IDAHO TRANSPORTATION DEPARTMENT

RESEARCH REPORT

RP 230

LED Luminaires for Roadway Sign Illumination

By

Jeffrey D. Miles

Texas A&M Transportation Institute

Prepared for

Idaho Transportation Department

Research Program, Contracting Services

Division of Engineering Services

http://itd.idaho.gov/highways/research/

October 2015

1. Report No. FHWA-ID-15-230	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle LED Luminaires for Roadway Sign Illumination		5. Report Date October 2015
		6. Performing Organization Code
7. Author(s) (LIST ALL AUTHORS- erase this phrase before final) Jeffrey D. Miles		8. Performing Organization Report No. 602061
9. Performing Organization Name and Address Texas A&M Transportation Institute		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address Idaho Transportation Department Division of Engineering Services, Contracting Services, Research Program PO Box 7129 Boise, ID 83707-7129		13. Type of Report and Period Covered Final or Interim Report 05/24/2013 – 10/31/2015
		14. Sponsoring Agency Code Leave Blank – erase before final
15. Supplementary Notes		

16. Abstract

The researcher collected data to assess the performance of different LED luminaires for use with overhead guide signs by ITD. The performance testing included illuminance and luminance measurements when the units were new and then after being weathered for one year outside. The impact of temperature was evaluated, and a prototype mobile luminance system was developed to provide ITD with a field tool to assess sign performance. Each luminaire was also modeled to provide ITD with information on the potential differences between modeled photometric values versus real world values. When considering current guidance on guide sign lighting, previous research, and the data collected on this project, it is believed that each of the luminaires tested could be used by ITD based on photometric data. It is recommended that the mobile luminance system developed during this project be used to supplement modeling data for evaluating additional luminaires that are being considered for the QPL. The mobile luminance system should also be used for assessing sign maintenance needs.

17. Key Words Light emitting diode, LED, luminaire, illuminance, luminance, modeling, weathering, temperature, mobile measurement, sign		18. Distribution Statement Copies available online at http://itd.idaho.gov/highways/research/	
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. 57 pages	22. Price None

FHWA Form F 1700.7

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					LENGTH		
in	inches	25.4		mm	mm	millimeters	0.039	inches	in
ft	feet	0.3048		m	m	meters	3.28	feet	ft
yd	yards	0.914		m	m	meters	1.09	yards	yd
mi	Miles (statute)	1.61		km	km	kilometers	0.621	Miles (statute)	mi
		AREA					AREA		
in^2	square inches	645.2	millimeters squared	cm^2	mm^2	millimeters squared	0.0016	square inches	in^2
ft^2	square feet	0.0929	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
yd^2	square yards	0.836	meters squared	m^2	km^2	kilometers squared	0.39	square miles	mi^2
mi^2	square miles	2.59	kilometers squared	km^2	ha	hectares (10,000 m^2)	2.471	acres	ac
ac	acres	0.4046	hectares	ha					
		MASS (weight)					MASS (weight)		
oz	Ounces (avdp)	28.35	grams	g	g	grams	0.0353	Ounces (avdp)	oz
lb	Pounds (avdp)	0.454	kilograms	kg	kg	kilograms	2.205	Pounds (avdp)	lb
T	Short tons (2000 lb)	0.907	megagrams	mg	mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME					VOLUME		
fl oz	fluid ounces (US)	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces (US)	fl oz
gal	Gallons (liq)	3.785	liters	liters	liters	liters	0.264	Gallons (liq)	gal
ft^3	cubic feet	0.0283	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
Note: Volumes greater than 1000 L shall be shown in m^3									
		TEMPERATURE (exact)					TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (°F-32)	Celsius temperature	°C	°C	Celsius temperature	9/5 °C+32	Fahrenheit temperature	°F
		ILLUMINATION					ILLUMINATION		
fc	Foot-candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
fl	foot-lamberts	3.426	candela/m^2	cd/cm^2	cd/cm^2	candela/m^2	0.2919	foot-lamberts	fl
		FORCE and PRESSURE or STRESS					FORCE and PRESSURE or STRESS		
lbf	pound-force	4.45	newtons	N	N	newtons	0.225	pound-force	lbf
psi	pound-force per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	pound-force per square inch	psi

Acknowledgments

The researcher, recognizing that no one person can truly complete a project by one's self, would like to thank several different groups and individuals that helped throughout the project. The staff of the Idaho Transportation Department (ITD), and in particular Ethan Griffiths and Ned Parrish, was exceptionally helpful from the original proposal submittal to the final deliverable. Mr. Parrish helped the researcher navigate the differences in proposal and reporting procedures experienced during the study in a manner that made it very easy to be in compliance with ITD requirements. Mr. Griffiths clearly showed the researcher what ITD was already doing with respect to sign lighting and where ITD needed assistance. He also extended the researcher's contacts within the lighting community that helped him obtain lighting luminaires at no cost to the project. The other ITD members of the research panel provided additional useful insight into the needs of ITD with respect to sign lighting.

The author would like to recognize the members of the lighting community that provided new luminaires for evaluation for the project at no cost to the project.

- Mr. Robert Ebbert, Eaton's Cooper Lighting
- Mr. Troy Harms, Acuity Brands
- Mr. Andy Miles, Hubbell Outdoor Lighting
- Mr. Tom Bevan, CREE

Within the Texas A&M Transportation Institute (TTI), there are several additional people that the researcher would like to thank. First, Ms. Fan Ye, who has since left for an academic teaching position in Ohio, was instrumental in the original proposal. The joint work between Ms. Ye and the researcher prior to this project was the foundation to this work. The researcher thanks Mr. Duane Wagner with TTI Facilities and Support who secured funds to build a lighting test deck and oversaw its installation at the Texas A&M University Riverside Campus for this project with no direct cost to the project. Mr. Jeremy Johnson was a great help by providing the necessary space and equipment to evaluate each luminaire with respect to its luminance output and temperature tolerance to freezing temperatures. Dr. Gerald Ullman was also integral to the project with his thorough peer review of the final report. Finally, the researcher thanks Mr. Ivan Lorenz, Mr. George Gillette, and Mr. Kyle Kingsbury for each of their unique contributions to the project.

Table of Contents

List of Tables

List of Figures

List of Acronyms

DOT—Department of Transportation

HPS—High-pressure sodium, a type of luminaire

GUI—Graphical User Interface

ITD—Idaho Transportation Department

LED—Light emitting diode

MH—Metal-halide, a type of luminaire

MUTCD—Manual of Uniform Traffic Control Devices

MV—Mercury-vapor, a type of luminaire

QPL—Qualified products list

TCD—Traffic Control Device

TTI—Texas A&M Transportation Institute

Executive Summary/Abstract

The researcher collected data to assess the performance of different light emitting diode (LED) luminaires for overhead guide signs in Idaho. The research was sponsored by the Idaho Transportation Department, and it was subdivided into four tasks. The researcher assessed the current state-of-the-practice with respect to LED usage for overhead guide sign lighting. He then used this assessment, available literature, and vendor support to identify LED luminaire attributes that should be considered when selecting LED luminaires for overhead guide sign use that would maximize their benefit for the driving public while decreasing the associated installation and maintenance costs for the state of Idaho. The researcher then selected and evaluated five LED luminaires. One high-pressure sodium (HPS) luminaire was also included as a baseline comparison to what ITD is already using. All of the luminaires were photometrically characterized before and after being weathered outdoors for one year. The exact products are listed below.

- Cooper Lighting XTOR Crosstour
- Cooper Lighting XTOR Crosstour MAXX
- Holophane Sign-Vue LED
- CREE 304-FL with Sign Optic
- Hubbell Prototype
- GE HPS150

Four of the LED luminaires and the HPS were also modeled in AGi32 to enable the researcher to provide insight as to how modeled performance compares to real world performance. AGi32 is a commercially available software product used by industry and practitioners to model simple to complex indoor and outdoor lighting conditions. The last primary task was to provide guidance to ITD on what LED luminaires should be allowed on their qualified products list (QPL), and what criteria should be used in the future to determine which luminaires make it onto the ITD QPL. The researcher also conducted temperature testing on each luminaire and developed a prototype mobile sign luminance measurement system.

While the performance of each product differed, all of the LED products evaluated are recommended for eligibility on ITD's QPL based on lighting distribution new and after a year of weathering outside. When considering cost, size, and weight versus performance, the Crosstour provided superior performance overall. The Crosstour MAXX performed well, but the lumen output provided by the 30-Watt Crosstour product was sufficient while having a lower weight, lower installation cost, and lower power consumption. Currently, ITD is considering requiring a 10-year warranty, and only the CREE 304-FL offers a 10-year warranty, while the other LED luminaires come with a 5-year warranty.

The researcher developed a prototype mobile luminance system based on TTI's current system to be used by ITD to evaluate new luminaires and to check in service performance of luminaires used on overhead guide signs. This system is designed to evaluate guide sign performance from the perspective of the driver and enable ITD to assess new luminaires that they are considering adding to their QPL. This

will be especially helpful since no software is currently available to model the luminance of luminaires off of a retroreflective surface. This is because the majority of retroreflective luminance for overhead guide signs is diffuse, but these relationships have not been clearly reported for use in modeling packages. The software used to model the luminaires for this study did over-estimate illuminance (and thus the resulting sign luminance) for all of the luminaires evaluated, so further research is needed in this area.

Chapter 1
Background

Introduction

Effective highway signing is an important component to driver decision making, comfort, and safety. Nighttime visibility of highway signing is a complex problem to investigate, as practitioners and researchers must consider the performance of not only the retroreflective sign sheeting, but the effect of sign geometry, vehicle lighting, sign lighting (when used), other ambient lighting that could help or hinder nighttime visibility, and the driving population (such as the percentage of elderly drivers) upon visibility. For instance, vehicle headlights have been modified to now have a sharper cut-off of their light patterns down and to the right. This is done to reduce the likelihood of vehicular glare to on-coming vehicles, but can put drivers at a disadvantage for seeing signs at night because it also reduces the amount of light illuminating a sign in the distance. Fortunately, there have been great advances in retroreflective sign sheeting that have offset some of these losses. These newer, more efficient retroreflective sign sheeting materials have also enabled some sign lighting to be turned off or removed. However, the decision to reduce sign lighting has largely been a subjective decision and not based on clear guidelines.

Idaho Transportation Department (ITD) is still using sign lighting, and like many transportation agencies, they are looking to reduce cost while maintaining or improving safety. ITD is interested in replacing high-pressure sodium (HPS) luminaires with light emitting diode (LED) luminaires for sign lighting. However, ITD has found it difficult to find meaningful guidance on sign lighting specific LED fixtures on the market, which has impeded the process of implementing this evolving lighting technology. As ITD considers these changes in sign lighting, they also want to consider whether they can remove some sign lighting with the use of newer more efficient retroreflective sign sheeting.

When transportation engineers go to the current standards and specifications, they find little to no assistance with such considerations. The pertinent sections of the engineer's resources, such as the *Manual of Uniform Traffic Control Devices* (MUTCD) were written when turning off or removing sign lights was the exception[(1)]. ITD follows the AASHTO *Roadway Lighting Design Guide* for the sign lighting design, which provides additional information beyond the MUTCD but still falls short of providing guidelines on how to determine if and when sign lighting is needed to achieve adequate nighttime visibility for traffic signs[(2)]. There is also the *FHWA Lighting Handbook*, but it does not discuss guide sign lighting[(3)]. The research discussed herein has been designed to address these concerns facing ITD.

Objective

The primary objectives of this research were to evaluate several different LED luminaires that could be used on overhead guide signs and to provide ITD with guidance on how to conduct future assessments of luminaires to add to their qualified products list (QPL). The objectives were achieved through the bulleted tasks listed below. The first task is discussed throughout this chapter, while the other two tasks are addressed in chapters 2 and 3.

- Review of literature and state-of-the-practice for individual state agencies within the United States of America.
- Photometrically characterize LED luminaires with respect to guide sign geometries and assess light loss through a before and after study.
- Assess the differences between modeling output of AGi32 and field measurements.

State-of-the-Practice

The state-of-the-practice is dictated by both federal and state regulations. Many of these regulations also refer to nationally and internationally recognized books and reports generated through experience and sponsored research, such as the *MUTCD* and the AASHTO *Roadway Lighting Design Guide*.

Before going any further, it would be helpful to define some of the common terms that will be used throughout this section and the rest of the report that may not be common to all readers of this report. Lighting is typically described in terms of illuminance and luminance. Illuminance is the amount of light that is falling or projected onto a surface, and it is measured in lux (lx) or foot-candles (fc). Luminance is the amount of light that an observer would see reflecting off a surface, and it is measured in candelas per meter squared (cd/m^2) or foot-lamberts (fL). Light can be reflected diffusely or specularly. Diffuse reflection means that a surface scatters the incoming light in all directions, while specular reflection reflects the incident light back out in an equal but opposite direction of the incoming light. An interior wall with flat paint would be considered a diffuse reflector, while a mirror would be a specular reflector. Retroreflection differs from diffuse and specular in that it enables a material to reflect light back in the direction of the incoming light; however, retroreflective material loses efficiency as the angle of incidence increases from 0 to 90 degrees, and goes from retroreflective reflection to diffuse reflection. In general, retroreflective material should have optimal return at 0 degrees and no return at 90 degrees. The light reflected from luminaires on overhead guide signs is typically diffuse for the majority of viewing geometries, and the retroreflective component of sign luminance comes from the retroreflected light of vehicle headlights. Subsequently, the luminance of overhead guide signs equipped with luminaires is a combination of diffuse and retroreflected light under nighttime conditions.

