LED TRAFFIC SIGNAL LUMINOUS INTENSITY DEGRADATION: A PRELIMINARY DATA ANALYSIS

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ABSTRACT

Light emitting diodes (LEDs) have replaced a high amount of incandescent lights in the past couple decades. LEDs, when they degrade keep bright even though they fall outside of the required specification values determined by the Institute of Traffic Engineers 2005 traffic signal specification. The purpose of this research study is to take measurements of various traffic signals in both Anchorage Alaska and Fairbanks Alaska to determine the rate of decay over their years of installment. This was done by visiting 34 intersections combined and using a spectroradiometer to measure for luminance which then converted to a luminous intensity value by applying the ITE guidelines of conversion. Results confirm what was expected that traffic signals show a trend as they do degrade at an increase the longer they are out on deployment. A hypothesis testing of means was one of the methods applied to prove this theory. LEDs do degrade over time, however it is important to find the trends so that department of transportations and engineers can make the safest and cost effective decision as to when to replace a LED traffic signal.

Keywords: Light-emitting Diodes, Department of Transportation, Replacement Schedule, Incandescent Lights, Traffic Signal, Luminous Intensity, Luminance

INTRODUCTION AND BACKGROUND

Light-emitting Diodes or LEDs have taken an important role within the Traffic Engineering community as of a couple decades ago. They have become the go-to style of light for many of the Department of Transportation's needs for light out-put along highways and roads. The importance of the physics of light will need to be understood, most importantly that of a LED light-source and how the human eye perceives of it. The Department of Transportation has evolved from the usage of incandescent lights to LED lights for its traffic signals. A main focus to a Traffic Engineer is the human eye perception of LED lights and the reliability of workmanship for extended periods of time while mounted to their respected traffic device.

Light-emitting diodes (LEDs) began to replace incandescent lights on traffic signal modules and as a result bring challenges since their replacement practices when comparing the two vary greatly. For example, incandescent lights provide the required light output up until the time they burn out. As for LED modules, they degrade over the years and remain showing light but may fall below the required light output regulation. This project report will focus on the degradation of light from a traffic signal over the years.

To understand the Physics of an LED light we must first understand the important properties of light as it relates to traffic signals. We look at the way light presents itself to the human eye and the properties which allow it to shine bright to the needs of a traffic highway or road. The scientific terms commonly applied to define a LED light were applied to this study. These properties will describe the functions of an LED, how it conducts its power saving capability, and a generalized description of a variety of lights having equal to similar functions.

Luminance can be defined as the luminous flux emitted or reflected from a surface, in a given direction, per unit solid angle, divided by the area of the surface, expressed as cd/m2 as defined by the Institute of Transportation Engineering (Institute of Transportation Engineers, 2005). Candela is a measure of light that was applied many years ago before taking the name Candela from its original name Candle light, and it is currently being applied today as a measure of light. The human eye, with its restricted solid viewing angle, is an ideal luminance, or brightness, detector (Ryer, 1997). The luminance detector in our eye give us the ability to take in the brightness of the light being shone on us.

Luminous intensity can be defined as the luminous flux emitted in a given direction from a source, per unit solid angle, expressed in candelas (cd) as defined by the Institute of Transportation Engineering (Institute of Transportation Engineers, 2005). This form of measurement is applied to designs on traffic signals or emergency lights on highways because the light measured is that which is being seen by the human eye directly. Similarly, luminous intensity is a measure of visible power per solid angle, expressed in candela (Ryer, 1997). Here the solid angle is the angle at which our eyes is receiving the light therefore it has been seen as the preferred measurement of light for highways.

Luminous flux is define as the amount of light output from a source in units of Lumen within the spectrum visible to the human eye at 400 nanometers (nm) to 700 nanometers (Rose, 2005). An image of a spectrum visible to the human eye can be seen in Figure 1. The Lumen (lm) is the photometric equivalent of the watt, weighted to match the eye response of the standard observer (Ryer, 1997). For this study we will be focusing less on the units of Watt, rather will focus on the photometric properties of light which includes the Lumen unit.

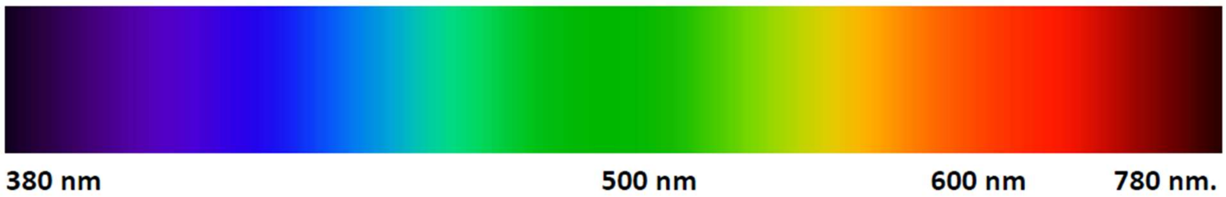

Figure 1. Spectrum Visible to the Human Eye (Photo Research, 2016)

Light is the unique phenomenon of multiple electromagnetic waves which are making their way through space (Ryer, 1997). There is an electromagnetic spectrum covering a broad range of waves ranging from ultraviolet to visible light and infrared light as seen in Figure 2. An example of this is waves classified as radio waves with wavelengths of a meter or more, down to x-rays with wavelengths of less than a billionth of a meter (Ryer, 1997).

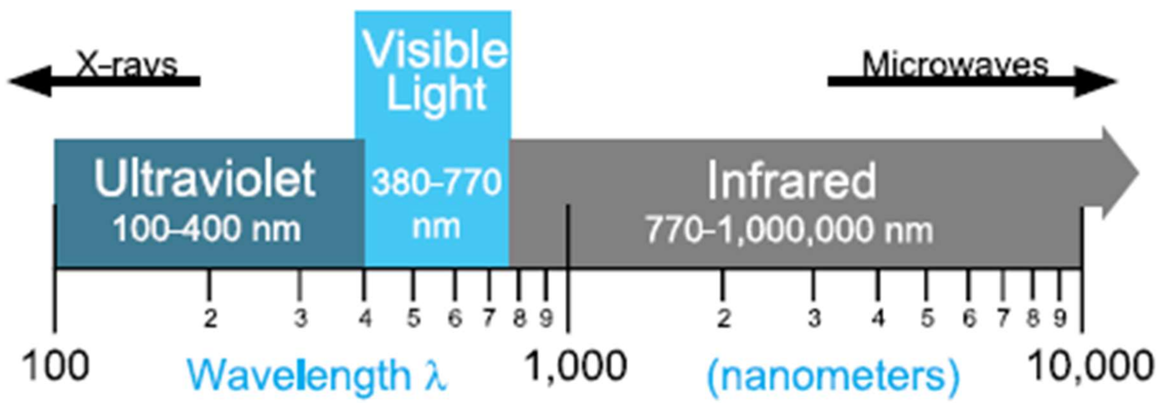

Figure 2. Electromagnetic Spectrum (Ryer, 1997)

Light measurement units will be either spectral, spatial, or temporal distribution of optical energy (Ryer, 1997). Planck's equation,

$$Q = h \times \frac{c}{\lambda} \tag{1}$$

Q is photon energy in joules, h is Planck's constant 6.623×10^{-34} Js , c is the speed of light $2.998 \times 10^{8} \frac{m}{s}$, and λ is the wavelength of radiation, is a description for photons since optical power is both a function of photons and wavelength (Ryer, 1997).

As for calculating for luminous intensity, there are many methods to measure light, however this study applies the luminance meter as the main tool to measure for luminous intensity. Once the luminance value is determined, it will need to be converted into luminous intensity so it can be compared to the values in the Institute of Transportation Engineering's 2005 specification for traffic signals. The ITE 2005 specification provides a series of equations to assist in determining their specification values.

$$f(I_{Horiz}) = 0.05 + \left(0.95 \times e^{-\frac{1}{2}\times\left((\frac{\theta_{Horiz}}{11})^2\right)}\right) \tag{2}$$

$$f(I_{vert}) = 0.05 + 0.9434 \times e^{-\left(\frac{\theta_{vert}+2.5}{5.3}\right)} \quad 3$$

$$f(I_{vert}) = 0.26 + \left(\frac{\theta_{vert}}{143}\right) + 0.76 \times \left(e^{-0.02\times(\theta_{vert}+2.5)^2}\right)^{(-0.07\times\theta_{vert})} \quad 4$$

$$I_{(\theta_{vert},\theta_{hori},size,color)} = [f(I_{vert}) \times f(I_{horiz})] \times I_{(-2.5,0)} \quad 5$$

Equation 3 is applied when the vertical angle, θ, is greater than -2.5º. Equation 4 is applied when the vertical angle, θ, is less than or equal to -2.5 º. Equation 5 is to calculate the minimum maintained luminous intensity value which will serve as the baseline requirement when comparing our measured luminous intensity values per their respective traffic signal color.

In the ITE 2005 Specification, it asks for measurements to be taken from a range of 12.5º above to 22.5º below the horizontal plane, as well as from 27.5º right and 7.5º left on the horizontal plane at 2.5º increments, while keeping the two highest values (Institute of Transportation Engineers, 2015). Within the same specification, there are tabled values providing the minimum required luminous intensity for each measurement angle, respectively.

Angle θ_{vert} is the angle measured above or below the horizontal plane perpendicular to the face of the modules lens. Angles above the horizontal plane are positive and angles below the horizontal plane are negative, see Figure 3 (Institute of Transportation Engineers, 2005).

