of the initial costs found in Equation (15), maintenance costs found in Equation ((19) and energy costs found in Equation (21) minus the salvage value found in Equation (23):

$$PV = \$4{,}190 + \$1{,}419.10 + \$831.76 - \$417.91 = \$6{,}022.95$$

where
PV is the present value of the total life-cycle costs per luminaire the assumed LED street light.

To find the life-cycle costs per mile road segment, the life-cycle cost per 10-mile road segment is computed, and then divided by 10. Thereby, rounding error is minimized. Since the pole spacing for the assumed LED street light is given as 228 ft, the number of luminaires required per 10-mile of road segment is $10 * 5{,}280/228 \approx 232$. Hence, the present value of the total life-cycle costs per ten-mile of road segment will be $232 * \$6{,}022.95 = \$1{,}397{,}324.40$. The present value of the total life-cycle costs per mile of road segment will be $\$1{,}397{,}324.40/10 \approx \$139{,}732$.

APPENDIX J LED MANUFACTURER QUESTIONNAIRE

Pursuant to our discussion of March 29th, 2001 at IDOT, would you please provide answers to the following items by April 30th, 2011?

1) Please provide the research team the following items?
   a) Copy of your presentation on that day
   b) Copy of technical data discussed in the presentation
   c) Copy of in-house testing procedures/requirements you discussed in the meeting
2) What is the unit price of your fixture? (assume the order is for 100 units)
3) How many years would the fixture would last (assume the light is on 24/7) before it needs to be replaced? If fixture replacement is not needed, then what components (e.g. power supply, light source, etc.) need to be replaced? And at every how many years?
4) Is there any scheduled maintenance expected to be performed during the life of the fixture?
5) What is the dirt depreciation factor your engineers use for lighting calculations and what cleaning cycle is it based upon?
6) Is the optical assembly IP 66 rated for moisture and dust ingress? If not what is it rated for?
7) Do you recommend high pressure washing of your fixture when it becomes dirty?
8) What is the lumen depreciation factor your engineers use for lighting calculations? (Please be very specific to define the point on the lumen maintenance curve it represents - e.g. L80, L70)
9) Does the lumen depreciation factor you use account for any yellowing or degradation of the lens and/or refractor over time? What material are the lens and/or refractor?
10) Is a ballast/driver depreciation factor used by your engineers for lighting calculations or any other factor goes into the total light loss factor?
11) What efficacy LED are you currently using (lumens/watt)? Do you have pending plans to use a higher output LED?
12) Can higher output LEDs be used in your current fixture or will heat management changes be required in order to use them?
13) What is the initial color temperature of the fixture and what is the end of life color shift that you could reasonably be held to by IDOT spec?
14) Does each LED produce the same light distribution in your fixture design or is each one individually aimed? If not the same distribution for all LEDs, can it be modified to this format? If not, how do you deal with dark spots as individual LEDs fail?
15) What is the warranty length and what is and is not covered?
16) Does a surge arrester come as standard equipment in the luminaire? If not, is it an available option? Can we get the electrical capabilities/spec of the surge arrester? The Surge Protection Device (SPD) does come standard with the product with an optional higher capability product:
17) How is lightning damage handled by the warranty?
18) At what percentage of its rated output do you drive the LED, and does that increase as individual LEDs in the fixture begin to fail?
19) Does the driver have overheating issues and at what temperature will it shut off if it does overheat? What is the driver expected service life?
20) Can we get a spec sheet on the driver? What's the value (0 – 1) of the power factor? Is it available at 480V now or in the near future? Are there lighting management add-ons available for the driver?
21) Are there independent test results (photometric, heat management, accelerated aging, electrical, vibration, etc.) on your luminaire and its components? Can we get a copy?

APPENDIX K PRELIMINARY SUGGESTIONS FOR NEW SPECIFICATIONS

This Appendix presents some suggested items to be included in the future LED Roadway Lighting Specifications by IDOT. The suggested specifications are brought together based on some existing LED Roadway Lighting Specifications published by other agencies such as Bureau of Street Lighting, City of Los Angeles. The reader may refer to Bureau of Street Lighting (2010; 2011) for detailed information on some existing LED Roadway Lighting specifications.

The suggested items for future LED Roadway Specifications by IDOT are divided into seven categories as follows:

1. Listing requirements,
2. Housing requirements,
3. Electrical requirements,
4. LED performance requirements,
5. Photometric (optical) requirements,
6. Layout requirements,
7. Warranty requirements.