The *MUTCD* is the governing document in reference to traffic control devices, and it also includes overhead guide signs [(1)]. Section 2A.07 clearly states that a sign must either be illuminated internally or externally, or the sign face must consist of retroreflective materials. Retroreflectivity, and in particular the minimum maintained values, are discussed in the *MUTCD*. The majority of Table 2A-3 from the 2009 *MUTCD* is replicated in Table 1, and all of the retroreflectivity values are in $cd/lx/m^2$. With regards to guide signing, if a sign does not have lighting, the sign shall have retroreflective sign sheeting that is prismatic for white with a minimum maintained retroreflectivity value of 250 $cd/lx/m^2$. The current practice is to use at least ASTM type III or better for new overhead guide signs, and so the minimum maintained retroreflectivity for green will be 25 $cd/lx/m^2$. These values are based on an observation angle of 0.2° and an entrance angle of -4.0°, which is not technically the viewing geometry for overhead guide signs. The majority of overhead guide signs have 16-inch letter heights or larger which provides a typical legibility distance range from 480 to 640 feet. The resulting observation angles could range from 0.17° to 0.95°, and the entrance angles could range from 2.0° to 3.2°. The *MUTCD* does not specify specific lighting level requirements.

The AASHTO *Roadway Lighting Design Guide* is a document for providing agencies and designers with a general to detailed overview of all things related to roadway lighting, including overhead guide sign lighting [2]. The guide contains information on sign illuminance and luminance with recommended minimum, maximum, average, and uniformity ratio values. These values are also subdivided into three ambient lighting conditions: low, medium, and high. Unfortunately, low, medium and high are only vaguely defined. Typically, agencies will use the low ambient condition that requires sign illuminance to be between 100 and 200 lux or to have sign luminance between 22 to 44 cd/m^2. Agencies also use the 6:1 uniformity ratio with respect to the maximum value versus the minimum value.

Table 1. Minimum Maintained Retroreflectivity Levels[1][a]

Sign Color	Sheeting Type (ASTM D4956-04)				Additional Criteria
	Beaded Sheeting			Prismatic Sheeting	
	I	II	III	III, IV, VI, VII, VIII, IX, X	
White on Green	W*; G ≥ 7	W*; G ≥ 15	W*; G ≥ 25	W ≥ 250; G ≥ 25	Overhead
	W*; G ≥ 7	W ≥ 120; G ≥ 15			Post-mounted
Black on Yellow or Black on Orange	Y*; O*	Y ≥ 50; O ≥ 50			[b]
	Y*; O*	Y ≥ 75; O ≥ 75			[c]
White on Red	W ≥ 35; R ≥ 7				[d]
Black on White	W ≥ 50				-

[a] The minimum maintained retroreflectivity levels shown in this table are in units of $cd/lx/m^2$ measured at an observation angle of 0.2° and an entrance angle of -4.0°.
[b] For text and fine symbol signs measuring at least 48 inches and for all sizes of bold symbol signs
[c] For text and fine symbol signs measuring less than 48 inches
[d] Minimum sign contrast ratio ≥ 3:1 (white retroreflectivity ÷ red retroreflectivity)
* This sheeting type shall not be used for this color for this application.

NCHRP 5-20: Guidelines for Nighttime Visibility of Overhead Guide Signs is a project that will conclude in 2015 with the intent to expand the guidance with respect to guide sign lighting [4]. The survey findings show that the majority of states nationally have stopped installing overhead guide sign lighting. Only the following six states appear to be using guide sign lighting:

- Florida,

- Idaho,
- Maryland,
- New Jersey,
- Pennsylvania, and
- Virginia.

Of those states, only Idaho has LED luminaires allowed on their qualified products list (QPL) for overhead guide signs. During the survey, only Maryland reported using LED luminaires, but nothing was posted on their website reflecting this point as of August 1, 2015. Maryland also reported that they were changing their guide sign lighting policy from case-by-case to all overhead guide signs ([6]). While it is not stated on the Florida Department of Transportation (DOT) website, the researcher knows from another research project that Florida DOT is at least considering LED and induction luminaires [(5)]. Florida, Idaho, and Maryland are the only states that continue to light the majority of their overhead guide signs. The other four states still have high-pressure sodium (HPS), Mercury-vapor (MV), or metal-halide (MH) luminaires on their QPLs, but all states are either moving from sign lighting, reducing sign lighting or at least replacing HPS luminaires with more efficient products. Delaware lighting guidelines specifically state, "Overhead guide signs installed in Delaware are made from Type IX retroreflective sheeting or better. Therefore, overhead guide sign lighting shall not be used.[(7)]" Regardless of the specific policy, DOTs are only removing guide sign luminaires or replacing them with more efficient luminaires as maintenance requires, or through construction projects.

Another finding of interest to ITD would be the reported reasons for policy changes with respect to overhead guide sign lighting. The most commonly noted reason was the improvement in retroreflective guide sign sheeting, which allowed for states to reduce costs. If a state still perceived a benefit of overhead guide sign lighting, then that state would consider replacing existing luminaires for more efficient units, such as LEDs. States that changed their policy to a case-by-case approach considered the following:

- geometry, such as left-handed exists and lane drops
- sight distance
  - poor sight distance related to weather, such as areas prone to fog
  - poor sight distance from vertical or horizontal curvature
  - Not enough sight distance to benefit from the illuminated sign that would have resulted from roadway curvature or sign obstruction
- traffic volume
- speed limit
- access to power, such as in rural areas
- adjusting lighting requirements based on retroreflectivity of sign sheeting

One piece of previous research that was not already directly mentioned was the work by Carlson and Hawkins concluded in 2003 entitled, *Minimum Retroreflectivity Levels for Overhead Guide Signs and Street-Name Signs* [(8)]. In this research, the researchers had participants evaluate overhead guide signs under varying levels of headlight illumination, which impacted the luminance of the sign. The data were collected at different distances, and a relationship between legibility distance and luminance was graphed (see Figure 1). The green dashed lines indicate the points of intersection of the 85 percentile legibility distance and the associated luminance. While the current AASHTO guidance suggests that the minimum luminance for overhead guide signs with lighting should be 22 cd/m^2, the data in Figure 1 shows that 10 cd/m^2 was sufficient luminance for at least 85 percent of drivers to read overhead guide signs at 40 feet per inch of letter height. It is stated in Section 2A.13 of the *MUTCD* that word messages only require 30 feet per inch of letter height, which according to Figure 1, would require less than 3 cd/m^2 to provide adequate luminance to at least 85 percent of drivers. This would support the idea to reduce the requirement for overhead guide sign illumination to something below 22 cd/m^2.

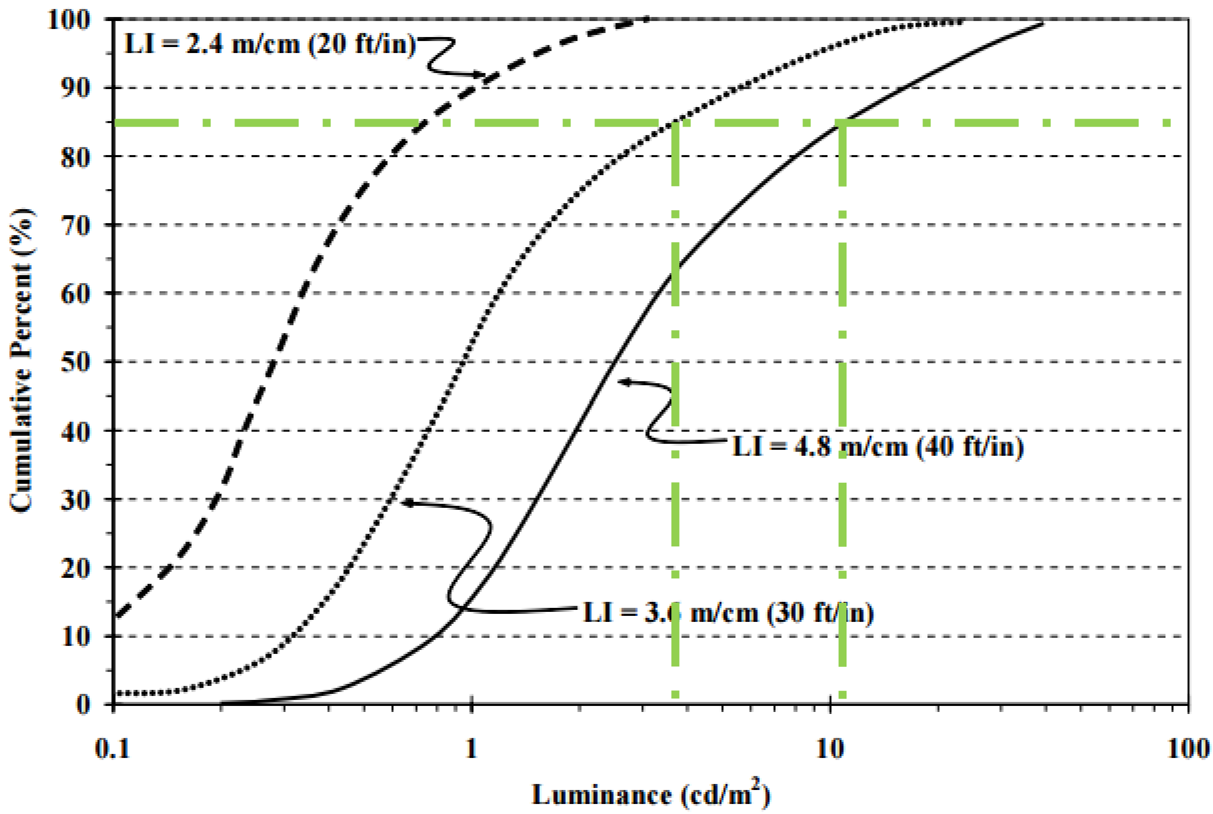


Figure 1. Relationship of Luminance to Overhead Guide Sign Visibility [(8)].

Chapter 2
Testing Methodology

The researcher completed three different types of testing. Five LED luminaires and one HPS luminaire were photometrically characterized, and then allowed to weather in the field for 1 year before being re-measured. Each luminaire was also tested in a temperature chamber and photometrically modeled. All of the luminaires were provided at no cost for testing, so there were residual funds left over for equipment.

Subsequently, TTI proposed purchasing equipment that could be used by ITD to photometrically characterize their own luminaires in the future. ITD approved the purchase of the necessary equipment. The equipment purchased consisted of an uncalibrated machine vision camera that was between ten and fifty times less expensive than commercially available products. The lower cost product required special calibration and software development to meet the needs of ITD, and TTI completed them prior to turning over the final product to ITD.

This chapter is subdivided into the photometric characterization and weather testing of the luminaires, the temperature testing, and the calibration of equipment purchased on the project for ITD to use in the future for photometric characterization of overhead illuminated guide signs.

LED Luminaire Testing

All of the testing was completed at the Texas A&M University Riverside Campus (see Figure 2). The photometric measurements were conducted inside the Environmental & Emissions Research Facility outlined with the dotted yellow box in Figure 2 in the bottom left corner of the figure. The smaller dotted yellow box above and to the right of the emissions building was the weathering test deck for the LED luminaires. The temperature testing of the luminaires was conducted inside the emissions building.

Figure 2. Texas A&M University Riverside Campus.

Testing Equipment

The photometric testing was conducted inside the instrumentation preparation bay of the emissions building (see Figure 3). The Prometric 1613F-1 photometer and colorimeter from Radiant Vision Systems was used to measure the luminance distribution of each of the test luminaires. Figure 3 shows the photometric measurement surface that consisted of a diffuse gray roll-up door of the preparation bay with 20 pieces of white ASTM Type III high-intensity beaded retroreflective sign sheeting. ASTM Type IV prismatic sheeting was also placed at a few key locations, as highlighted with the yellow dotted circular in Figure 3. The researcher used the diffuse gray surface to assess illumination uniformity, and the retroreflective sheeting was used to predict field performance. A Minolta T-10 illuminance meter was also used during the testing to assess illuminance uniformity.

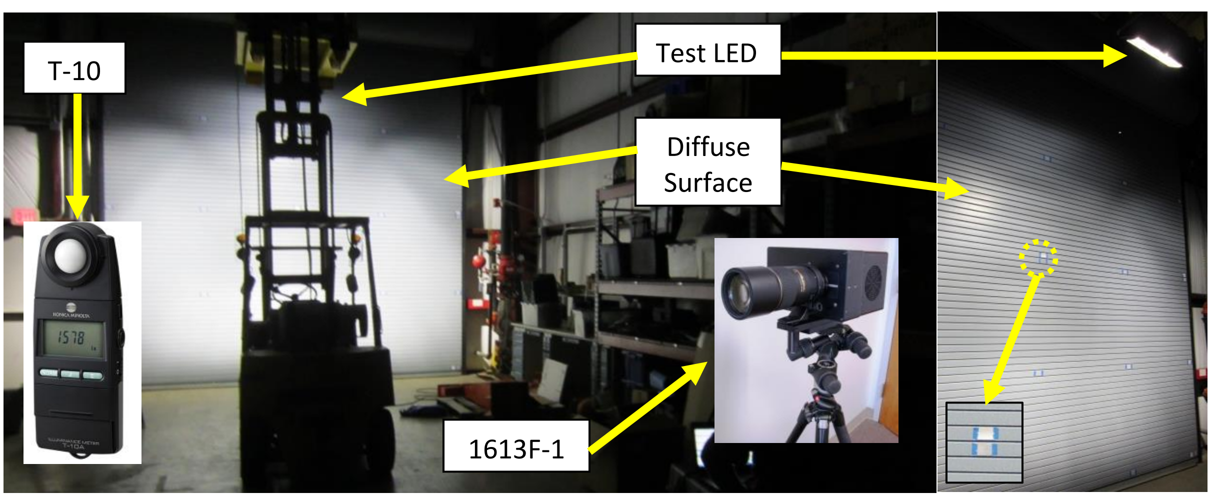


Figure 3. Emissions Building Setup for Photometric Testing.