Calculating the measured luminous intensity value is done by applying the following equation (Bullough, Snyder, Smith, & Klein, 2009),

$$I = L \times A \quad 6$$

Here the L is Luminance in $\frac{Cd}{m^2}$ and A is the area of the capture circle or "spot-size" in m^2. Equation 6 was also given and confirmed as the method to convert luminance into luminous intensity by the luminance meter manufacturer, Jadak.

$$Percent\ Error = \frac{|\ Approximate - Actual|}{|Actual|} \times 100\% \quad 7$$

Equation 7 was applied to calculate the percentage error. Where *Actual* value within the equation was the average luminous intensity values, and *Approximate* was the ITE minimum maintained luminous intensity value.

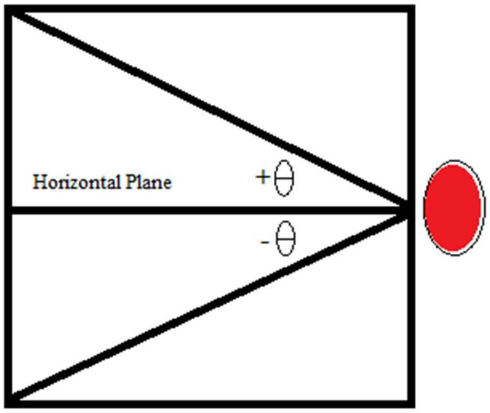

Figure 3. Vertical angle defined by ITE guidelines

OBJECTIVE

The objective of the project was to conduct an analysis to study the degradation of the luminous intensity of traffic signals over time, and to test the luminous intensity values with the existing standards (ITE guidelines).

LITERATURE REVIEW

The purpose of the literature review is study traffic signal measuring methods in preparation to generate a replacement schedule. The State of Alaska made the switch from incandescent lights to Light-emitting Diodes on their traffic signals around the nearing of the twentieth-first century, following the Institute of Transportation Engineering 1998 Traffic Signal Specification release. Light-emitting Diodes (LEDs) add a cost saving factor to maintenance operations along with light manufacture expenses and safety to the drivers or pedestrians. This work was compiled through research of documents, articles, and similar information to learn about methods applied by colleges, organizations, and state departments to study the effectiveness of LED lights on traffic signals with the development of a replacement schedule for Transportation organizations. Research methods applied were through search engines within the University of Alaska-Anchorage system, passed along articles by LED light measuring meter manufacturers, and online articles from organizations like the Transportation Research Board. Along with research on articles, videos were also studied through video platforms such as YouTube. The results were quite compelling. There was a variety of resources out on the internet from various institutions, Universities, and businesses all working for their local Department of Transportation to develop either a LED traffic signal exchange schedule or a study on the shine proportions of LEDs on Traffic apparatus' such as on walk-man lights or cross-walks and the brightness of LED on advertisement signs along government traffic roads. It has been concluded that the study of LED lights on traffic objects is minimal, however there are a few studies reported between the years 1998 and 2014 with unique information that closely relate to one another.

Measuring Device to Capture LED Light Output

Measuring devices to capture LED light output range from factory-built photometers to spectro-radiometer to in-house built devices which measure the same light output. Photometers are applied to measure the luminance output of the measured light. Conversely, a spectroradiometer is also applied to measure luminance of LED light with the addition of the capability of measuring the color output within the color spectrum visible to the human eye. Therefore, for the study of traffic signals and all other lights within the highway system, a spectroradiometer may be applied best since roads rely on color for many light operations. These measuring devices can either be stationary or mobile such as a handheld friendly device. While others may require to be stationary in a darks room, others may be able to be taken out on the field during the day and experience similar to a low percentage of error in their measured values.

Properties of Measuring Tool Devices

There were three main devices looked at towards the research of this project and those are a Spectro-radiometer which is a product produced by the Photo Research Group, a Spectra Colorimeters which is also produced by Photo Research Group, a Photometer and a house-made product Fresnel lens which captures illuminance created by the Missouri University of Science and Technology. Aside from the mentioned measuring devices, articles also mentioned luminance meters which describes a device which measures the luminance value of a light source (Finkle, 1997). A photometer captures the light being emitted by the source being measured (Wachtel, Report on Digital Sign Brightness, 2014). Spectra Colorimeter is a spectrally based colorimeter which performs complete photometric and colorimetric measurements for both steady state and repetitively pulsed light sources (Jiang, 2004), thus a colorimeter measures both the luminous and color of a light source while a spectra colorimeter does the same with the additional property of being spectrally based. The researched house-made device included commercial light meter, a range finder, a laser pen, and a custom made Fresnel lens (Long, Qin, Gosavi, & Wu:, 2011).

Aperture Angle

The aperture angle on a measuring meter governs many properties of the measurements being taken such as the distance at which the data is to be collected and the accuracy of the measured luminous intensity. Measuring meters with an applied multi-aperture setting are ideal for measuring both large and small targets without the need for additional lenses or accessories, and with minimal repositioning of the measuring meter (Photo Research, 2016). Essentially, when taking measurements, as will be talked about and explained in a future section, the measuring meter will produce what is called a “spot-size” which is the image shown when looking through the aperture view lens. This “spot-size” will need to cover all the area of the measured module or parts of the module depending on the type of study one is conducting. As long as the “spot-size” circle captures light only from the module of measurement and not the surrounding area, the meter will provide accurate readings of luminance (Wachtel, Report on Digital Sign Brightness, 2014). An example of a “spot-size” view to the user can be seen in Figure 4.

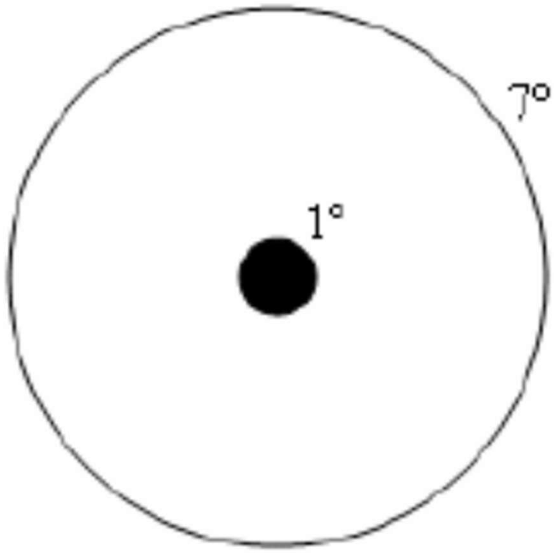

Figure 4. Aperture 1° capture circle within meter viewpoint (Jiang, 2004)

Instruments to Measure Luminous Intensity

JADAK

The Jadak PR-670 is one of the many PR modules provided by the company Jadak, also recolonized as Photo Research thus the (PR) at front of the instrument's name. This instrument is equipped with multiple aperture angle settings with the ability to take measurements at 1°, $\frac{1}{2}^{\circ}$, $\frac{1}{4}^{\circ}$, $\frac{1}{8}^{\circ}$ aperture angles. As previously mention, a varying aperture angle setting allows for flexibility in measuring the light source from a distance of the light source. Conversely, one may elect to measure the entirety of the module, half of the module, or a variety of points throughout the module and with the multiple aperture size option, this becomes readily easier. This instrument also has the capability to take measurements at an 8nm or 5nm spectral bandwidth dependent on the request at purchase. The Institute of Transportation Engineering (ITE) published the *Vehicle Traffic Control Signal Heads: Light Emitting Diode (LED) Circular Signal Supplement* in 2005, which has a requirement for measuring traffic signal modules to be at a 4nm spectral bandwidth. Although, the PR-670 is slightly short of that requirement, it was the only spectro-radiometer found closest to meeting ITE's specification.

Konica Minolta

The CS-200 is a colorimeter produced by Konica Minolta and has the capability of allowing the user to choose from either a 1°, $\frac{1}{5}^{\circ}$, or $\frac{1}{10}^{\circ}$ aperture angle. This meter can hold a maximum of 101 measurements within the unit, however those measurements will need to be recorded onto a device and emptied from the measuring meter before taking new measurements. This instrument has a measuring uncertainty of 2.2% which fully meets ITE's specification as listed on their *Vehicle Traffic Control Signal Heads: Light Emitting Diode (LED) Circular Signal Supplement* of a luminance uncertainty value of less than 2.5% (Institute of Transportation Engineers, 2005).

Missouri S&T Fresnel Lens

The Missouri University of Science and Technology built their own creation for measuring light output of a traffic signal module in their study conducted in the year 2011. They applied a

Fresnel lens, which was mentioned to be able to capture light at a distance by drowning out the light output from the LED with the application of the surrounding ambient light (Long, Qin, Gosavi, & Wu:, 2011). An image of the measurement operation with the Fresnel lens along with the image of the Fresnel lens itself, can be seen in Figures 5 and 6. The instrument works by filtering light output emitted from the LED where it was then focused by the Fresnel lens into a concentrated beam (Long, Qin, Gosavi, & Wu:, 2011). This allowed for a light meter to be placed behind the Fresnel lens to capture the light emitted from the tested traffic signal module.