Some of the suggested items specify the upper and/ or lower limit of a particular characteristic such as minimum correlated color temperature, maximum pole spacing, etc. The specification of the limiting values for particular characteristics is not within the scope of this report. Therefore, those limiting values are not specified in this section. The following subsections list the suggested items for future LED roadway specifications by IDOT.

K.1 LISTING REQUIREMENTS

1. The luminaire shall be listed and labeled by a National Recognized Testing Laboratory (NRTL) as being in compliance with UL 1598 *(Underwriters Laboratories standard for safety of luminaires)* and suitable for use in wet locations
2. The luminaire shall be RoHS (Restriction of the use of certain hazardous substances in electrical and electronic equipment) compliant.
3. The luminaire shall have an International Electrotechnical Commission (IEC) 529 Ingress Protection (IP) rating of IP 66 *(Dust-tight and protected against water jets)* or greater.

K.2 HOUSING REQUIREMENTS

1. The luminaire housing shall have … housing *(e.g. Die Cast aluminum, etc.).*
2. The luminaire shall be corrosion resistant *(e.g. by being painted bronze, etc.).*
3. The hardware *(e.g. cover, latch, etc.)* on the exterior of the housing shall be made of … *(e.g. stainless steel, zinc, etc.).*
4. The housing shall have …. *(e.g. a clamping assembly with … bolts)* to provide secure assembly to the light pole.
5. The housing shall have provisions for …. *(e.g. 4-bolt slip fitter)* type mounting on …. *(e.g. 2-inch)* type pipe brackets.

6. The housing shall be easy to open both when mounted and when placed on the ground.
7. The housing shall not weight more than … *(e.g. 75)* pounds when fully assembled.
8. The projected area of the housing shall not exceed … sq.-ft.
9. The housing shall comply with the ANSI IEEE C136.31 Roadway Lighting Equipment- Luminaire Vibration for both normal and bridge/ overpass applications.

K.3 ELECTRICAL REQUIREMENTS

1. The luminaire shall have an fully encased and potted integral ballast or power supply that shall:
   i. operate within the voltage range of … to … *(e.g. 120 to 277)* Voltage in alternating current (VAC) ± …% *(e.g. ±10%)* at … *(e.g. 60)* Hertz.
   ii. have a power factor of the ballast or power supply of at least … *(e.g. 0.90)* at full load.
   iii. have total harmonic distortion of less than …% *(e.g. 20%)* at full load.
   iv. have load regulation of ± …% *(e.g. ±1%)* from no load to full load.
   v. have output ripple of less than …% *(e.g. ±10%).*
   vi. have overheat, self-limited short circuit and over-load protection.
   vii. be tabbed for push on terminal connections.
2. If a ballast is used, the precision wound binding of the ballast shall be made of … *(e.g. copper).*
3. The luminaire shall have life rating on all electrical components of at least … *(e.g. 50,000)* hours.
4. The LEDs should not be overdriven more than … percent of the suggested value at an ambient temperature of …^{o}C.
5. The surge protector should function at least … times at …. Voltage level.

K.4 LED PERFORMANCE REQUIREMENTS

1. The light source shall have minimum total initial lumens of … *(e.g. 18,720).*
2. The light source shall have a minimum … *(e.g. 61)* lumens per watt.
3. The light source shall deliver …% *(e.g. 70%)* of initial delivered lumens after … *(e.g. 150,000)* hours of operation.
4. The light source shall lose no more than …% *(e.g. 15%)* of initial delivered lumens due to thermal loading at an ambient temperature of …^{o}C *(e.g. 25^{o}C).*
5. The Correlated Color Temperature (CCT) of the light source shall be …K ± …K. *(e.g. 6000 K ± 500 K).*
6. The Color Rendering Index (CRI) of the light source shall be greater than or equal to … (*e.g. 75*).
7. The light sources should be Energy-Star qualified.

K.5 PHOTOMETRIC REQUIREMENTS

1. Current design criteria in the IDOT tables (e.g. average illuminance/ luminance, Avg/ Min, max/ Min) for different road classifications.
2. IES photometrics from independent test laboratories shall verify the light levels.

K.6 LAYOUT REQUIREMENTS

1. The luminaire shall have a mounting height of between … ft and … ft.
2. The luminaire shall have a … ft *(e.g. 23 ft)* set back from the right edge of driving lane.
3. The luminaire shall have an arm length of … ft. *(e.g. 9 ft).*
4. The pole spacing shall not be greater than/ less than … ft.

K.7 WARRANTY REQUIREMENTS

1. The entire luminaire assembly shall have a minimum of … year warranty from the date of installation.
2. Each individual component (i.e. solid state lighting, heat management, power supply, and housing) shall have a minimum of … year warranty from the date of installation.