Each one of the luminaires was mounted on a man lift platform attached to a forklift, as depicted in Figure 4. Each luminaire had a slightly different shape, size, and mounting condition, so the position on the man lift and the position of the forklift were adjusted to ensure proper alignment. Each luminaire was hoisted 12 feet in the air referenced from the bottom of the measurement surface to the optical center of each luminaire and 6 feet longitudinally away from the door to the optical center of each luminaire. Each luminaire was also centered on the measurement wall laterally. The angle of each luminaire was set to minimize light trespass to optimize the amount of light projected on the sign and to minimize potential glare to adjacent, on-coming traffic. Each angle was recorded with a digital level, as depicted in Figure 4c, and the same angle was used in the outside weathering setup.

This setup simulated a downward facing luminaire that would be vertically in-line with the top of an overhead guide sign that was 12 feet tall and 16 feet wide with the luminaire longitudinal offset 6 feet away from the front of the sign. This was done based on discussions with ITD, because the agency was looking at changing their policy to downward facing light luminaires to minimize the likelihood of snow accumulation on the optical surface of the lights and to minimize light trespass into the sky.

a) HPS

b) LED

c) Alignment

Figure 4. Luminaire Mounting for Photometric Testing.

The temperature testing was conducted in the emissions building drive-in environmental chamber, shown in Figure 5. This chamber could maintain temperatures between -13 °F to +131 °F (-25 °C to +55 °C) with a relative humidity up to 70 percent at 104 °F (40 °C). The chamber was 7,500 gross square feet with solar loading lights and wind simulator fans. Special access ports allows for various sensors to be placed in the environmental chamber and to monitor the environment and the state of all devices loaded within the chamber.

Figure 5. Emissions Building Drive-In Environmental Chamber.

The testing facility for the outside weathering is shown in Figure 6 and consisted of several electrical outlets with timers to control the period of on-time. Each luminaire was mounted differently based on its size, shape, and mounting hardware. Figure 7b and Figure 7c show how two different luminaires were mounted. Figure 7a shows the mounting pole base used for each pole that held up a luminaire. Only one luminaire was mounted on a pole and each luminaire had at least a one foot clearance on all sides from adjacent objects. There were no nearby buildings or other objects that could shelter the luminaires from the sun or weather.

Figure 6. Weathering Test Deck Setup.

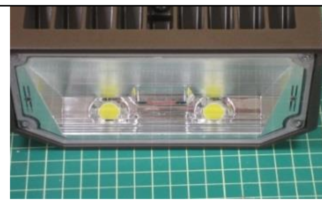
a) HPS pole mounted   b) LED pole mounted

Figure 7. Luminaire Weathering Mount Setup.

Luminaires

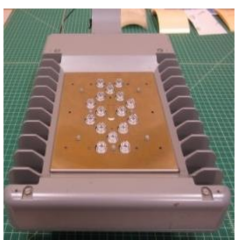
There were five different LED luminaire models and one HPS luminaire model tested. The luminaires are shown in Figure 8. The luminaires vary in wattage from 30 to 180 watts, size, shape, number of LEDS, style of optics, and mounting design. The higher wattage fixtures state higher output, but they require more power to operate. The varying sizes impact their respective weight where lighter luminaires would require less substantial and lower weight mounting hardware, which would decrease installation costs. Luminaires a through c and f use reflectors, and luminaires d and e are individual LED optics. All luminaires were affixed with a 120VAC three prong plug. While all of the luminaires were provided at no cost for testing, a quick search revealed that they ranged in price from $200 to $800.

a) Cooper Lighting Crosstour



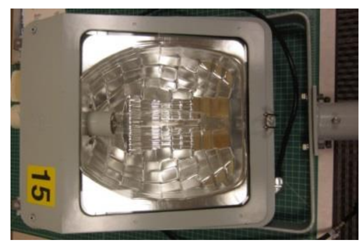
b) Cooper Lighting Crosstour MAXX

c) Holophane Sign-Vue LED



d) Hubbell Prototype LED

e) CREE 304-FL Series (Sign Optic)



f) GE HPS150

Figure 8. Test Luminaires.

Procedure

The temperature testing was completed prior to the photometric characterization. Then the luminaires were installed on the weathering test deck. After one year, the luminaires were removed from the test deck and retested with respect to photometric measurements, but temperature testing was not redone. It was decided by the researcher and ITD that the post temperature testing was not needed. This section is subdivided into three subsections: temperature testing, photometric measurements, and weathering.

Temperature Testing

The primary interest around the temperature testing was to assess whether any fixture had difficulty with a “cold start” when a luminaires was below freezing. A cold start for the purposes of this document denotes the situation when a fixture has been off during the daytime period, and it will be turned on at nightfall when the temperature is below freezing, 32°F. Some fixtures, such as fluorescent tubes have difficulty with turning on under freezing conditions.

A related interest was to see if luminaires that may have accumulated snow under freezing conditions might have difficulty melting snow when they are turned on. This is not a big concern when considering that ITD is looking at moving to top mounted luminaires that would keep the lens of the luminaires blocked from snow accumulation, but it was believed that there might be need for bottom mounted luminaires under certain conditions.

All of the testing was conducted inside the drive-in environmental chamber in the emissions building (see Figure 9). As some luminaires have difficulty with turning on in a cold state, all of the luminaires were left off until the chamber reached the desired minimum temperature. The minimum start temperature was set at -10°F. This is a conservatively low number based on 2013 climatic data reported by Weather Underground, which was -7°F for Boise and -4°F for Sandypoint(1). The chamber and the devices were allowed to reach equilibrium for over an hour after the chamber reached -10°F. It took approximately 8 hours for the chamber to reach -10°F.

Figure 9. TTI Drive-In Environmental Chamber

Once all of the luminaires and the chamber were at equilibrium with respect to temperature, each luminaire was turned on and allowed to stabilize for at least 30 minutes. At that point, the wattage was measured for each luminaire. The wattage, or power consumed by each luminaire, was measured under varying ambient temperatures because some luminaires will require more power than others, and this would be a consideration for ITD when selecting a luminaire when total cost savings are incorporated into the selection process. Once each luminaire was measured and at equilibrium, the chamber was increased to 0°F and held for at least 30 minutes before the wattage was remeasured. This was repeated for +10°F and again at +75°F.

Data were collected every second from two contact sensors placed on each luminaire and at three other locations within the chamber. Each sensor reported data out to 0.01°F. Figure 10 shows one contact sensor was placed at the edge of the optical face of each luminaire and one was placed at the optical center of each luminaire. This would allow for the researcher to assess any temperature gradient differences across the optical surface. It was anticipated that the center of the luminaire would be hotter than the edge and might melt sooner than the outside edge of the luminaire. One of the chamber temperature sensors was located away from the luminaires. For feasibility of data collection, the luminaires needed to be placed in close proximity to each other, which might artificially increase the ambient temperature around the other luminaires. Subsequently, two additional temperature sensors were placed around the luminaires. One sensor was placed at the farthest edge from the luminaires and nearest edge to the fan circulation system, and one was placed on the outside luminaires nearest the wall that could receive heat off the luminaires and potentially be more isolated from the circulation fans.

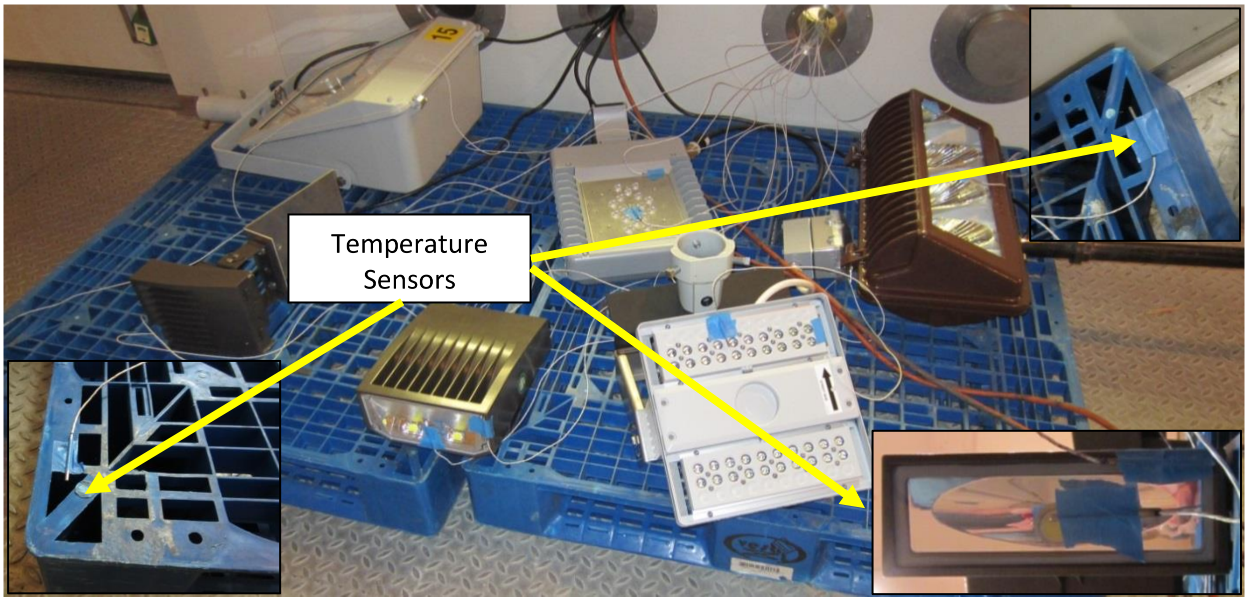


Figure 10. Luminaire Layout for Temperature Testing.

Photometric Testing

Each luminaire was individually mounted to the lift and photometrically measured. Once aligned for measurement, each luminaire was turned on and allowed to warm-up for 10 minutes. During that period, a Minolta T-10 illuminance meter was used to periodically measure light falling on the gray diffuse measurement area to assess if each light was at equilibrium prior to recording photometric measurements. No luminaire required more than 10 minutes to warm-up.

After the warm-up period, the exposure was optimized for taking images with the Prometric 1613-1F, and a single reading was taken. Then the researcher recorded handheld illuminance reading from 20 different equidistant points along the gray diffuse measurement surface over an area that was 16 feet wide and 12 feet high. Subsequently, each position was approximately 4 feet apart vertically and horizontally from each adjacent point of measurement. Once this was complete, two additional luminance images were recorded. These images would be compared to the first image to assess if any additional warm-up had occurred that would have changed the luminaire output. No changes were reported related to warm-up. The lift was lowered, and the next luminaire was mounted when the measurements were completed for one luminaire.

One other aspect to the photometric characterization was performed through modeled illuminance. ITD wanted an objective assessment of the potential differences between modeled luminaire performance and real world performance. The data collected prior to weathering were compared to the data from the models developed in the software AGi32. As there are not any known values for diffuse reflectance with retroreflective sheeting, the research focused this effort on illuminance, because illuminance directly impacts luminance. If illuminance values were over or underestimated, the luminance values would also be over or underestimated. Furthermore, surface reflectance would impact the luminance estimates, which AGi32 does not currently have reflectance values for retroreflective sign sheeting. The procedure for this task required importing the photometric data files for each luminaire. The researcher then modeled a similar testing environment to the one used to conduct real world photometric measurements for each luminaire.

Weather Testing

After completing the photometric testing, the luminaires were taken to the weathering test deck in College Station, Texas. They were installed on individual poles and connected to 120VAC power that was controlled by an electronic timer. Periodically, the researcher went and inspected the lights to ensure that they were cycling on and off correctly, and clear of debris. Weathering ended one year after installation, and then each luminaire was photometrically remeasured using the same procedure detailed in the previous subsection.

Mobile Luminance Calibration

ITD did not currently have an objective method to evaluate new overhead guide sign luminaires when installed, so the researcher proposed purchasing a low-cost machine vision camera with respect to commercially available systems that would run between $20,000 and $100,000. A USB 3.0 Basler ACE 1920-155um camera was purchased along with the necessary accessories (a 1-inch format, 1.5 MP Fujinon 50mm and a V-lambda correction filter) for approximately $2,000. The reason why this system was less expensive was because it required calibration to measure overhead guide sign luminance and software, while the other products included these calibrations. TTI had the equipment and the experience to photometrically calibrate the system and the capability to provide software as well to run the system.