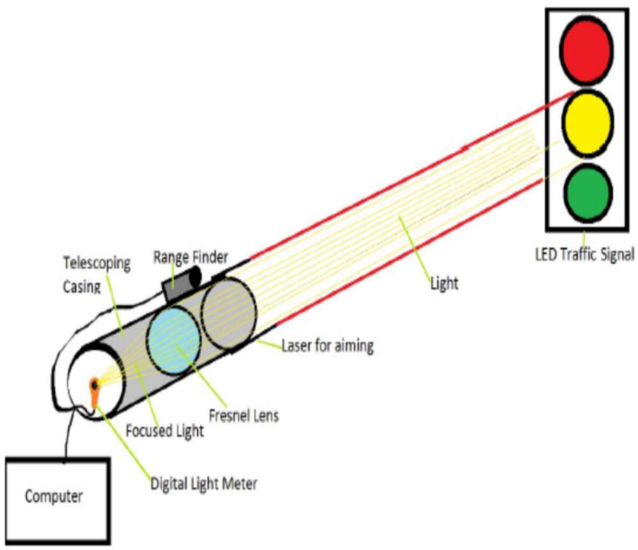

Figure 5. Illustration of the Fresnel lens (Long, Qin, Gosavi, & Wu:, 2011)

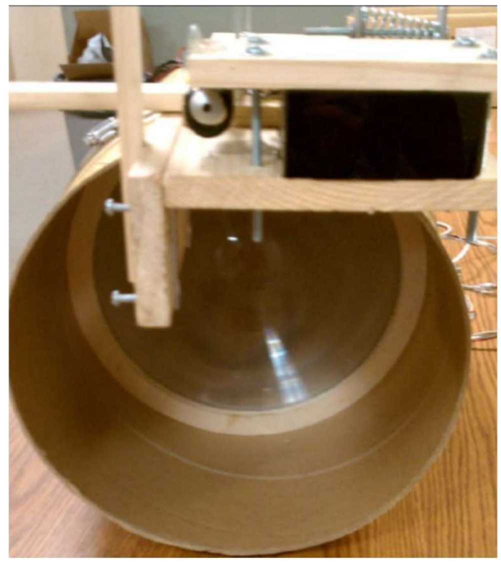

Figure 6. Fresnel lens (Long, Qin, Gosavi, & Wu:, 2011)

Data Collection Procedure

When taking a field measurement for luminance, one needs to account for the amount of ambient daylight, the specific measurement geometry, angle position, and natural factors like wind, which will play a role in the accuracy of the measurements (John D. Bullough, 2009). The 2005 Institute of Transportation Specification, Vehicle Traffic Control Signal Heads: Light Emitting Diode (LED) Circular Signal Supplement, covers luminosity, color, and power output. As mentioned in the ITE specification, the modules shall be identified on the backside with the manufacturer's name, model, operating characteristics, and serial number (Institute of Transportation Engineers, 2005). Additionally, those same modules shall include the nominal operating voltage and stabilized power consumption, in watts and volt-amperes (Institute of Transportation Engineers, 2015). It is important to perform all luminance calculations with a well-calibrated, portable light meter. However, it needs to be understood that not all portable light meters will necessarily provide an accurate measurement regarding the actual luminance of LED traffic signal modules (Institute of Transportation Engineers, 2005).

How to Take Measurements

The traffic signals have a casing around the light, so taking measurements from a horizontal angle will not cover the total 12-inch or 8-inch traffic signal. Photo research meters are sensitive to their angle; therefore, they need to have a strong base or tripod to be mounted onto when taking measurements (Jiang, 2004). When the measuring meter is pointed towards the light module, as long as the small circle or "spot-size" within the aperture opening captures the light being measured, and not the surrounding area, it will provide an accurate reading (Wachtel, 2014). Similarly, the "spot-size" within the measuring meter must capture and fill the most possible area of the light module, while keeping in mind that the area increases as the measuring meter becomes further away from module, increasing the number of points contributing to the measurement (Finkle, 1997). A good practice to keep in mind is that when comparing measured values to a variety of modules, one needs to take into notice that they may differentiate in properties and will need to be adjusted to compensate for the differentiation between the modules (Cohn, Greenhouse, & Knowles, 1998). Conversely, a good practice is to recognize that yellow, orange, and white colors will appear brighter than red, blue, and green (Wachtel, 2014).

Weather and Temperature

As mentioned in the ITE 2005 specification, when testing for luminance uniformity, the modules shall be compliance tested to ensure they meet the requirements for luminance uniformity at a temperature of 25ºC or 77ºF (Institute of Transportation Engineers, 2015). A study done by Florida State University in 2004 with a Photo Research measuring meter, concluded that when the temperature was at a low degree, the power of the traffic signal luminance was a lot higher (Jiang, 2004). Similarly, the ITE 2005 specification states that light output of LEDs diminishes as the ambient temperatures increase, and internal temperatures substantially reaches a 74ºC or 165ºF upper limit, which could result in an unacceptable LED module performance (Institute of Transportation Engineers, 2005).

When taking measurements in the presence of light, luminance measurements are to be taken when the module is on and off, then they are to be subtracted from one another for a final luminance reading before being applied to in calculations for luminous intensity (Bullough, Snyder, Smith, & Klein, 2009). Measurements must be taken within a few seconds of one another when applying the on-and-off method, and keeping in mind that measurements may be taken as accurately during the day as at night, but the measurement readings will result in a small percent error (Finkle, 1997).

Wachtel explains his experience with both nighttime and daytime measurements, but recommends nighttime measurements to ensure the readings are unobstructed as the daytime can cause obstruction in the measurements (Wachtel, Report on Digital Sign Brightness, 2014). Wachtel also mentions that the United States Sign Council prefers measurements be taken with luminance meters because of their versatility in taking measurements during the day or night. Additionally, Wachtel recommends daytime measurements be taken two hours after morning civil twilight and two hours before evening civil twilight. He also recommends nighttime measurements be taken after the end of evening civil twilight and before the beginning of morning civil twilight (Wachtel, 2014).

Angle of Measurement

In the ITE 2005 Specification, it asks for measurements to be taken from a range of 12.5º above to 22.5º below the horizontal plane, as well as from 27.5º right and 7.5º left on the horizontal plane at 2.5º increments, while keeping the two highest values (Institute of Transportation Engineers, 2015). Within the same specification, there are tabled values providing the minimum required luminance for each measurement angle, respectively.

Finkle, in his study, states that as the meter is further away from the light module, the angle will be reduced, and when the angle is at an extreme, the meter will be measuring the effect of the inverse square law, and as a result, the module will act as a point source (Finkle, 1997). In Rea's 2000 study, they concluded that if the inverse square law was to be applied, then a percent error of less than 5% will be required for calculations of the luminous intensity (Rea, 2000). A study conducted by Cohn, Greenhouse, and Knowles shows that the values for luminous intensity decline when taken off-axis of the measured module by an extreme (Cohn, Greenhouse, & Knowles, 1998). Missouri S&T, in their 2011 study, gave insight on their methods for measuring luminance values from a driver's perspective. They took their measurements at a 0º horizontal angle and a 10º angle below the vertical, then afterwards they compared those values to the values presented in the ITE 2005 Specification (Long, Qin, Gosavi, & Wu:, 2011).

Distance of Measurement
A 2009 study conducted by Bullough, Snyder, Smith, and Klein, recommends that the distance from the measuring meter to the module must be at least five times greater than the dimensions of the measured module (John D. Bullough, 2009). Conversely, it does not matter at what angle or distance the measuring meter is from the light module, all which is important is that the capture circle "spot-size" falls only within the module itself and not its surrounding area (Wachtel, 2014).

Finkle mentions he was limited to a 53-meter measuring distance when equipped with a $\frac{1}{3}^{\circ}$ aperture opening on his measuring instrument as he measured a 12-inch traffic signal light module (Finkle, 1997).

Calculating Luminous Intensity
The ITE 2005 Specification states that all modules shall be tested for luminous intensity. A single point measurement may be applied with a correlation to the intensity requirements listed within the tables provided in the ITE 2005 Specification. You may also apply a single point measurement with a correlation to the intensity requirements of Sections 4.1.1 and 4.1.2 of the 2005 Specification (Institute of Transportation Engineers, 2005). In the NCHRP Web-Only Document 146 report by Bullough, Snyder, Smith, and Klein, they mention how luminous intensity LED traffic signal modules degrade over time (Behura, 2007). They brought to the attention how the ITE 2005 Specification recommends that LED traffic signals be replaced when the intensity of the module no longer produces the minimum specified luminous intensity (Institute of Transportation Engineers, 2005).

Lastly, when the area of the module is larger than the area of the aperture "spot-size," the area of the module is applied to the calculation for luminous intensity being $I=L\times A$, where I is luminous intensity, L is luminance, and A is the area of the traffic signal module (Finkle, 1997). When calculating a luminous intensity value with luminance, there is sometimes the application of a scale factor. The luminous intensity equation becomes $I=L\times A\times\text{Scale Factor}$, where the scale factor is calculated by dividing the area of the aperture "spot-size" by the area of the traffic signal module (Bullough, Snyder, Smith, & Klein, 2009).

EQUIPMENT USED IN THE STUDY

In this project the PR-670 from JADAK was used. The Photo Research (PR) 670 came in a hardened case with all the required items to take measurements for luminous intensity and color of a traffic signal module. An image of the PR-670 and its accessories can be seen in Figure 7.

The battery equipped within was a Li-ion battery at a 3.68 Volt; 6800 mAh battery. This battery is placed inside of the PR-670 measuring unit by opening the battery case on the unit by pressing and sliding left the button located at the front left of the measuring meter. The battery location is next to the lens slot which is also at the font of the camera. To eject the battery, press the white button located at the top right inside of where the battery is inserted. After pressing this white button, the battery will eject outwards.

The measuring unit includes a MS-75 Macro-Spectar camera lens that attaches to the measuring unit itself, which needs to be inserted onto the measuring unit prior to taking measurements. This is done by first twisting off the connection cover from the PR-670, rotating off the cap at the connecting end of the MS-75 lens, and then applying the lens onto the PR-670 and twisting it counter-clockwise. Be certain to only twist on the lens by holding onto the lower portion of the lens and keeping the grip off of the lens focus adjuster.

To charge the measuring unit, with the 6XX power supply, the AC DC Adapter by Photo Research will need to be connected to one of the two power cords which mount onto a power outlet. One of the power cords has the standard three metal connections of a typical wall power connection. The other power cord in the package is also a three-piece connection, however this outlet connection has each metal piece at equal distance from one another such as a commercial-type connection. Conversely, the AC DC adapter is capable of a 5-Volt output along with a 3.0A and 15-watt max power output.

Figure 7. PR-670 measuring unit with its accessories

The PR-670 is equipped with a 512MB memory digital card and a USB drive, along with a certificate of calibration. A 512MB is capable of storing about three thousand luminance measurements. A requirement by the Institute of Transportation Engineers in their 2005 specification for measuring traffic signals states, a measuring unit needs to be certified prior to taking measurements for luminance.

The PR-670 measuring unit itself comes with a measuring output screen facing the observer who is taking the measurements. On the same side of the PR-670, to the right of the measuring screen, there will be an up/down/right/left button along with a center button which is one of two ways to toggle information provided on the measuring unit's screen. The screen is a touchscreen, and that is the other way to select items on the screen. Additionally, above the arrow buttons is the "on" button. To turn off the measuring unit select the "power-off" option presented on the home section on the touchscreen. To the left of the screen is the aperture's eye piece in which is needed to be look through when taking measurements. Above the measuring unit there is only one button and it is labelled "measure," which is pressed once to begin a measurement when the unit is on. If the multiple measurement option is selected, the button needs to only be pressed once, as the measuring unit will recognize that the multiple measurement option was selected.

On the left of the measuring unit, there are a few output connections such as to an ethernet cable port, two PS/2 cable ports, a micro-USB connection port, and a connection to charge the battery charger. To the right of the measuring unit, there is an adjustable strap handle which makes it easy to hold the PR-670.

IN-LAB TESTING

Classroom Testing

The measuring unit will have to be setup internally. The PR-670 user manual will contain all the information to set up the PR-670 prior to taking measurements. Given the labs size, we are restricted to a 6-inch or 5-inch "spot-size" on a 1^{o} aperture opening given the calculated measuring distance applying the Jadak minimum distance equation. The maximum workable distance in the lab was thirty feet, and the calculated minimum distance 6-inch "spot-size" was around twenty-eight feet. Remember, "spot-size" referrers to the black circle within the eyepiece of the PR-670 that will be seen while taking measurement, which will need cover to the LED light (Jadak recommends at least 80% of the LED is covered by the "spot-size" for an accurate measurement.)

To set-up the traffic model for testing, insert a LED signal inside of the traffic module's metal casing (Figure 8). The metal casing consists of a one-piece casing that opens on one side by turning each of the two-bolt wing-nuts counter-clockwise and rotating the bolts vertically once loose. The bolts will remain attached to the metal casing since the wingnut is unable to easily be completely removed, and that is fine (Figure 9). The opposite side of the metal casing consists of a hinge, which allows the metal casing to provide the sufficient amount of room when inserting the LED signal. When inserting the LED signal, rotate the four metal slips along edges of the circular portion of the casing to allow the signal to fit. Then rotate the four metal slips over the LED signal edges once inserted. The metal slips can be tightened or loosened with either a cross-head or flat-head screwdriver as needed. Once the LED signal is set in place, locate its two power wires; one will be white and the other will either be red for a red signal, brown for a green signal, or yellow for a yellow signal, respectively. Connect the white wire to the white wire connection within the traffic module's metal casing and connect the other colored wire to the black wire connection also within the metal casing. The LED signal's connecting wire needs to have a slip-in connection piece that allows it to easily be slipped onto its connecting wire's, also needed, metal piece. To complete installation of the traffic signal LED light, close the metal casing and tighten the two fly-bolt wingnuts. To turn on the traffic module signal, connect the traffic signal's metal casings power outlet to any regular indoor common light power outlet. The final set up can be seen on Figure 12.

For clarity and accurate measurements, lay down a measuring line on the floor that indicates the length at which light measurements will be taken, such as a ruler, measuring tape, or any similar tool. For this experiment, a surveying tape measure was set down. Painters tape was placed on the floor at one-foot increments along the surveying tape and marked with a permanent marker showing the number of feet from the traffic signal module. The distance from the PR-670 to the traffic signal module will need to be as accurate as possible, to the calculated distance by the Jadak equation, for the best accurate readings.

Prior to taking measurements with the PR-670, self-calibrate the measuring unit. To do this, un-focus the MS-75 lens when connected, then twist the diopter adjustment (eyepiece) clockwise or/and counter-clockwise in order for the "spot-size", or black circle, to be focused. Next, focus the MS-75 lens on the LED signal by twisting the lens either clockwise or counter-clockwise until the target is in focus. Once the diopter adjustment and the MS-75 lens are in focus, measurements can be taken. Measurements are taken by pressing the "measure" button located at the top of the PR-670 measuring unit on the right-hand side.

Figure 8. Traffic signal metal casing

Figure 9. Fly-bolt wingnut

A required distance for a respected aperture angle and “spot-size” is calculated by Equation 8, provided by Jadak (Photo Research);

$$L = \frac{S \times z}{a} \tag{8}$$

$Where, S = Aperture$ spot-size $diameter\ in\ meters, z =$ max $working\ distnace\ or\ 305m,$
$a =$ max $working\ disnce\ per\ aperture\ size\ in\ meters$

Values for (a), provided by Jadak,
Aperture 1º = 5.32 (meters
Aperture 0.5º = 2.66 meters
Aperture 0.25º = 1.33 meters
Aperture 0.125º = 0.665 meters

Values of (a) are the maximum “spot-size” diameter each aperture angle setting can achieve when the meter is at its maximum working distance of 305 meters.
Values for S are chosen depending on the project’s need. For example, if a 12-inch traffic signal is being measured, then maybe a 10-inch “spot-size” is needed and chosen, therefore the value for S is 10-inch. “Spot-size” will vary with distance and the selected aperture angle. The Institute of Transportation Engineer’s 2005 traffic signal specification calls for the majority of the signal to be covered by the “spot-size” for full-tests. Alternatively, the specification calls for a 25mm “spot-size” when calculating luminous uniformity. Photo Research recommends the “spot-size” cover a minimum of 50% of the traffic signal for good measurements and at least 80% for the most accurate measurements.

The value for z remains fixed at 305 meters since that is the maximum cleared distance for the PR-670 measuring unit, respectively. An example question calculation for minimum horizontal distance can be seen on Figure 10.

Example (1): Calculate the maximum working distance for a Traffic Signal LED Light of Diameter of 12inch with a 0.125 degree aperture. Assume the spot size is the distance of the entire traffic signal. Determine if the aperture degree allows for a working distance of 100ft or greater.

s = 12inch = 0.3048m
Using a 0.125 degree aperture opening, d = 0.665m
Max Distance = 305m

(0.3048m) * (305m) / (0.665m) = 140m = 460ft

The 305m is the limit max working distance for the PR-670. A 12inch traffic signal becomes 0.3048m when converting to meters. 0.665m was provided by Table 1 for a 0.125 degree aperture opening.

As we can see, the max working equals to 460ft and goes well beyond a desired 100ft.

Figure 10. Distance Calculation for a Jadak PR-670 (Esteves, 2020)

Crane Lift LED Traffic Signal Testing

The traffic signal LED module equipment was taken to the Engineering Industrial Building (EIB) room 103, or The Student Innovation Center to test at actual traffic signal heights of 20-15 feet. The traffic signal LED is then mounted into its metal casing. For the traffic signal to be mounted onto the crane, a crane-trained employee of the University will need to perform this task.

As the traffic signal is mounted on the crane and tightly strapped, a measuring tape and an extension cord will need to be connected to the traffic signal. The measuring tape is to determine the height of the traffic signal when lifted. The extension cord is to power the traffic signal. The traffic signal was lifted to a 15-foot height for preliminary tests, then to a 17-foot height for final test (Figure 11). Keep note that the traffic signal will attempt to rotate horizontally in a circular manner. In order to keep the traffic signal still, one way to approach it, is to tie the power cable extension cord connected to the traffic signal onto some object down below.

Figure 11. Setting for in-lab testing using

Figure 12. Red traffic signal module in-lab setting

With a 25-foot measuring tape, mark the ground with painters tape and label each mark with a permanent marker indicating the distance away from the traffic signal. A distance of 75 feet at 25-foot increments was applied to this experiment. Begin testing for luminous intensity measurements with the PR-670 once it has become self-calibrated and the required measuring distances have been determined. Applying the Pythagorean Equation, the required angled (θ) measuring distance, as seen in Figure 3, can be calculated. The measuring unit will be elevated when taking the measurements of an elevated traffic signal, therefore the required measuring distance may vary depending on the height of the measuring meter and the height of the traffic signal during testing.

Appendix B summarizes several tests done in the lab setting and in the outdoor setting as practice and testing for questions that arose prior to going out for field work at the main locations.

DATA COLLECTION

Data were collected in Anchorage and Fairbanks in October and November of 2020. Data for Fairbanks were collected on October 23 and 24. Data for Anchorage were collected on October 19, 27, 29, November 2 and 9. This section discusses the details of the data collection.