Testing Equipment

The photometric testing was conducted inside the TTI Visibility Research Laboratory (VRL) using the Prometric 1613F-1 photometer and colorimeter from Radiant Vision Systems. In the VRL, the researcher used a diffuse white grid and several different light sources to create various luminance contrast conditions to calibrate the Basler ACE camera. Figure 11 shows the calibration grid on the left and a luminance map of the grid on the right.

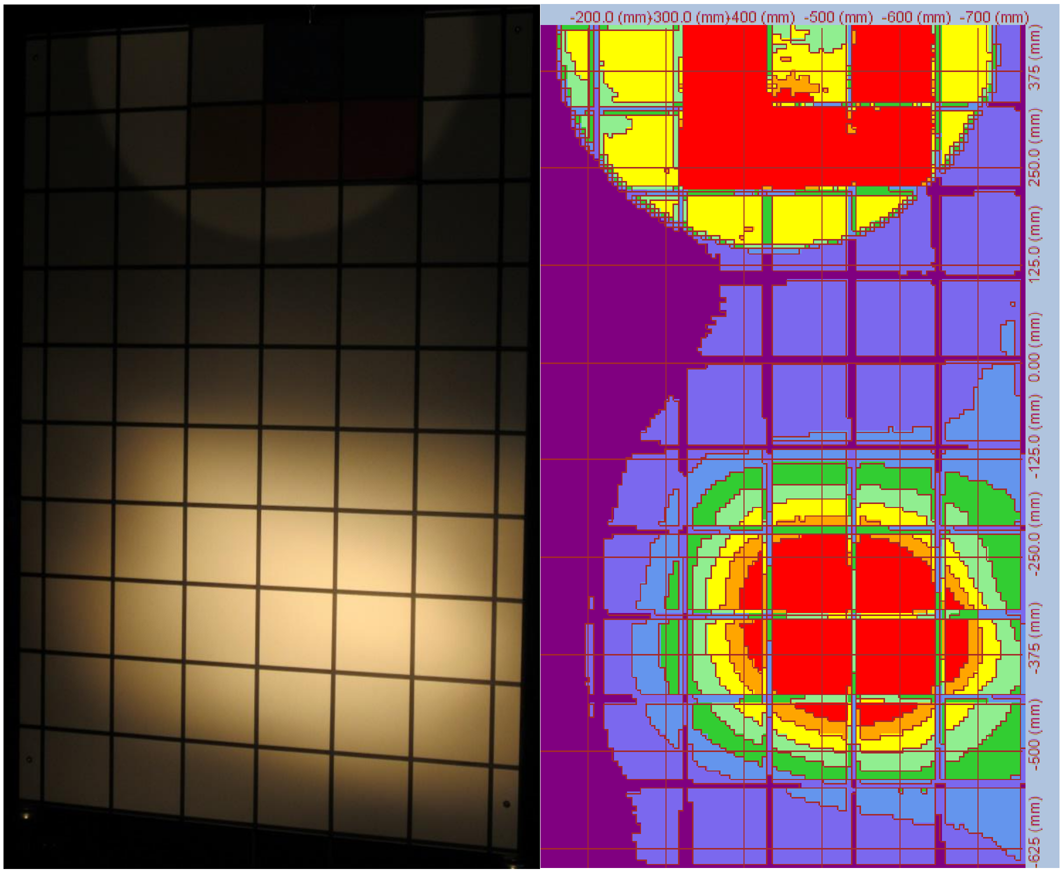


Figure 11. Camera Calibration Grid.

Procedure

The researcher set up three different luminance ranges and took images with both the camera and Prometric 1613F-1. The low condition ranged in luminance from 0.01 to 35 cd/m^2. The medium luminance condition ranged from 20 to 100 cd/m^2. The high luminance condition ranged from 50 to 550 cd/m^2. These ranges were selected to evaluate all signs, including internally illuminated signs, and the overlap was created to ensure that there were not gaps between the measurement setups.

For each of these conditions, the researcher took images with the Basler ACE camera at varying f-stop, exposure, and gain values. There was at least one overlap in f-stop position and exposure with each of the adjacent luminance conditions. The gain was set at 0, 6, and 12 decibels. The exposures and f-stops were selected based on whether the brightest part of the image exceeded the dynamic range of the camera under the given settings.

Chapter 3
Analysis

This chapter is subdivided into three sections:

- Temperature
- Photometric
- Calibration

Temperature

Temperature data were collected every second for over 20 hours from 19 different temperature sensors placed on the test luminaires and in the environmental chamber. Figure 12 shows the temperature data with respect to time from the optical center of each luminaire and the average temperature of the chamber. The first question asked was about cold start below freezing, and each of the five LED and one HPS luminaires started without issue from -10°F.

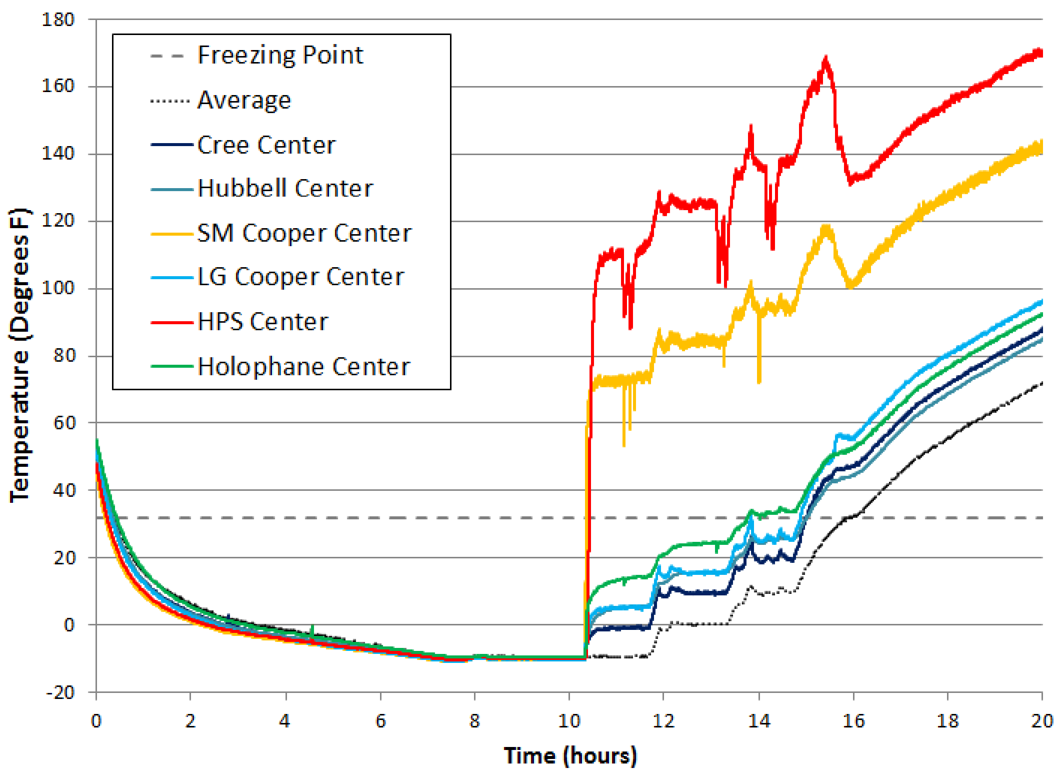


Figure 12. Temperature with Respect to Time for Optical Center.

The temperature gradient associated with each luminaire differed with respect to the ambient temperature in the chamber. Both the HPS and the Crosstour, also referred to here as the SM Cooper Center, luminaire immediately increased their respective surface temperature at their optical centers above freezing, even when the ambient temperature was -10°F. The Holophane LED Sign-Vue, referenced in the graph as Holophane Center, rose above freezing once the ambient conditions reached approximately 10°F. The other LED luminaires rose about freezing once the ambient temperature was around 20°F and rising. Subsequently, at the freezing temperature of water to within approximately 10°F below freezing, all of the luminaires should generate enough heat to melt snow.

In Figure 13, the researcher showed a close-up shot of the HPS, a luminaire with individual exposed LED optics (CREE), and a luminaire with enclosed LED optics with a reflector. Both the temperatures at the optical center and the edge of the luminaires are shown. The HPS and the small Cooper luminaire have large temperature differentials in excess of 70°F, while the exposed individual optics in the CREE fixture differ by less than 1°F with the edge of the luminaire. The small temperature differential on the CREE could be the result of very efficient heat management, but the researcher believes it was more related to the inefficiency with which the contact temperature sensors measured the individual LEDs on the CREE product. There is insufficient data to assess whether the differences are related to measurement error or design, but the individual LEDs in the CREE product would either be the same as the adjacent casing where the contact sensor was attached or warmer. Again, all luminaires were above freezing when the ambient chamber temperature was at the freezing temperature of water.

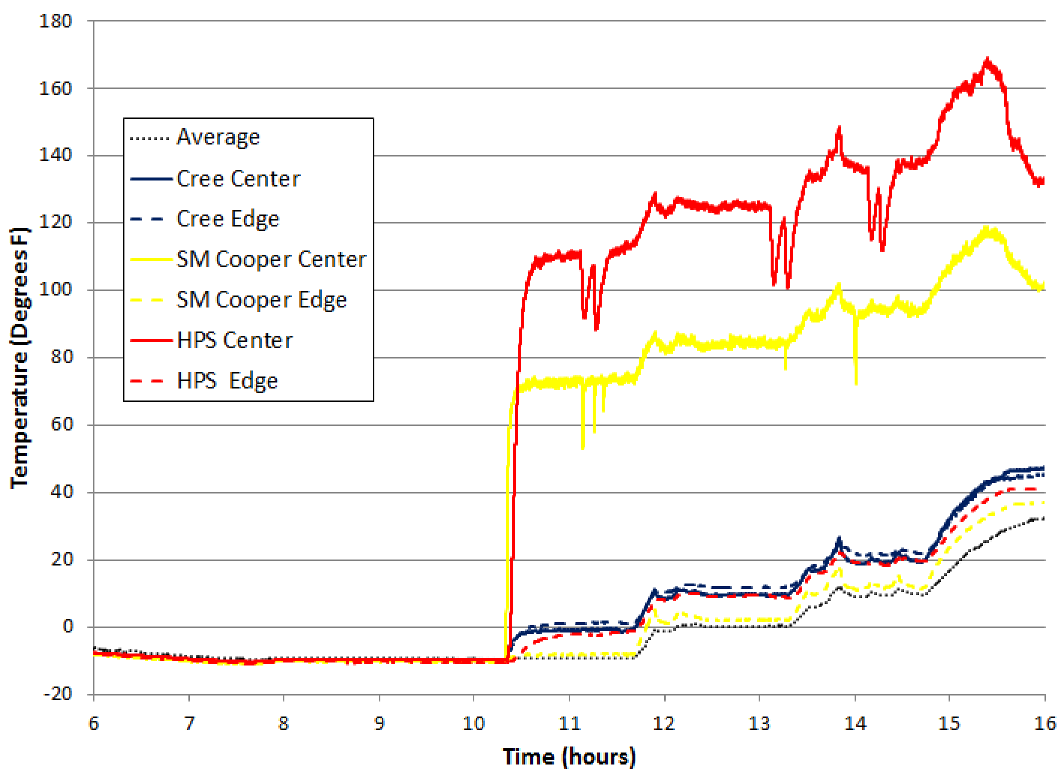


Figure 13. Temperature Gradient Across Surface of Luminaires.

Another set of data collected was the wattage of each luminaire with respect to the temperature of the ambient chamber to assess whether power consumption would be impacted by temperature. Table 2 shows the variation in the wattage for each luminaire, and the HPS showed no variation while the CREE showed the greatest variation. The trend for all of the LED luminaires was for power consumption to increase during winter temperatures, which would be further increased by the longer nighttime hours. However, the decrease in power consumption by all of the LED luminaires ranged between 47 and 83 percent when compared to the current HPS luminaires.

Table 2. Luminaire Wattage at Varying Ambient Temperatures.

Luminaire	Wattage at ~120 VAC for the Following Chamber Ambient Temperatures			
	-10° F	0° F	10° F	75° F
HPS	186	186	186	186
Cooper 30W	30.7	30.4	30.2	29.3
Cooper 80W	89.3	88.5	87.9	84.8
Hubbell	38.6	38.3	38.1	37.1
CREE	98.7	97.5	96.7	91.3
Holophane	82.0	81.7	81.4	79.5

Photometric

This task was broken into four tasks:

- Measurements
- Depreciation
- Modeling

The illuminance and luminance measurements are presented first, followed by a discussion of the light depreciation or light loss. Finally, the initial readings are compared to the modeled results from AGi32.

Measurements

With respect to the before period luminance, the researcher was only able to measure a portion of the measurement surface area because the forklift occluded all of the left most vertical measurement points, and a portion of the next adjacent column of measurement points. Figure 14 shows that only 12 (see the yellow dotted boxes) of the 20 points could be measured for luminance. This was not considered a problem, because the researcher tried to align each luminaire to be horizontally centered on the measurement wall, and it was assumed that each luminaire would have optical symmetry about the vertical axis. Furthermore, the researcher was able to measure all 20 points with illuminance to verify the assumption of vertical symmetry, so only the luminance from the center of the measurement area over to the right side are reported in Table 3 for the HPS luminaire versus the Crosstour MAXX and the Sign-Vue LED.

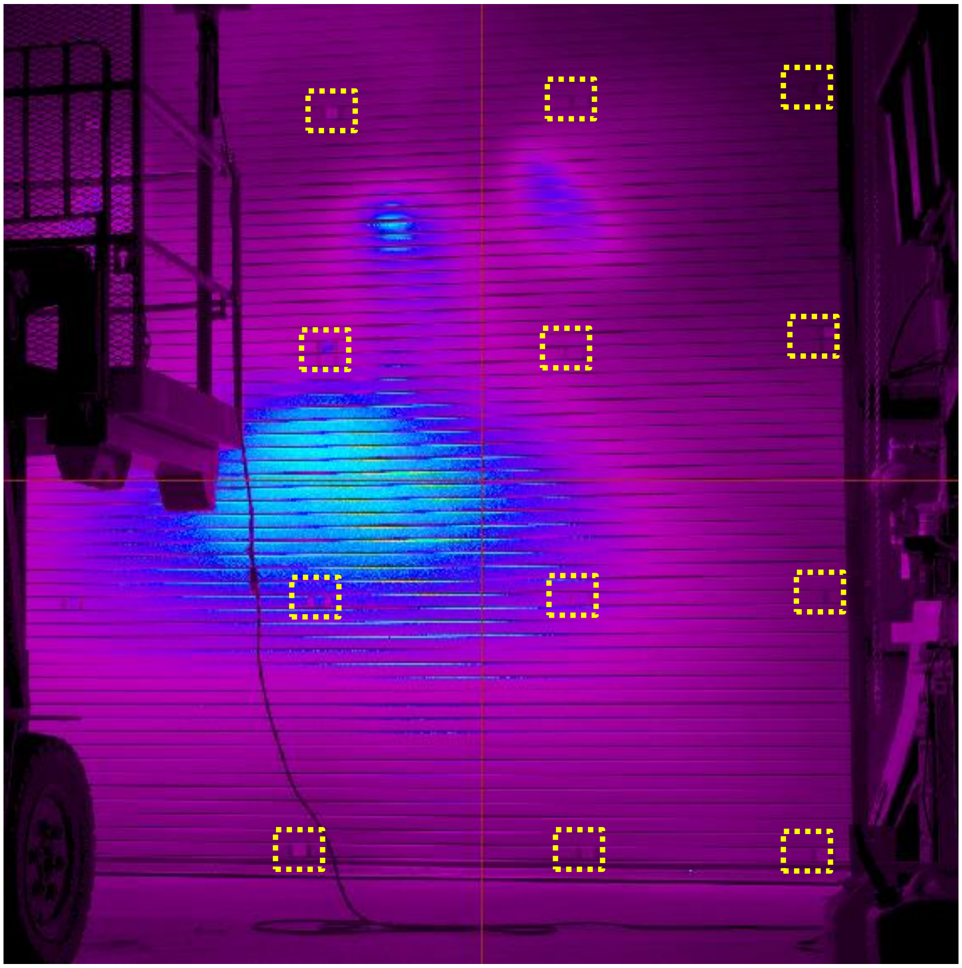


Figure 14. Luminance Measurement Areas.

Table 3. Before Luminance for HPS versus Crosstour MAXX and Sign-Vue LED[a].

Vertical Offset (in)[b]	Luminance (cd/m²) with respect to Horizontal Offset (in)[b]								
	Crosstour MAXX			Sign-Vue LED			HPS		
	96	144	192	96	144	192	96	144	192
143.5	136.6	34.4	4.9	15.2	2.9	1.7	14.1	4.0	2.4
97.5	66.9	34.8	8.9	29.2	22.1	10.1	20.2	16.1	9.2
51.5	19.2	13.8	6.7	31.5	28.7	18.4	13.4	11.1	8.0
5.5	8.6	7.2	5.1	25.1	19.9	8.8	11.1	9.1	7.4

[a] The light gray fill indicates the value is below the AASHTO suggested minimum of 22 cd/m^2 [(1)].
[b] The vertical offset was measured from the pavement surface at the bottom of the door to the vertical center of the measurement location. The horizontal offset was measured from the horizontal center of the left most location to the horizontal center of the next adjacent location.

Not one of the luminaires under the given geometry could provide the suggested minimum luminance across the entire measurement area, which is further supported by the illuminance readings. It should be noted that a new standard HPS luminaire was not providing the AASHTO recommended minimum luminance for the given geometry at 22 cd/m^2[(1)]. Table 4 shows that the other three luminaires had similar, but even lower overall luminance with respect to the portion of the measurement surface.

Table 4. Before Luminance for Crosstour, 304 Series, and Prototype

Vertical Offset (in)[b]	Horizontal Offset (in)[b]								
	Crosstour			304 Series			Prototype		
	96	144	192	96	144	192	96	144	192
143.5	28.8	5.0	1.0	154.0	12.7	1.9	5.9	3.7	1.0
97.5	16.2	10.0	2.8	114.0	49.4	6.9	10.9	6.6	2.5
51.5	7.0	5.0	2.5	17.8	11.7	4.8	17.5	12.4	3.3
5.5	4.0	3.2	2.0	6.3	4.8	2.7	3.7	4.3	3.5

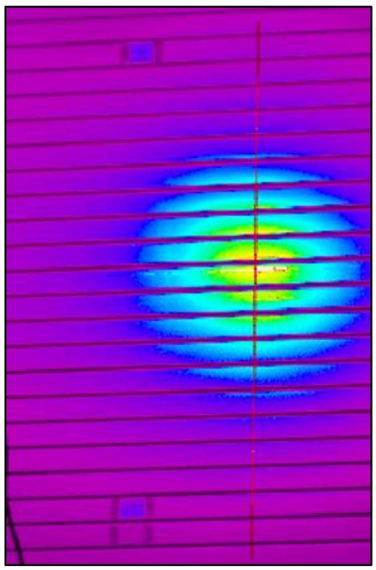
[a] The light gray fill indicates the value is below the AASHTO suggested minimum of 22 cd/m^2 [(1)].
[b] The vertical offset was measured from the pavement surface at the bottom of the door to the vertical center of the measurement location. The horizontal offset was measured from the horizontal center of the left most location to the horizontal center of the next adjacent location.

Another criterion provided by AASHTO is the 6:1 uniformity ratio based on the maximum to minimum values on the sign surface with respect to both illuminance and luminance[(1)]. Applying this criterion to the data from Table 3 and Table 4, a majority of the luminaires would be able to accommodate a sign that was 8-foot wide and 8-foot tall, and some, such as the Sign-Vue LED, could accommodate a 16-foot wide and 8-foot tall sign. An 8-foot tall sign would be able to accommodate three lines of text at 16-inch in height and standard interline spacing. The width of the words and font types would require varying width signs, but multiple luminaires could be used to maintain a 6:1 uniformity laterally across a sign. The Crosstour and the Hubbell prototype could be spaced on 16-foot centers, with two luminaires, a guide sign could be illuminated with a 6:1 ratio with a width of 24 feet. The Sign-Vue LED accommodates the largest spacing at 20-foot centers, which should accommodate a 40-foot wide sign.

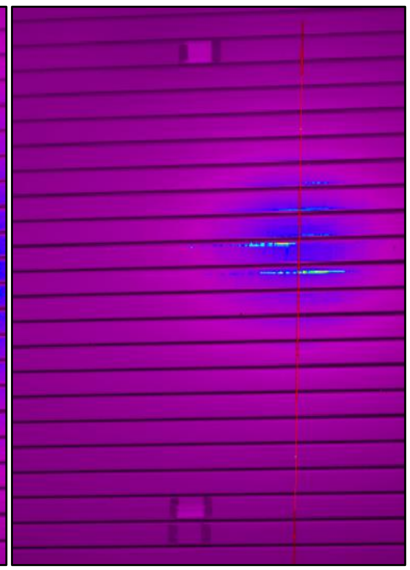
Depreciation

The researcher calculated the depreciation from the luminance measurements that passed vertically through at least one identical hotspot from the before and the after period for each luminaire. Figure 15 shows images for the Crosstour MAXX of the lines measured for comparison, and Figure 16 shows the data for the Crosstour MAXX, the Sign-Vue LED, and the HPS luminaires.

Luminance images were taken for each luminaire in the before period, in the after period with dirt accumulation, and in the after period after the dirt has been removed with room temperature water and a clean cloth. The cleaning was not done for the 304 Series or the prototype luminaires that had individual exposed LEDs, because it was not believed that field crews would be dispatched to wash individual LEDs. Table 5 shows the average depreciation for each of the luminaires. On average, the depreciation was more than 10 percent; however, the illuminance and luminance profiles across the measurement area did not change with respect to the AASHTO recommended minimum values after one year of weathering. In addition, the data collected after cleaning 4 of the 6 luminaires does not support the idea of cleaning the luminaires to improve performance after weathering. There is the possibility that the field performance could differ between Texas and Idaho, but it is not expected to be considerable for the luminaire downward facing mounted to the top of an overhead guide sign because dirt accumulation should be minimal.



a) Before



b) After

Figure 15. Crosstour MAXX Vertical Luminance Profile for Depreciation Calculation.

Table 5. Average Depreciation.

Luminaire	Before to After (Dirt)	After (Dirt) to After (Clean)[a]
Crosstour MAXX	20%	-2%
Crosstour	13%	0%
Sign-Vue LED	8%	0%
304 Series	3%	NA
Prototype	22%	NA
HPS	10%	0%

[a] Negative values in this column indicate that the dirt removal increased the input from the luminaire, and the “NA” values indicate that the luminaire was not cleaned because it was not seen as something field staff would be able to do in a cost-effective and safe manner.

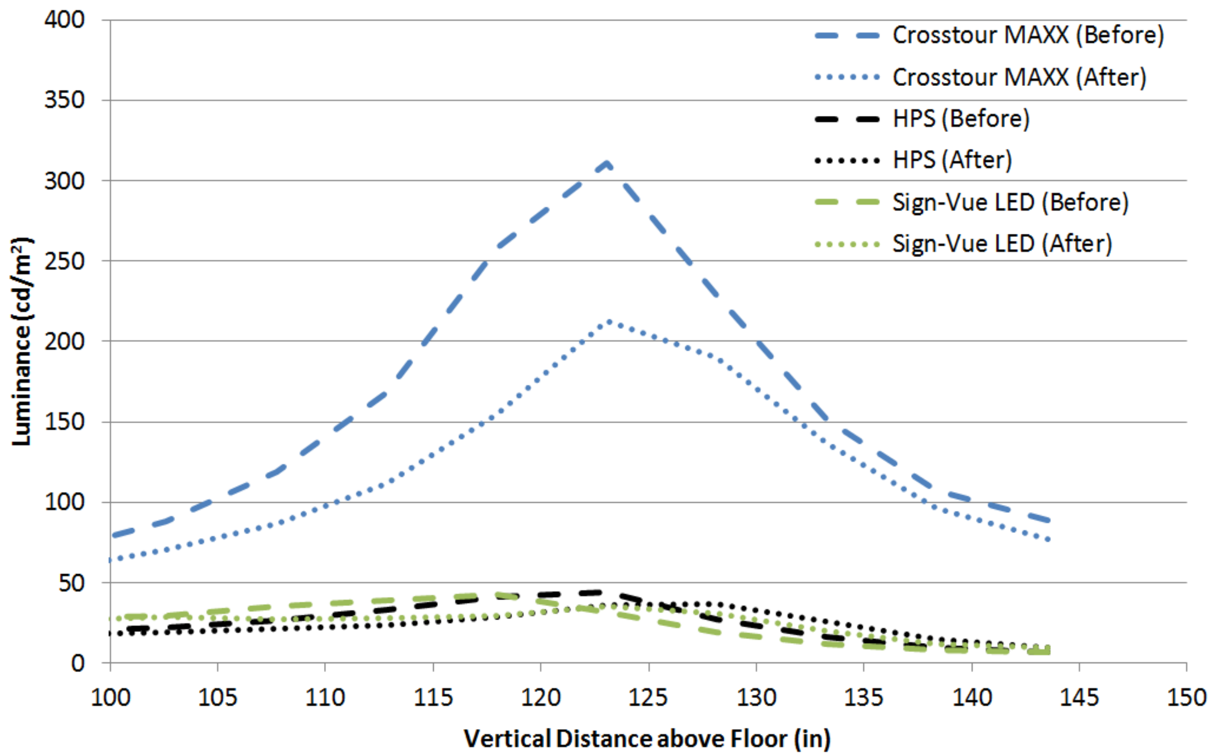


Figure 16. Before and After Luminance Comparison.

The researcher studied the fixture designs to consider possible reasons for differences in the different depreciations associated with each luminaire. Four of the six fixtures have internal light sources behind some lens. The 304 Series and prototype product had individual exposed LEDs, except the 304 Series had a lower depreciation versus the prototype. The Sign-VUE and the HPS had lower depreciation rates than the Crosstour and the Crosstour MAXX, while each of these fixtures had lenses protecting the light sources. The primary similarity between the 304 Series, Sign-VUE, and HPS is they each appear to be designed with drip edges to minimize water run-off over the lens or individual LEDs (see Figure 17). Drip edges were not stated in any of the luminaire design specification of these devices and the current data collected cannot confirm that the edge effectively reduced the run-off, but this is a plausible theory.