One of the testing locations was in Fairbanks, Alaska, where the temperature was nearing the single digits in Fahrenheit at night. Once we arrive at our city of testing and get settled in, all the equipment to measure the traffic signals was organized and prepared for testing that night. Prior to leaving for Fairbanks that same morning, all the equipment was organized and inventoried in preparation for the trip. The same was done when arriving to the hotel that following afternoon. After the inventory was complete, a trip to a nearby post outside of the hotel was visited to test the new equipment occupied to measure the distance of the traffic signal to the measuring meter. Later that night, a Department of Transportation night crew foreman was met to assist with traffic control during the traffic signal measurements. To be prepared for nighttime measurements in the cold, such as in Fairbanks, Alaska, in the month of late October, proper clothing will be required along with low temperature snow boots and gloves. Accessories such as hand warmers are also recommended, because it will become challenging to combat the low degree weather for the time it takes to complete an entire intersection. A total of sixteen intersections were completed in two nights, with some intersections having two signals per direction and others having three signals in total when adding up all signals per direction. Equipment applied to the measurements were the following,

- Tripod
- Tripod mount for precise adjustments for the spectro-radiometer
- PR-670 spectro-radiometer and its included accessories
- DSLR Camera and its included accessories
- Power bank
- Hand warmers to be applied to the PR-670 spectro-radiometer
- Laser distance measurement device
- Clipboard
- Writing utensils
- Paper

A power bank was needed to energize the spectro-radiometer when the battery began to reduce its life due to the low temperatures of the outdoors in Fairbanks. The spectro-radiometer was plugged into the battery bank after every intersection or rather it was attempted to be done. Additionally, hand warmers were researched and were determined to be a viable resource to be applied onto the spectro-radiometer when exposed to cold temperatures, and they also served as hand warmers for the members taking the measurements outdoors. Similar to the function of the power bank and hand warmers, an extra battery was acquired to serve the DSLR camera, in case the cold and low temperature was to drain its battery while taking photos in the outdoors. The laser distance measuring device was applied to measure the distance required to place the spectro-radiometer, which was based on the minimum distance requirements determined by calculating the desired "spot-size" per aperture setting, whether it be a 1º, 0.5º, 0.25º, or 0.125º, respectfully. The laser distance measurement device has the capability to show a visual, on the tool itself, of the area at which it is being pointed at. For this reason, it is recommended to get a laser which shows on a screen, within the tool, the location of interest. This will save lots of time when taking distance measurements. In addition, the distance measuring device was applied to measure the height of the mast arm on which the traffic signal mounts on. Conversely, a clipboard, writing utensil, and paper as applied to data collection and served to write down the luminance measurements that the spectro-radiometer gave for each measurement. As the measurements were automatically saved onto the SD memory card present inside of the PR-670, they were also noted down in case of an emergency were to occur or if for any reason backup data was to be needed. A tripod mount was needed for spectro-radiometer for it to take precise measurements when mounted. Previous mounts would cause the spectro-radiometer to move after each measurement was taken or when moving from one traffic signal to the next. The mounts acquired for this project made it to where the height of the meter was easily adjustable in the vertical and horizontal direction. Conversely, while two members were taking measurements and noting down data measurements taken with the spectro-radiometer, one managed the DSLR camera, and one stood by the pedestrian crosswalk button to rotate the lights, for some intersections gave the high volume streets the extended period of time compared to cross streets. Each night took about five to six hours to complete without including preparation and travel time. Which practice and being prepared each traffic intersection will take roughly half-an-hour to complete. It is recommended to bring snacks and water and perhaps chosen drinks to boost one's energy after midnight. The work shifts went well beyond midnight and lasted on average to three in the morning.

Testing nights on the field for Anchorage and Fairbanks totaled to be eight nights, and all had the same procedure other than some measurements were taken at varying distances to accommodate the available distance. A combined total of 34 intersections were visited. Figure 13 shows an example on how the tri-pod was stationed facing the traffic signal of interest. Figure 14 shows a traffic control vehicle behind the tri-pod controlling traffic around when taking measurements.

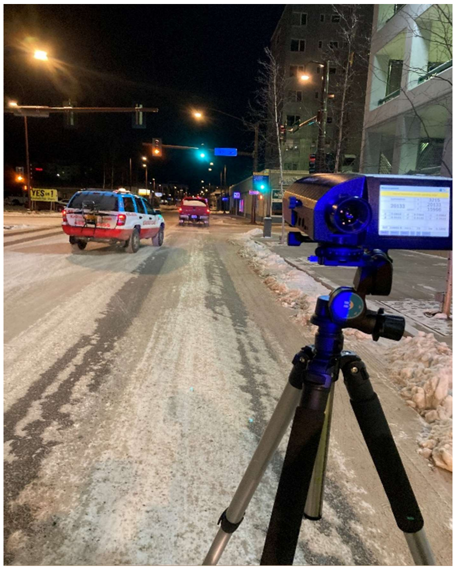

Figure 13. Spectro-radiometer In-Field

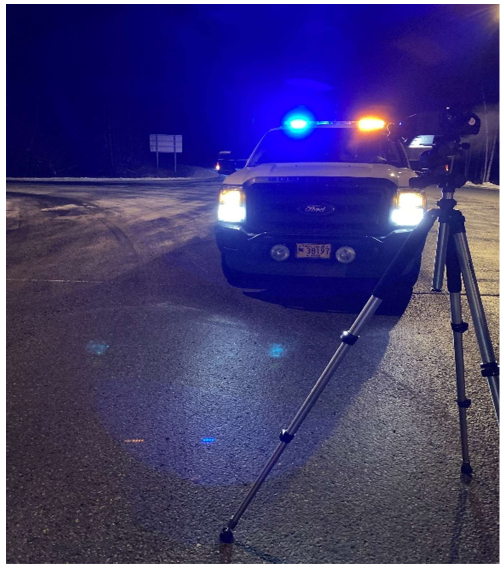

Figure 14. DOT Traffic Control

METHODOLOGY

Data Analysis

To convert luminance into luminous intensity, apply the measured values for luminance along with the calculated area, determined with the diameter of the circular marker or "spot-size," into Equation 6. To calculate the minimum maintained luminous intensity value as per the ITE 2005 Specification, apply the calculated vertical angle and horizontal angle, if applicable, to Equations 2-5. Table 1 shows the values to be imputed into Equation 5 to complete the calculation. The 2005 ITE specification also has pre-calculated minimum maintained luminous intensity values listed in tables for varying amounts of horizontal and vertical angles. If chosen, the measured luminous intensity and ITE's minimum maintained luminous intensity value can be compared to one another to see if the traffic signal meets the required specification.

Data are organized in four bins, each bin being a five-year data set. A bin for all data measurements for the years 2000-2005, 2006-2010, 2011-2015, and 2016-2020 are created. These bins contain the calculated luminous intensity values for the five measured luminance values per intersection. The mean of all the values in each bin year along with the standard deviation were calculated. Then the calculated minimum luminous intensity values from the ITE specification were compared to the calculated mean values for each year bin.

Table 1. Standard Values from ITE (ITE, 2005)

$I_{(-2.5,0)}$		
Color	200mm	300mm
Red	165 cd	365 cd
Yellow	410 cd	910 cd
Green	215 cd	475 cd

Table 2. ITE Minimum Maintain Luminous Intensity Values for a 154 Foot Measuring Distance Away from the Traffic Signal

ITE Minimum Maintain Luminous Intensity Values		
Distance	I (Green)	I (Red)
154 ft.	444	341

[1]Units for luminous intensity are in candela

Table 2 shows the values for minimum luminous intensity from the 2005 ITE specification as calculated by their provided equations. The meter can present a larger circular when it is further away from the source.

An excel file is to be created with columns for site ID, site name, year of installation, direction, number of light measured per direction, distance from the source in feet, aperture degree, spot-size in inches, area of spot-size in squared meters, luminance values in candela per square meter, luminous intensity values in candela, mean, and standard deviation. Depending on the distance and spot-size applied for each measurement, the area of the spot-size may vary. A total of five measurements was recorded for the green and red light on each traffic signal module.

Data was then imported into the Jadak SpectraWin2 software which shows all the properties of the measurements. For this report's study, only the photometry property was of interest, as it provided the luminance values for each of the measurements. The data was then exported from the SpectraWin2 software onto an excel file and named with respect to its created site ID as defined by the intersection.

The area of interest was to split the data by year of distribution, and analyzed the results to see if there were any connections to the degradation of light based on the year of the signal was installed. Hypothesis testing of mean was applied to the analysis to see what trends were seen in the results. For the year approach, the data focused mostly on the year of installation and the luminous intensity value for all five measurements. All luminous intensity values were then applied to find the mean and standard deviation for each grouped year set. Grouped year sets were from 2001-2005, 2006-2010, 2011-2015, and 2016-2020. Year group sets or bins were then compared to one another. The null hypothesis is $H_0: \mu_1 = \mu_2$ and the alternative hypothesis is $H_a: \mu_1 \neq \mu_2$. The test is to see if there is a significant difference between the performances of traffic signals installed at varying years. So it is believed that their performances will not be the same. So what is being tested is the alternative hypothesis. The following equations were applied to perform hypothesis testing of mean method.

$$t_0 = \frac{\overline{X_1} - \overline{X_2}}{S_p \times \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \tag{9}$$

$$S_p = \sqrt{\frac{(n_1 - 1) \times S_1^2 + (n_2 - 1) \times S_2^2}{n_1 - n_2 - 2}} \tag{10}$$

$$df = n_1 + n_2 - 2 \tag{11}$$

$$\frac{S_1}{S_2} \qquad 12$$

Where,

$\bar{X} - Mean$

$n - Sample\ size$

$S_p - Pooled\ Standard\ Deviation$

$S - Standard\ Deviation$

$df - Degrees\ of\ Freedom$

A pooled standard deviation was applied since the populations were independent, the sample size was large, and the population variance ratio (see Equation 12) fell between 0.5-3, respectively.