There were specific visible issues associated with some of the lenses that would impact depreciation that could not be addressed with simple surface cleaning of a lens. Looking closer at the Crosstour luminaire lens in the bottom left corner of Figure 17, there is a haze present on the inside of the lens, but there is not an apparent haze on the Crosstour MAXX shown in the bottom right corner. It is believed that the lens on the Crosstour MAXX may be better sealed because it has both an adhesive gasket and screws to affix the lens to the housing. There were also bugs that had accumulated on some of the luminaires, such as on the 304 Series in the top left of Figure 17, but they were not adhered to the optic. However, the HPS shown in the top right of Figure 17 shows a larger quantity of bugs that accumulated inside the luminaire and were not removed through surface cleaning. The Sign-VUE did not show any bug accumulation inside the lens. The larger quantity of bugs inside the HPS is certainly a contributing cause to the higher depreciation for the HPS versus the other two luminaires with drip edges.

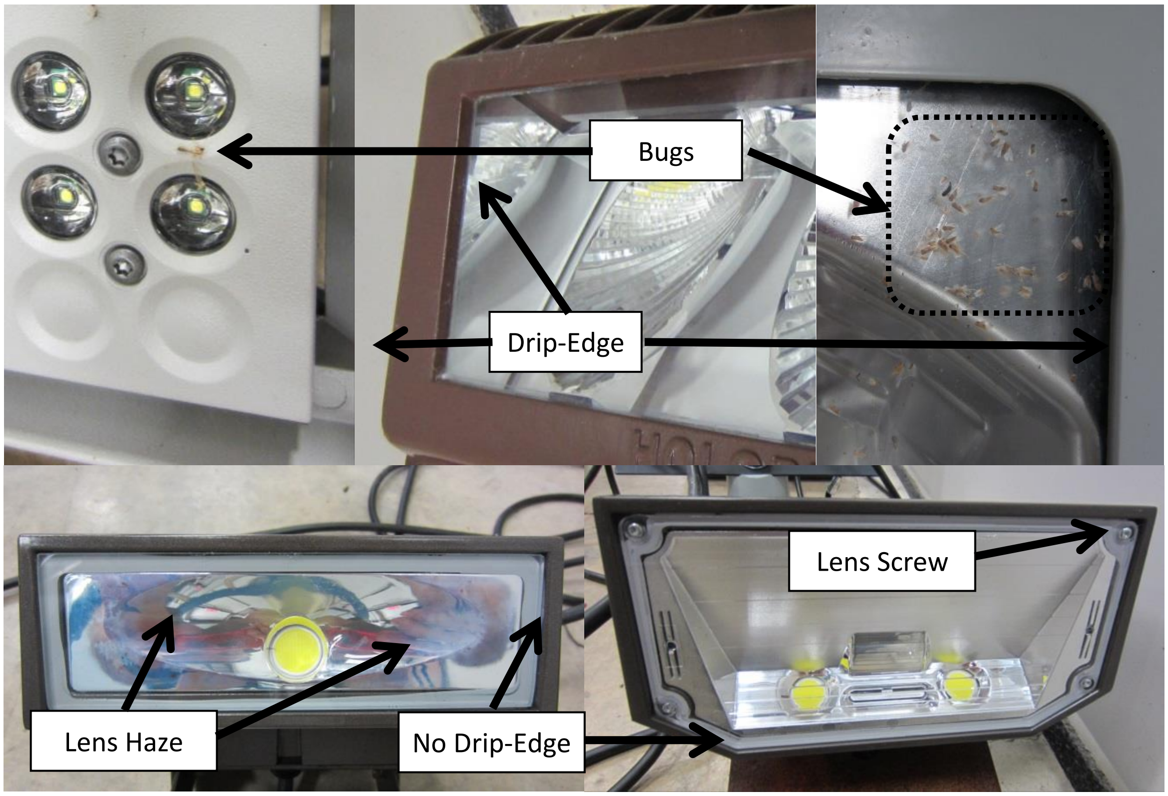
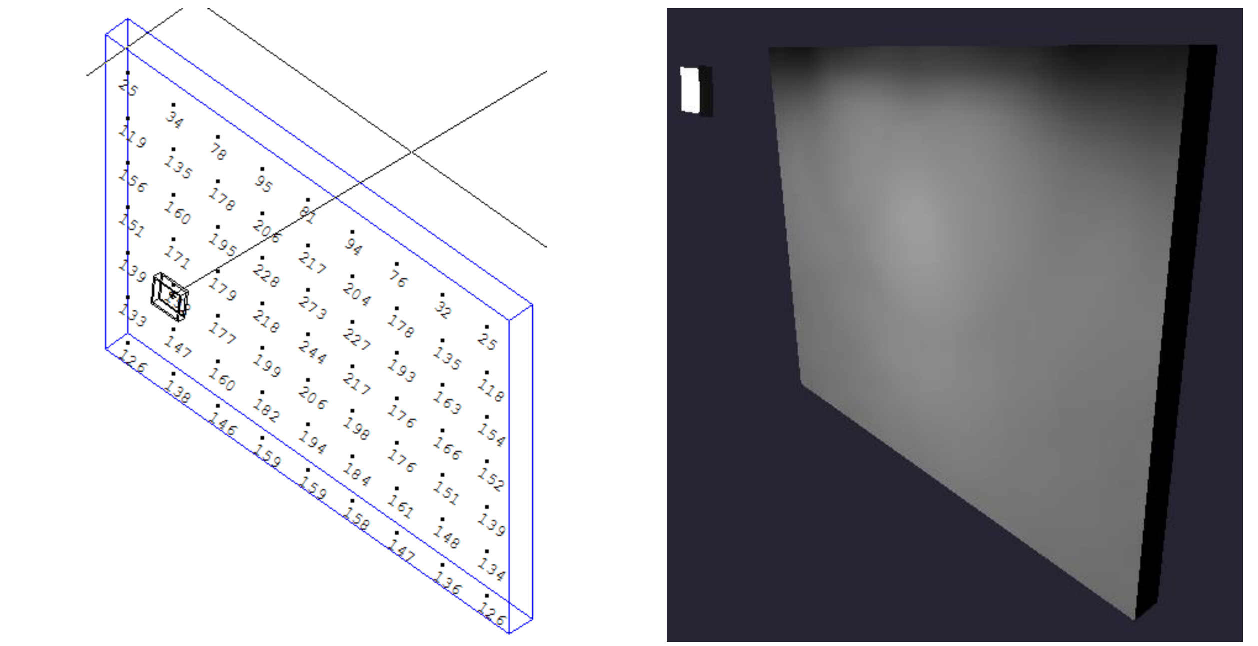


Figure 17. Images of Luminaires after Weather Exposure.

Modeling

The researcher modeled five of the six luminaires in AGi32. Hubbell had not had a chance to generate an IES file for their prototype prior to testing. An example of one of the resulting models is shown in Figure 18. The predicted illuminance values in lux for the HPS luminaire are shown in Figure 18a within a two-foot grid centered on the modeled wall with a one-foot buffer around the outside edge.

For the analysis, percent error was calculated. Of the four LED luminaires modeled, the Crosstour luminaire modeled illuminance was closest to the actual with a range of percent error from 0 to 29 percent and an average percent error of 12 percent. The predicted values and the percent error for the Crosstour are shown in Table 6. The average percent errors for the Crosstour MAXX, Sign-VUE LED, and 304-FL series were 29, 47, and 62 percent, respectively. For comparison, the HPS luminaire had 47 percent error for the predicted illuminance values. For all modeled luminaires, the predicted illuminance values were higher than the real world values. All of the data are tabulated in Appendix A.



a) Modeled Illuminance (lx) b) Visualization

Figure 18. HPS Modeled in AGi32.

There is not a clear reason for the differences between the modeled and the real world data. Modeled data are only as good as the input, and there could be several contributing factors with the measured data, such as optical inefficiencies for the tested unit to errors in the original IES file. With respect to the IES files, the 304 Series data used was actually created from the manufacturer by modifying the measured output from a similar luminaire that had 50 percent more LEDs and a lower Kelvin temperature at 4000K versus the luminaire tested in this study was 5700K. The HPS IES file was from the year 1990, and not the specific unit tested. The IES files for the Crosstour, Crosstour MAXX, and the Sign-Vue were for those specific luminaires from that year's product line. The researcher did not have a file for the prototype luminaire.

While the researcher took great care with luminaire alignment and the testing space conditions, there was also the possibility of misalignment of the unit, misalignment of the detector, or adjacent surface reflectance. It is believed that the best modeling result would be from setting up a test luminaire in a sufficiently large dark room (no ambient light and minimal surface reflectance), and aligning the luminaire as it would be installed on a sign that maximizes sign illumination while minimizing light trespass. The researcher did this, but his measurement grid did not capture the peak point of illuminance. If the measurement grid had been oriented to the peak illuminance for comparison with the modeled data, the comparison may have been closer.

Table 6. Percent Error for Predicted Illuminance for Crosstour.

Vertical Offset (in)[a]	Horizontal Offset (in)[a]									
	Predicted[b]					Percent Error				
	0	48	96	144	192	0	48	96	144	192
143.5	13	70	178	69	12	19%	8%	2%	22%	29%
97.5	33	125	211	124	33	6%	3%	13%	6%	7%
51.5	32	61	75	62	32	5%	2%	11%	0%	11%
5.5	18	25	29	26	18	18%	26%	25%	21%	7%

[a] The vertical offset was measured from the pavement surface at the bottom of the door to the vertical center of the measurement location. The horizontal offset was measured from the horizontal center of the left most location to the horizontal center of the next adjacent location.
[b] The predicted illuminance values were generated using the AGi32 modeling software.

Mobile Luminance System Calibration

Images taken with the V-lambda corrected Basler ACE camera were analyzed with respect to the luminance images taken with Prometric 1613F-1 photometer/colorimeter. Three luminance conditions were setup and analyzed.

- Low—luminance from 0.01 to 35 cd/m^2
- Medium—luminance from 20 to 10 cd/m^2
- High—luminance from 50 to 550 cd/m^2.

Figure 19 shows the calibration grid with diffuse and retroreflective material with the comparison data between the luminance in cd/m^2 and 16-bit unsigned grayscale luminance. The Basler ACE recorded the images in 12-bit grayscale, but when opened in National Instruments Vision 2012, the grayscale values were reported in 16-bit signed format. To avoid graphing below the x-axis, the researcher converted the 16-bit signed format to the unsigned format.

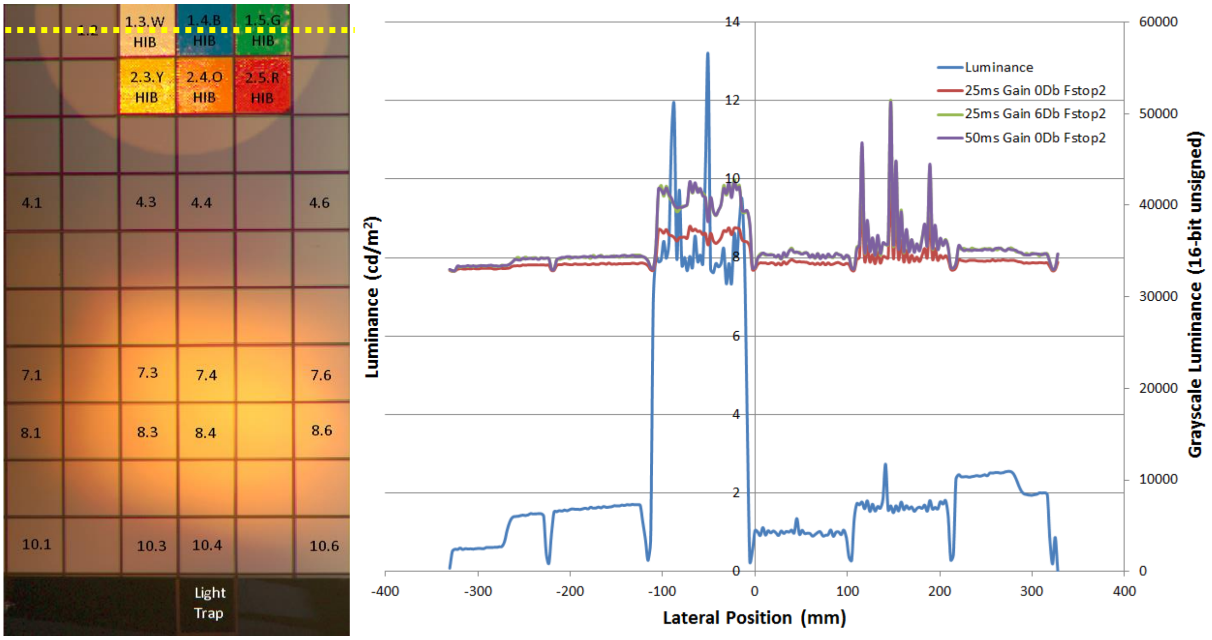


Figure 19. Luminance Comparison.

For each of these conditions, the researcher made sure to have at least one overlapping image between the different conditions. While images were taken at various gain levels, the gain appeared to simply add noise to the images without improved fit, so only the results with gain set at 0 are presented here. The exposures and f-stops were selected based on whether the brightest part of the image exceeded the dynamic range of the camera under the given settings. Figure 20 shows the resulting fits. The trend formulas can be used to estimate the conversion factors for a given grayscale value for a given exposure and f-stop. The researcher believes the optimal setting would be to set the lens at f-stop 4 and gain at 0, because f-stop 4 overlapped all of the luminance conditions and provides a greater depth of field than f-stop 1.8 or 2.8. Greater depth of field allows for objects at different distances from the lens to remain in focus at the same time, which is desired when collecting images while traveling toward objects. While exposure could be changed as well as f-stop, it is recommended to change the f-stop. To further support this recommendation, the current software generated for data collection and analysis has been designed to only account for the f-stop, and the gain and exposure have been fixed to 0 and 50 ms, respectively. A brief description of the software and its operation are detailed in Appendix B.

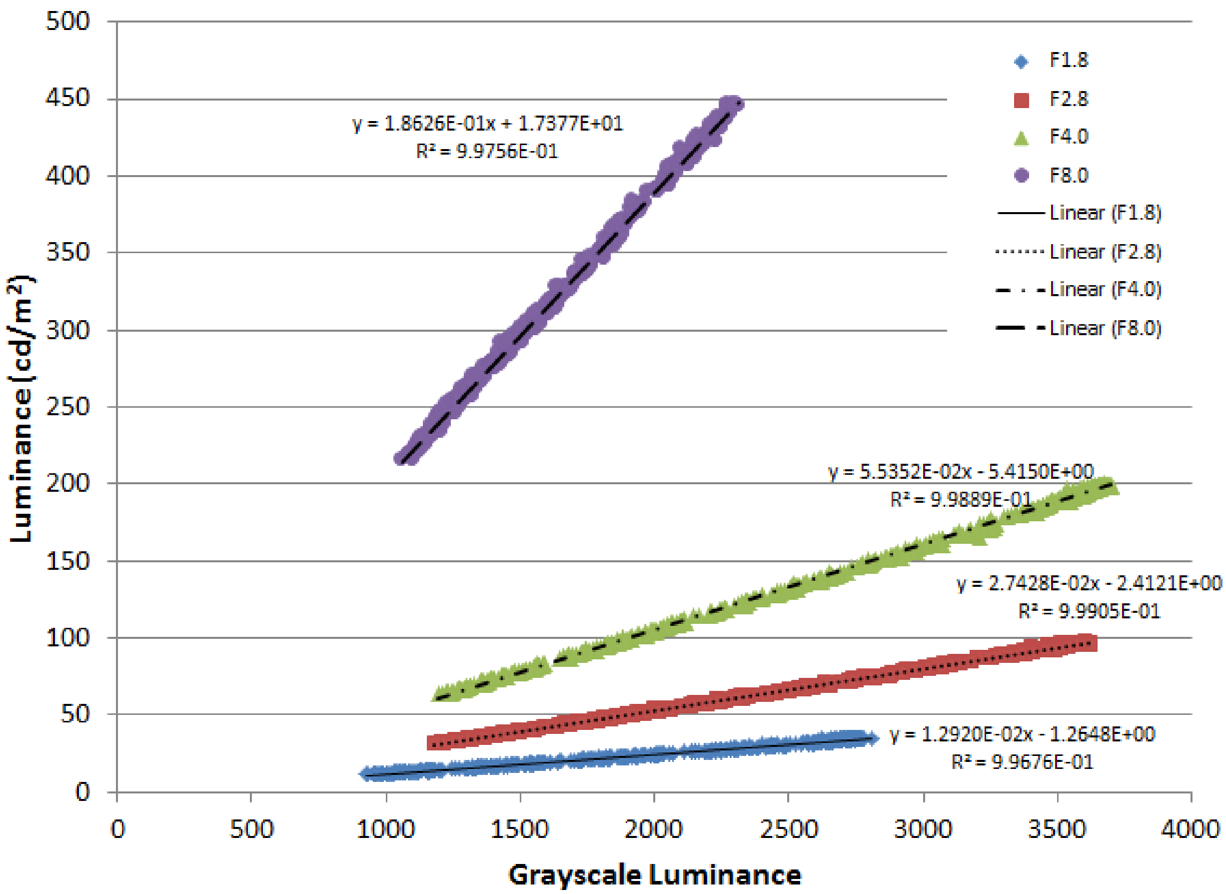


Figure 20. Conversion Formulas.

Chapter 4
Summary

The researcher evaluated multiple different LED luminaires for use with overhead guide signs in Idaho. The testing included photometric characterization, temperature evaluation, modeling, and weathering. The researcher also developed a mobile luminance system that ITD could use to evaluate their overhead guide sign luminaires in the future.

Each of the luminaires performed adequately for use by ITD and should be considered for addition to the QPL, but some designs did have various features that should be considered. The low cost, small size, and weight of the Crosstour and Crosstour MAXX make these products attractive. When considering power input requirement and that less than 3 cd/m^2 is needed by 85 percent of drivers [(8)], the researcher believes that the 30 watt Crosstour would be optimal for ITD. The 304-FL series and the Hubbell prototype could each have individual LED failures that would have a smaller impact on the overall performance. It should be noted that the prototype is not ready for deployment given its current configuration for mounting. A specialized mounting bracket was needed to install the luminaire for weather testing, but a completely different assembly would be required for deployment on an overhead guide sign above the driving public. It would be the most difficult luminaire to mount in its current form. The 304-FL series had the lowest light depreciation between the before and after periods. The Sign-VUE LED appeared well designed with respect to maintenance once deployed on a sign, however it was the biggest and heaviest luminaire.

Recommendations

Based on the findings of this research, the researcher recommends the following:

- The Cooper Lighting Crosstour and Crosstour MAXX, the Holophane Sign-Vue LED, and the CREE 304-FL series should be added to ITD’s QPL. The Hubbell prototype should not be considered until it has been retested with redesigned mounting hardware.
- Modeling software can be beneficial to estimate sign lighting performance prior to field installation, however it is recommended to use the mobile luminance measurement system to assess true field performance.
- Overhead guide sign luminaires should be installed at the top of guide signs when possible and aimed downward to minimize snow accumulation on the lens or individual LEDs.
- Change the language in ITD manual to reflect the research findings.
- Research should be conducted to evaluate diffuse reflectance with respect to different types of retroreflective sign sheeting with the intent to improve model prediction.
- Research should be conducted to develop crash modification factors associated with sign luminance. A CMF based on sign luminance would allow ITD to model the impact of different

retroreflective sign sheeting materials and sign luminaires to quantify the benefits of sign lighting.

References

1. FHWA, *Manual on Uniform Traffic Control Devices for Streets and Highways*, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. 2009.
2. AASHTO, *Roadway Lighting Design Guide*, American Association of State Highway and Transportation Officials, Washington, DC, 2005.
3. FHWA, *FHWA Lighting Handbook*, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. August 2012.
4. TRB. *Projects*. Transportation Research Board. www.trb.org accessed on August 1, 2015.
5. Jackson, N.M., G.R. Jackson, P.J. Carlson, and F. Ye. *Use of High Intensity Reflective Sheeting in lieu of External Lighting of Overhead Roadway Signs (Final Report)*. Tallahassee, Florida: University of North Florida, 2013. www.dot.state.fl.us/research-center/ accessed on August 1, 2015.
6. MDDOT. *Lighting Design*. Maryland: Maryland Department of Transportation, 2006. www.marylandroads.com/OOTS/part4.pdf accessed on August 1, 2015.
7. DelDOT. *Lighting Design Guidelines*. Delaware: The State of Delaware Department of Transportation, 2012. www.deldot.gov/information/pubs_forms accessed on August 1, 2015.
8. Carlson, P.J. and H.G. Hawkins. *Minimum Retroreflectivity Levels for Overhead Guide Signs and Street-Name Signs*. McLean, Virginia: Federal Highway Administration, December 2003. www.fhwa.dot.gov/publications accessed on August 1, 2015.
9. *Weather Underground*. The Weather Channel. www.wunderground.com accessed on April 21, 2014.

Appendix A
Raw Data

This section contains the additional raw data collected from the study that was referenced in the report, but not needed to explain the results.

Table 7. Illuminance Hubbell Prototype.

Vertical Offset (in)[a]	Horizontal Offset (in)[a]									
	Before					After				
	0	48	96	144	192	0	48	96	144	192
143.5	10.8	41.4	39.5	42.7	10.3	13.1	40.8	46.9	35.1	11.3
97.5	25.3	82.2	136	80.1	29.3	26.3	71.3	101	57.4	21.3
51.5	37.8	152	215	151	36.9	40.4	143	217	121	30.9
5.5	35.9	45.5	38.1	44.4	34.8	37.0	50.7	51.7	51.8	30.1

[a] The light gray fill indicates the value is below the AASHTO suggested minimum of 100 lux [(1)].
[b] The vertical offset was measured from the pavement surface at the bottom of the door to the vertical center of the measurement location. The horizontal offset was measured from the horizontal center of the left most location to the horizontal center of the next adjacent location.

Table 8. Illuminance Crosstour.

Vertical Offset (in)[a]	Horizontal Offset (in)[a]									
	Before					After				
	0	48	96	144	192	0	48	96	144	192
143.5	10.9	65.1	182	56.7	9.31	10.6	55.1	130	46.2	9.45
97.5	35.0	121	186	117	30.8	34.5	119	183	109	32.4
51.5	30.5	62.5	84.2	61.9	28.8	30.1	62.5	83.7	62.6	30.8
5.5	22.0	33.6	38.7	33.1	19.4	21.8	34.0	40.2	32.4	21.9

[a] The light gray fill indicates the value is below the AASHTO suggested minimum of 100 lux [(1)].
[b] The vertical offset was measured from the pavement surface at the bottom of the door to the vertical center of the measurement location. The horizontal offset was measured from the horizontal center of the left most location to the horizontal center of the next adjacent location.

Table 9. Illuminance Crosstour MAXX.

Vertical Offset (in)[b]	Horizontal Offset (in)[b]									
	Before					After				
	0	48	96	144	192	0	48	96	144	192
143.5	64.1	463	883	395	49.1	61.3	430	772	336	44.9
97.5	113	427	750	399	96.4	117	435	734	378	90.1
51.5	78.2	168	229	160	72.1	81.2	171	227	158	73.0
5.5	47.1	72.9	87.1	70.7	43.6	47.7	76.3	94.2	72.7	44.4

[a] The light gray fill indicates the value is below the AASHTO suggested minimum of 100 lux [(1)].
[b] The vertical offset was measured from the pavement surface at the bottom of the door to the vertical center of the measurement location. The horizontal offset was measured from the horizontal center of the left most location to the horizontal center of the next adjacent location.

Table 10. Illuminance Sign-Vue LED.

Vertical Offset (in)[a]	Horizontal Offset (in)[a]									
	Before					After				
	0	48	96	144	192	0	48	96	144	192
143.5	13.9	46.6	99.8	28.6	15.8	13.6	47.7	121	23.4	14.9
97.5	175	244	293	253	112	177	349	339	357	101
51.5	249	354	385	368	218	258	486	598	425	212
5.5	38.0	140	249	199	84.2	46.1	60.4	75.0	67.2	48.8

[a] The light gray fill indicates the value is below the AASHTO suggested minimum of 100 lux [(1)].
[b] The vertical offset was measured from the pavement surface at the bottom of the door to the vertical center of the measurement location. The horizontal offset was measured from the horizontal center of the left most location to the horizontal center of the next adjacent location.

Table 11. Illuminance 304-FL Series.

Vertical Offset (in)[a]	Horizontal Offset (in)[a]									
	Before					After				
	0	48	96	144	192	0	48	96	144	192
143.5	13.2	145	839	112	11.5	17.3	266	1820	280	16.7
97.5	83.5	560	1010	530	68.5	75.0	404	656	383	75.4
51.5	54.6	126	175	124	49.5	50.0	106	151	105	47.6
5.5	29.5	49.9	60.8	48.8	27.6	29.6	52.1	64.2	52.5	30.4

[a] The light gray fill indicates the value is below the AASHTO suggested minimum of 100 lux [(1)].
[b] The vertical offset was measured from the pavement surface at the bottom of the door to the vertical center of the measurement location. The horizontal offset was measured from the horizontal center of the left most location to the horizontal center of the next adjacent location.

Table 12. Illuminance HPS.

Vertical Offset (in)[a]	Horizontal Offset (in)[a]									
	Before					After				
	0	48	96	144	192	0	48	96	144	192
143.5	21.1	44.6	82.6	40.8	21.7	27.0	106	86.1	90.1	22.9
97.5	107	168	227	195	110	104	159	245	178	89.2
51.5	79.7	123	160	136	89.7	85.0	137	174	125	86.3
5.5	55	87.1	113	93.5	65.8	67.7	97.5	121	92.0	69.9

[a] The light gray fill indicates the value is below the AASHTO suggested minimum of 100 lux [(1)].
[b] The vertical offset was measured from the pavement surface at the bottom of the door to the vertical center of the measurement location. The horizontal offset was measured from the horizontal center of the left most location to the horizontal center of the next adjacent location.

Table 13. Percent Error for Predicted Illuminance for Crosstour MAXX.

Vertical Offset (in)[a]	Horizontal Offset (in)[a]									
	Predicted[b]					Percent Error				
	0	48	96	144	192	0	48	96	144	192
143.5	87	401	814	403	87	36%	13%	8%	2%	77%
97.5	86	414	721	414	87	24%	3%	4%	4%	10%
51.5	67	168	190	169	66	14%	0%	17%	5%	8%
5.5	12	22	25	22	13	75%	70%	71%	69%	70%

[a] The vertical offset was measured from the pavement surface at the bottom of the door to the vertical center of the measurement location. The horizontal offset was measured from the horizontal center of the left most location to the horizontal center of the next adjacent location.
[b] The predicted illuminance values were generated using the AGi32 modeling software.