RESULTS AND DISCUSSION

Figure 15 and Figure 16 show a plot of the green traffic signal luminous intensity values and red traffic signal luminous intensity values by their installment year. Figure 15 for the green signal shows a decrease in luminous intensity value as the installment year increases. A similar pattern in seen for the red traffic signal in Figure 16.

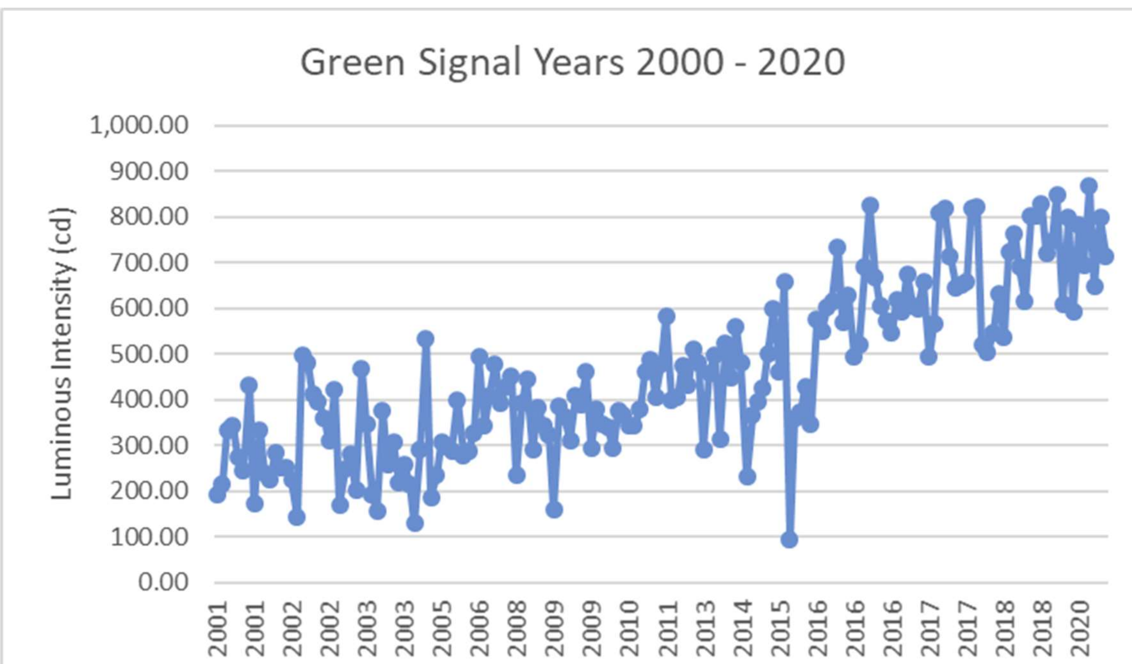

Figure 15. Trend of Average Luminous Intensity Values For Green Light

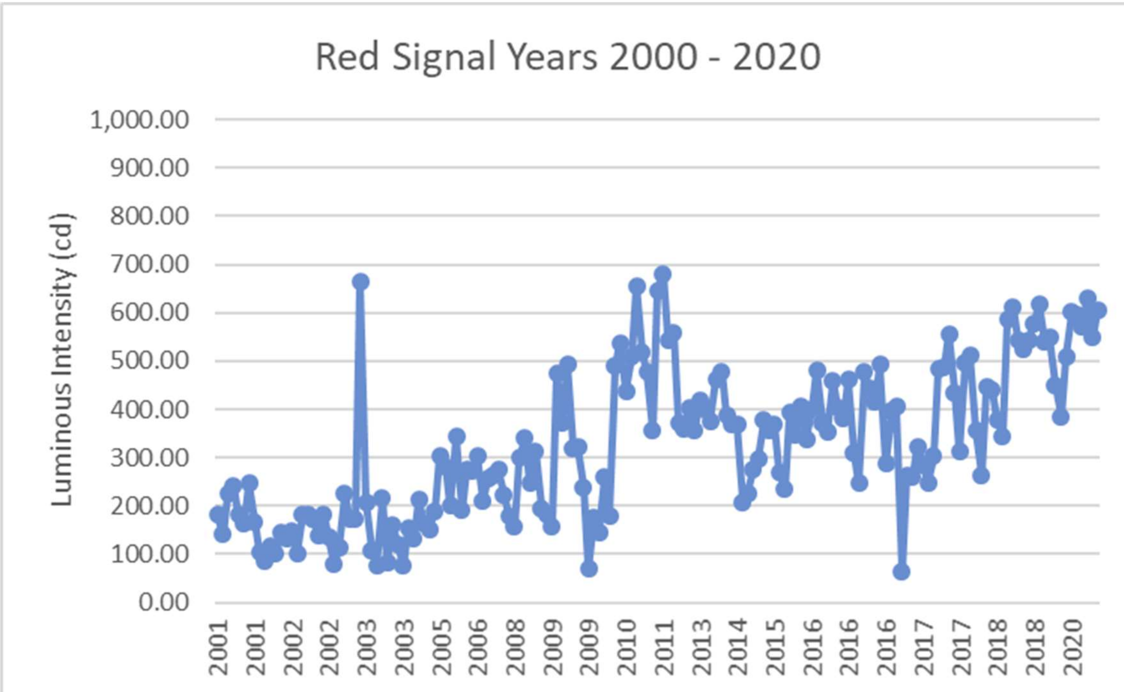

Figure 16. Trend of Average Luminous Intensity Values for Red Light

Table 3 shows the calculate mean and standard deviation values of green traffic signals at a distance of 154 feet between the meter and the traffic signal at that inclined distance. The results show that from year bin 2016-2020 to 2000-2005 the luminous intensity value dropped by roughly 4000 candelas. That is about a 15-year age gap. The trend is a decreases value of luminous intensity the further the signal light is out on deployment. The surprising notice was a large value decrease of about roughly 300 candelas at a 154 foot distance from year bin 2016-2000 to 2011-2015.

Table 3. Green Signal Yearly Distribution Mean and Standard Deviation per Distance of Measurement

Mean				
Year/Distance	2000-2005	2006-2010	2011-2015	2016-2020
154 ft.	312.15	377.13	401.71	721.55
Standard Deviation				
154 ft.	113.57	73.69	81.78	93.95

[1]Units for luminous intensity are in candela

Table 4 shows the similar values as the previous table, but this time they are for the red traffic signal light measurements. The data shows a similar decreasing trend over the years, however the discrepancy between the two colored lights is that the red traffic signal degrades at a steady rate rather than a large immediate drop in luminous intensity as the green traffic signal. The 154 foot distance show the trend of a steady decline without major large drops. The values dropped by about 100 cd over the 5-year set intervals.

Table 4. Red Signal Yearly Distribution Mean and Standard Deviation per Distance of Measurement

Mean				
Year/Distance	2000-2005	2006-2010	2011-2015	2016-2020
154 ft.	266.86	323.44	405.97	502.89
Standard Deviation				
154 ft.	51.64	141.52	129.22	92.36

!Units for luminous intensity are in candela

Table 5 contains the same values mentioned on Table 3 with the addition of a percent error calculated with the ITE 2005 specification minimum luminous intensity value. It shows the percentage errors determined for the green traffic signals at a 154 foot measuring distance. What can be seen is that the 2000-2005 year bin had the largest percent error 30 %. The percentage error for year bin 2006-2010 was 15%. This table shows that for a green traffic signal installed in the years 2011-2015 or below, the luminous intensity value has a high probably of falling below the minimum required luminous intensity value as they degrade over time.

Table 5. Percent Error for Mean of the Green Signal Luminous Intensity Value per Year Compared to the Calculated ITE Minimum Luminous Intensity Value

2000-2005^{+}	Percent Error, %	2006-2010*	Percent Error, %	2011-2015*	Percent Error, %	2016-2020*	Percent Error, %
312.15	30	377.13	15	401.71	10	721.55	0

(*) – Values remained actual without applying the standard variation due to them meeting or would have met the ITE standard with the application of the standard deviation

($^{+}$) – Values included the application of the calculated standard deviation since it fell below ITE standard

!Units for luminous intensity are in candela

Table 6 has the same values mentioned in Table 4 with the addition of a percent error calculated with the ITE 2005 specification minimum luminous intensity value. The luminous intensity over of the years has a relatively steady decrease averaging at a decrease of about 100 every 5-year interval. This is showing the degradation of light output for a red traffic signal as the number of years it has been installed increases.

Table 6. Percent Error for Mean of the Red Signal Luminous Intensity Value per Year Compared to the Calculated ITE Minimum Luminous Intensity Value

2000-2005^{+}	Percent Error, %	2006-2010*	Percent Error, %	2011-2015*	Percent Error, %	2016-2020*	Percent Error, %
266.86	22	323.44	5	405.97	19	502.89	0

(*) – Values remained actual without applying the standard variation due to them meeting or would have met the ITE standard with the application of the standard deviation

($^{+}$) – Values included the application of the calculated standard deviation since it fell below ITE standard

!Units for luminous intensity are in candela

The identifications using the letters A, B, C, and D are to define a set of years. Years 2000-2005 was labeled as bin A, which includes all the luminous intensity values for traffic signals installed within that year range. Similarly, 2005-2010 was labelled as B, 2011-2015 was labeled as C, and 20015-2010 as labeled as bin D. The reason for doing this is to see if there is any relation between the luminous intensity values between each set of years. This we can compare each of the bins and see if the LED lights show degradation between the years.

Results from Tables 7 and 8 required hypothesis testing with four sample means. A test was conducted on four different year bins to see if there were any significant differences between the performances between green traffic signals at varying years of installment. The five measured luminous intensity values per traffic signal for 166 traffic signal modules were split into four five-year bins. A mean and standard deviation were determined for each bin. Raw data values and calculations can be seen in Appendix A. The largest mean of the two values compared was μ_1 for the null H_0: μ_1=μ_2 and alternative H_a: μ_1>μ_2. The later the year of installment, the higher the mean value for its measured luminous intensity value was. Testing was to see if there was any major differentiation at the 1% significance level. Calculated t-values for green and red traffic signals all fell in the rejection region, therefore the null hypothesis was rejected. This shows there is a significant difference at a 1% percent significance level. So the performance of the green and red traffic signals between the 5-year bin increments are not the same, there is a significant difference between their performance.

Table 7. Hypothesis Testing of Mean with Separation of Data by Year Bins Organized with Green Luminous Intensity Data in 5-year Increments for All Distances Combined. Full Data can be found in Appendix A

Comparison	A to B	A to C	A to D	B to C	B to D	C to D
n_1	165	150	274	150	274	274
n_2	245	245	245	165	165	150
S_1	72	112	106	112	106	106
S_2	96	96	96	72	72	112
$\overline{X_1}$	373	432	668	432	668	668
$\overline{X_2}$	292	292	292	373	373	432
S_p	87	102	101	93	95	108
t_0	9.2	13	42	6	32	21
df	408	393	517	313	437	422
α	0.01	0.01	0.01	0.01	0.01	0.01
t	2.326	2.326	2.326	2.326	2.326	2.326
Hypothesis Test	Reject H_0	Reject H_0	Reject H_0	Reject H_0	Reject H_0	Reject H_0

[1]Units for luminous intensity are in candela
A to B: B represents data set 1 (n1, s1, etc.) and A represents data set 2 (n2, s2, etc)

Table 8. Hypothesis Testing of Mean with Separation of Data by Year Bins Organized with Red Luminous Intensity Data in 5-year Increments for All Distances Combined. Full Data can be found in Appendix A

Comparison	A to B	A to C	A to D	B to C	B to D	C to D
n_1	165	150	275	150	275	275
n_2	245	245	245	165	165	150
S_1	141	109	121	109	121	121
S_2	93	93	93	141	141	109
$\overline{X_1}$	312	388	437	388	437	437
$\overline{X_2}$	180	180	180	312	312	388
S_p	115	100	109	127	129	117
t_0	11.388	20.110	26.832	5.325	9.880	4.151
df	408	393	518	313	438	423
α	0.01	0.01	0.01	0.01	0.01	0.01
t	2.326	2.326	2.326	2.326	2.326	2.326
Hypothesis Test	Reject H_0	Reject H_0	Reject H_0	Reject H_0	Reject H_0	Reject H_0

[!]Units for luminous intensity are in candela
A to B: B represents data set 1 (n1, s1, etc.) and A represents data set 2 (n2, s2, etc)

CONCLUSION

Light-emitting diodes (LEDs) have been bringing challenges for traffic engineers ever since the major switch over from incandescent light to light-emitting diode on traffic signals. The objective of this research was to study the degradation of light output of the LEDs on traffic signals over the years. Major points for the conclusion of this report include the following,

- The value for luminous intensity satisfies the ITE guidelines for recently installed traffic signals
- The results from the preliminary analysis,
    - Traffic signals installed in earlier years (10-year or older) look to fall below the ITE guidelines
    - A hypothesis testing of means shows significant reduction of luminous intensity over the years
- More data may be used to validate these preliminary results

This will ultimately be one step closer to creating the information required for traffic engineers to make a determination on the safest and cost effective replacement schedule for LED traffic signals. LED lights as they degrade, remain showing light but may fall below the required luminous intensity value as recommended by the Institute of Transportation Engineers. To test for luminous intensity, several trips were made for a total of 34 intersections in both Anchorage Alaska and Fairbanks combined to measure for luminous intensity during the night. The equipment used to measure for luminous intensity was the 670 spectroradiometer by Photo Research. Test were done to determine if there was a pattern in the degradation of light output over the years. It was seen in the results that there is a pattern in the degradation of light output over the years for both green and red traffic signals. The value for luminous intensity starts at a high value on traffic signals at first installment and show to be below or nearing falling below the ITE guidelines by the time they have been mounted for 10 or more years. A hypothesis testing of means data analysis has proven such a case that LED lights installed in recent years compared to later years show to have higher values for luminous intensity. This case was to be expected. A recommendation for similar studies is to include other potential factors such as,

- Degradation rate by direction of approach
- Degradation of color
- Study by region

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APPENDIX

Appendix A

Table 9. Luminous Value Calculated Values Applied to Hypothesis Testing of Mean for Green Signal at Each Intersection Grouped in 5-year Increments, along with each Bins Average Value and Standard Deviation.

			Luminous Intensity				
Site Id	Site	Year of installation	1	2	3	4	5
XAA	15th / C St.	2001	193.69	193.42	193.17	190.66	191.95
XAA	15th / C St.	2001	206.15	201.56	225.13	225.31	224.78
XAA	15th / C St.	2001	333.28	335.27	333.28	335.02	336.75
XAA	15th / C St.	2001	343.21	348.17	341.22	342.71	344.20
XAB	15th / E St.	2001	261.07	259.08	265.04	288.86	300.03
XAB	15th / E St.	2001	242.78	250.89	246.92	244.12	236.72
XAB	15th / E St.	2001	388.12	411.45	408.22	473.74	477.21
XAB	15th / E St.	2001	172.72	173.89	172.70	172.89	170.78
FAA	Airport Wy/Cushman St	2002	335.51	336.75	335.27	332.04	333.53
FAA	Airport Wy/Cushman St	2002	235.45	245.06	249.40	238.23	230.62
FAA	Airport Wy/Cushman St	2002	223.20	222.20	226.07	226.50	224.54
FAA	Airport Wy/Cushman St	2002	273.47	287.12	286.63	287.12	286.63
FAF	Cowles Street / Kennicott Avenue	2002	250.89	251.14	249.15	253.87	256.10
FAF	Cowles Street / Kennicott Avenue	2002	266.77	251.14	244.19	251.14	245.26
FAF	Cowles Street / Kennicott Avenue	2002	228.26	221.38	221.78	228.43	222.80
FAF	Cowles Street / Kennicott Avenue	2002	146.79	136.02	140.53	141.28	148.13
FAO	Badger Road / Hurst Road	2002	501.78	493.34	500.79	493.84	496.82
FAO	Badger Road / Hurst Road	2002	479.94	477.46	482.92	492.85	466.54
FAO	Badger Road / Hurst Road	2002	427.33	408.97	428.08	397.06	402.76
FAO	Badger Road / Hurst Road	2002	372.49	388.37	406.74	404.25	412.20

FAO	Badger Road / Hurst Road	2002	357.10	359.83	362.56	352.14	363.56
FAO	Badger Road / Hurst Road	2002	298.29	314.92	311.69	309.95	311.69
XAC	33nd / Denali	2003	418.40	432.05	422.87	419.14	413.93
XAC	33nd / Denali	2003	160.78	155.65	166.02	194.73	177.14
XAC	33nd / Denali	2003	261.56	223.12	258.34	250.15	245.28
XAC	33nd / Denali	2003	293.57	290.84	275.46	277.44	273.47
XAC	33nd / Denali	2003	187.88	207.07	206.12	206.02	206.27
XAC	33nd / Denali	2003	475.72	456.37	471.26	474.24	469.52
XAD	36th / Denali	2003	352.88	315.66	348.67	356.86	352.14
XAD	36th / Denali	2003	214.39	195.82	192.52	179.69	177.04
XAD	36th / Denali	2003	161.80	152.25	142.59	147.83	175.72
XAD	36th / Denali	2003	374.47	377.70	375.96	380.93	376.46
XAD	36th / Denali	2003	266.03	261.07	246.72	250.64	265.04
XAD	36th / Denali	2003	317.15	310.45	311.44	304.74	288.11
XAD	36th / Denali	2003	233.57	211.48	220.49	211.93	211.38
XAD	36th / Denali	2003	265.28	300.03	239.40	245.28	246.42
XAE	64th / C St.	2004	215.03	216.82	216.47	218.65	217.98
XAE	64th / C St.	2004	127.70	127.60	129.59	131.25	130.09
XAE	64th / C St.	2004	293.82	283.15	287.62	301.27	292.09
XAE	64th / C St.	2004	497.07	539.50	535.53	523.37	575.48
XAE	64th / C St.	2004	161.97	161.45	203.89	204.98	198.28
XAE	64th / C St.	2004	233.32	237.69	236.67	235.28	232.33
XAI	Old Seward / Tudor	2005	316.25	309.28	288.73	296.80	323.51
XAI	Old Seward / Tudor	2005	300.86	300.66	302.44	280.08	305.82
XAI	Old Seward / Tudor	2005	287.02	287.60	290.22	290.13	287.31
XAI	Old Seward / Tudor	2005	397.71	401.92	396.73	402.24	397.71
XAI	Old Seward / Tudor	2005	304.00	271.75	248.80	267.89	298.10
XAI	Old Seward / Tudor	2005	283.90	287.21	285.49	299.95	284.97
XAI	Old Seward / Tudor	2005	327.69	325.10	326.07	324.78	326.40
			AVG	291.93	Std. Dev.	95.76	
XAX	Minnesota / Northern Lights	2006	504.02	488.46	478.74	487.16	504.99