Table 14. Percent Error for Predicted Illuminance for Sign-VUE LED.

Vertical Offset (in)[a]	Horizontal Offset (in)[a]									
	Predicted[b]					Percent Error				
	0	48	96	144	192	0	48	96	144	192
143.5	35	50	153	49	34	152%	7%	53%	71%	115%
97.5	138	370	385	364	134	21%	51%	31%	44%	20%
51.5	225	480	576	469	227	10%	36%	50%	27%	4%
5.5	45	68	91	73	47	18%	51%	63%	63%	44%

[a] The vertical offset was measured from the pavement surface at the bottom of the door to the vertical center of the measurement location. The horizontal offset was measured from the horizontal center of the left most location to the horizontal center of the next adjacent location.
[b] The predicted illuminance values were generated using the AGi32 modeling software.

Table 15. Percent Error for Predicted Illuminance for 304-FL Series.

Vertical Offset (in)[a]	Horizontal Offset (in)[a]									
	Predicted[b]					Percent Error				
	0	48	96	144	192	0	48	96	144	192
143.5	27	279	607	280	26	105%	93%	28%	151%	126%
97.5	65	622	1723	629	64	22%	11%	71%	19%	7%
51.5	22	87	209	87	22	60%	31%	19%	30%	56%
5.5	4	9	14	9	4	86%	82%	77%	82%	86%

[a] The vertical offset was measured from the pavement surface at the bottom of the door to the vertical center of the measurement location. The horizontal offset was measured from the horizontal center of the left most location to the horizontal center of the next adjacent location.
[b] The predicted illuminance values were generated using the AGi32 modeling software.

Table 16. Percent Error for Predicted Illuminance for HPS.

Vertical Offset (in)[a]	Horizontal Offset (in)[a]									
	Predicted[b]					Percent Error				
	0	48	96	144	192	0	48	96	144	192
143.5	25	78	81	76	25	19%	75%	2%	86%	15%
97.5	156	195	273	193	154	46%	16%	20%	1%	41%
51.5	139	177	206	176	139	74%	44%	29%	30%	55%
5.5	126	146	159	147	126	129%	68%	41%	57%	91%

[a] The vertical offset was measured from the pavement surface at the bottom of the door to the vertical center of the measurement location. The horizontal offset was measured from the horizontal center of the left most location to the horizontal center of the next adjacent location.
[b] The predicted illuminance values were generated using the AGi32 modeling software.

Appendix B
Mobile Luminance Measurement System

A USB 3.0 Basler ACE 1920-155um camera was purchased along with the necessary accessories (a 1-inch format, 1.5 MP Fujinon 50mm and a V-lambda correction filter) and a QStarz BT-Q818XT GPS receiver for approximately $2,000. This equipment is used in conjunction with specialized software to gather images of traffic control devices (TCDs) at night and measure their luminance performance under nighttime driving conditions to ensure that the TCDs are visible to the driving public. The equipment should be installed in the data collection vehicle in a manner that minimizes vibration to the camera and GPS and does not obstruct the view of the driver.

There were two software packages created. One interface is used to collect the imaging and GPS data in the field and it has two tabs in the graphical user interface (GUI). The first tab is the GPS Raw data. Figure 21 depicts GPS tab and shows the serial port connection, communication rate, refresh rate, and raw GPS output. The serial port should be verified in Device Manager and set prior to starting the software. It is recommended to set the baud rate to 9600 and the refresh rate to 100. To start the software, select the arrow on the top left. When you are ready to stop the software, select the round red button two icons to the left of the arrow.

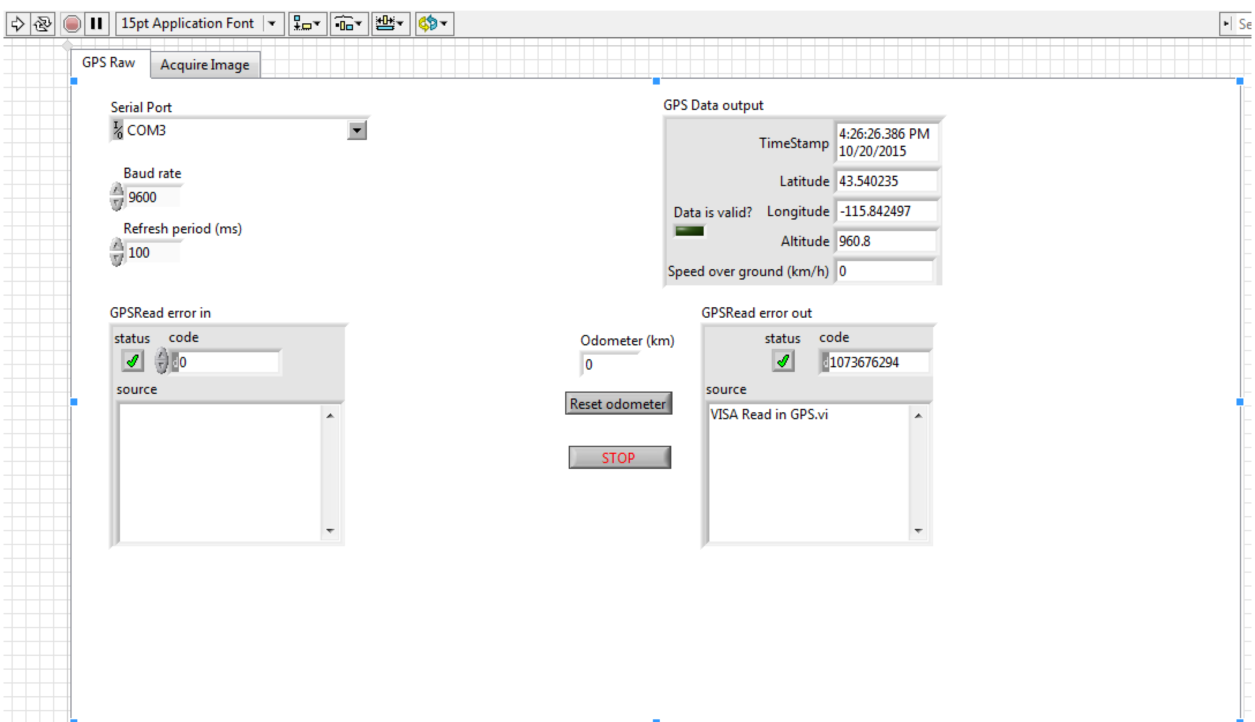


Figure 21. GPS Tab

Figure 22 shows the Acquire Image tab. Prior to starting the software, the log path should be set. The default of C:\ works fine, but the "Session In" camera channel should be set prior to starting the software. The software will only list connected cameras, which could be an installed computer webcam. When the software is started, select the "Save Images?" button when you wish to save images to the computer. The save image rate may vary, but you should always obtain at least one image per second. To start the software, select the arrow on the top left. When you are ready to stop the software, select the round red button two icons to the left of the arrow.

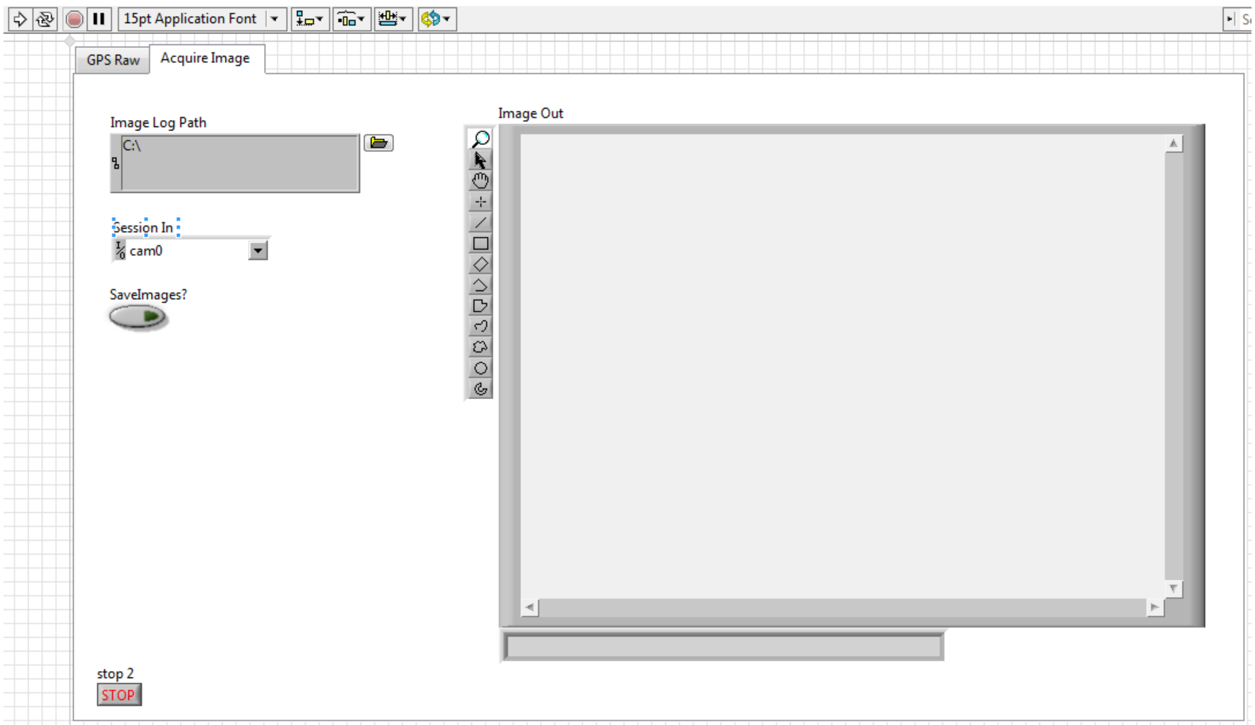


Figure 22. Acquire Image Tab.

The analysis GUI allows the user to analyze captured images (see Figure 23). The user selects a folder location and image, and f-stop and starts the software. The image will be imported, and every time the user draws a line across the image with the cursor, the data will be output in the graph to the right of the image. The descriptive statistics will also be summarized below the graph. If the user just selects the legend and background, the descriptive statistics could be used to access the contrast ratio. To start the software, select the arrow on the top left. When you are ready to stop the software, select the round red button two icons to the left of the arrow.

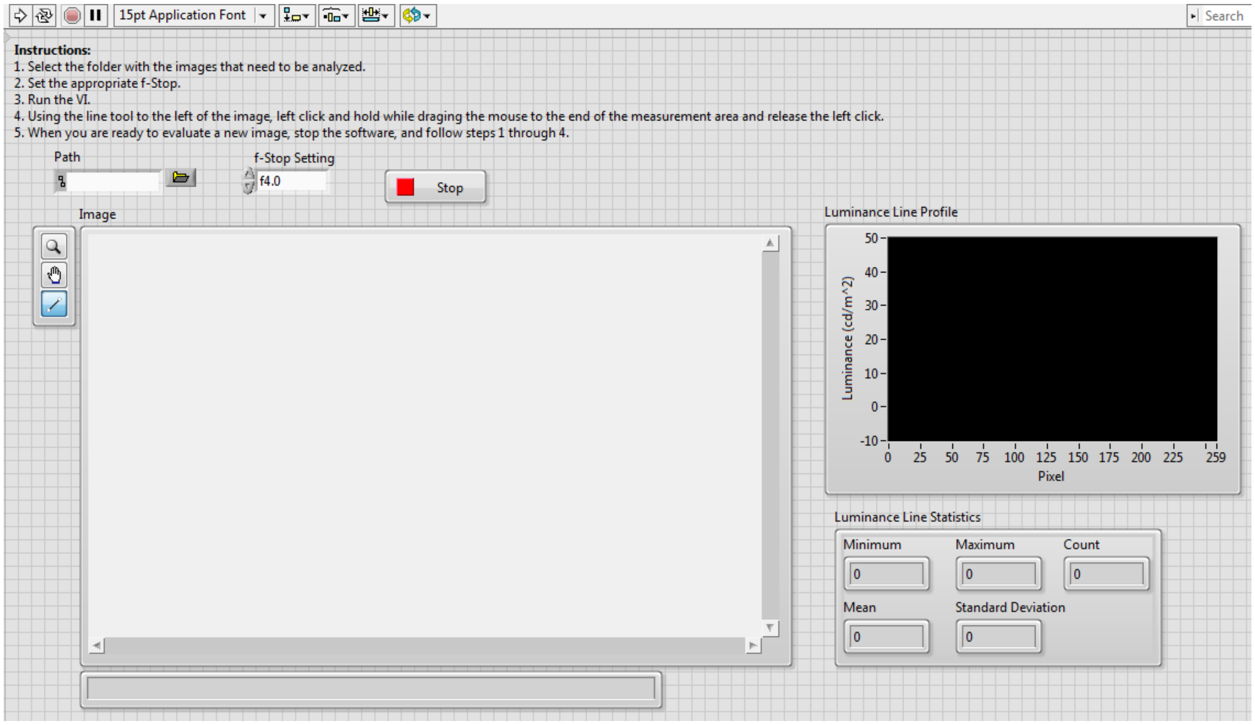


Figure 23. Analysis.