XAX	Minnesota / Northern Lights	2006	350.06	334.18	341.31	343.90	349.41
XAX	Minnesota / Northern Lights	2006	408.40	407.43	397.71	404.19	422.99
XAX	Minnesota / Northern Lights	2006	492.03	473.23	473.55	469.99	476.79
XAX	Minnesota / Northern Lights	2006	391.55	388.95	393.17	390.25	391.87
XAX	Minnesota / Northern Lights	2006	434.01	422.34	426.55	417.48	442.44
XAX	Minnesota / Northern Lights	2006	440.81	452.16	475.82	446.65	448.59
XAN	88th / Old Seward	2008	259.89	220.73	209.84	221.12	256.68
XAN	88th / Old Seward	2008	386.36	381.50	393.49	395.44	397.38
XAN	88th / Old Seward	2008	454.75	428.82	446.65	434.66	467.07
XAN	88th / Old Seward	2008	284.65	299.04	292.10	271.26	307.21
XAN	88th / Old Seward	2008	396.08	401.60	378.26	374.69	367.24
XAN	88th / Old Seward	2008	341.63	343.58	338.71	343.90	343.25
XAQ	63rd / Lake Otis	2009	328.99	328.02	328.67	332.23	305.78
XAQ	63rd / Lake Otis	2009	154.64	157.43	159.08	162.00	162.03
XAR	Dowling / Elmore Rd	2009	387.33	387.33	371.78	372.42	413.26
XAR	Dowling / Elmore Rd	2009	365.62	364.64	360.11	362.70	367.89
XAR	Dowling / Elmore Rd	2009	322.60	303.16	291.72	293.24	344.87
XAW	06th / E St.	2009	410.99	414.24	411.64	409.70	400.30
XAW	06th / E St.	2009	393.17	392.20	388.95	390.25	387.98
XAW	6th / E St.	2009	459.94	460.91	461.23	460.26	458.97
XAW	6th / E St.	2009	294.63	296.45	292.43	293.37	294.11
XAW	6th / E St.	2009	380.85	381.17	381.82	378.91	381.17
FAP	Richardson Highway (south ramp) / Buzby Road	2010	345.69	346.93	347.43	350.40	345.19
FAP	Richardson Highway (south ramp) / Buzby Road	2010	336.26	340.23	343.70	342.46	339.73

FAP	Richardson Highway (south ramp) / Buzby Road	2010	293.82	297.30	293.57	286.87	292.33
XAV	09th / C St.	2010	376.31	372.42	374.04	377.29	376.31
XAV	09th / C St.	2010	372.75	364.64	371.13	361.73	363.02
XAV	9th / C St.	2010	346.82	338.07	340.01	337.74	347.79
XAV	9th / C St.	2010	343.25	342.93	341.63	339.69	344.87
XAV	9th / C St.	2010	379.88	379.55	377.93	379.55	377.93
XAV	9th / C St.	2010	462.21	461.88	458.32	460.59	455.72
XAV	9th / C St.	2010	486.19	487.49	488.14	483.92	486.19
			AVG	372.56	Std. Dev.	72.10	
XAS	40th / Lake Otis	2011	392.84	409.70	406.13	415.21	405.48
XAS	40th / Lake Otis	2011	481.01	484.57	478.09	470.31	474.52
XAS	40th / Lake Otis	2011	592.83	583.76	575.65	577.60	580.51
XAS	40th / Lake Otis	2011	443.41	389.28	390.90	385.71	378.58
XAS	40th / Lake Otis	2011	402.24	405.16	407.43	404.19	401.92
XAS	40th / Lake Otis	2011	450.54	489.11	466.10	478.09	492.35
FAK	Illinois Street / Phillips Field Road	2013	420.63	444.70	417.41	432.30	443.22
FAK	Illinois Street / Phillips Field Road	2013	495.83	507.74	516.17	495.58	531.06
FAK	Illinois Street / Phillips Field Road	2013	465.30	472.99	494.58	493.59	470.76
XAL	Arctic / Raspberry	2013	312.43	263.68	287.50	260.28	338.39
XAL	Arctic / Raspberry	2013	475.82	385.39	499.16	467.07	470.31
XAL	Arctic / Raspberry	2013	497.86	498.19	497.86	499.48	498.51
XAL	Arctic / Raspberry	2013	247.73	310.29	306.85	339.04	368.86
FAC	Cushman St./10th Ave	2014	533.30	509.72	536.03	519.90	517.66
FAC	Cushman St./10th Ave	2014	459.84	458.35	458.60	436.02	425.84
FAC	Cushman St./10th Ave	2014	559.35	550.42	566.05	558.61	560.60
FAC	Cushman St./10th Ave	2014	443.22	471.26	487.64	502.03	503.27

XAT	Northern Lights / UAA Drive	2014	230.13	224.30	225.92	224.98	246.50
XAT	Northern Lights / UAA Drive	2014	370.48	363.02	364.97	364.00	365.62
XAT	Northern Lights / UAA Drive	2014	382.80	408.08	396.73	378.58	409.05
XAT	Northern Lights / UAA Drive	2014	439.19	417.15	422.66	390.25	455.72
FAL	College Road / Aurora Road	2015	530.07	414.92	503.27	518.16	534.79
FAL	College Road / Aurora Road	2015	601.54	610.48	591.62	586.40	600.80
FAL	College Road / Aurora Road	2015	464.06	463.07	460.83	453.89	464.81
FAL	College Road / Aurora Road	2015	642.24	641.99	661.84	673.01	667.30
FAL	College Road / Aurora Road	2015	94.18	93.23	95.52	95.24	95.79
XAK	Dowling / Raspberry	2015	359.78	359.78	359.78	363.02	363.02
XAK	Dowling / Raspberry	2015	375.99	369.51	369.51	369.51	372.75
XAK	Dowling / Raspberry	2015	428.82	429.47	424.93	424.61	428.50
XAK	Dowling / Raspberry	2015	350.06	347.14	347.79	342.60	349.09
			AVG	432.48	Std. Dev.	111.73	
FAB	Cushman St./Gaffney St.	2016	580.70	583.18	565.81	555.88	595.59
FAB	Cushman St./Gaffney St.	2016	558.36	543.47	531.06	560.84	548.44
FAB	Cushman St./Gaffney St.	2016	612.96	598.07	603.03	600.55	
FAB	Cushman St./Gaffney St.	2016	607.99	625.37	600.55	620.40	627.85
XBC	Golden bear / Muldoon	2016	750.44	693.36	752.42	726.86	745.97
XBC	Golden bear / Muldoon	2016	598.07	550.92	570.77	541.24	586.16
XBC	Golden bear / Muldoon	2016	633.06	614.20	626.11	631.32	632.81
XBC	Golden bear / Muldoon	2016	486.40	481.68	495.58	501.28	497.31

XBC	Golden bear / Muldoon	2016	519.65	467.53	500.29	551.66	560.10
XBC	Golden bear / Muldoon	2016	696.88	696.23	665.11	665.44	721.51
XBC	Golden bear / Muldoon	2016	828.15	831.39	839.17	809.67	822.96
XBC	Golden bear / Muldoon	2016	679.37	682.29	653.12	667.38	661.22
XBC	Golden bear / Muldoon	2016	605.15	622.97	605.15	565.28	634.32
XBC	Golden bear / Muldoon	2016	556.20	576.30	587.97	585.38	562.69
XBC	Golden bear / Muldoon	2016	556.38	556.87	503.77	558.86	555.63
XBC	Golden bear / Muldoon	2016	634.97	595.42	613.90	617.14	628.48
FAD	Noble St./10th Ave.	2017	591.62	585.16	596.58	581.44	601.54
FAD	Noble St./10th Ave.	2017	696.34	688.89	688.40	621.89	682.19
FAD	Noble St./10th Ave.	2017	594.35	611.47	615.19	597.32	615.94
FAD	Noble St./10th Ave.	2017	595.59	615.44	590.62	590.62	598.07
FAE	Noble St./3rd Ave.	2017	659.12	665.07	652.66	651.17	658.37
FAE	Noble St./3rd Ave.	2017	506.00	489.87	490.37	491.36	499.55
FAE	Noble St./3rd Ave.	2017	533.30	561.84	569.78	588.64	571.27
XAO	Abbott / Lake Otis	2017	820.69	812.91	804.81	796.71	801.89
XAO	Abbott / Lake Otis	2017	792.49	833.33	829.44	800.27	835.28
XAO	Abbott / Lake Otis	2017	714.05	691.37	721.83	710.17	733.50
XAO	Abbott / Lake Otis	2017	630.75	628.81	645.02	651.50	669.33
XAO	Abbott / Lake Otis	2017	622.65	666.41	657.98	676.46	641.13
XAO	Abbott / Lake Otis	2017	674.51	659.28	643.72	653.12	657.33
XAO	Abbott / Lake Otis	2017	822.96	829.12	836.25	811.29	798.65
XAO	Abbott / Lake Otis	2017	842.41	810.00	797.03	800.60	850.51

FAN	Geist Road / Fairbanks Street	2018	551.91	528.83	522.63	506.99	486.64
FAN	Geist Road / Fairbanks Street	2018	498.56	512.20	512.20	508.73	492.85
FAN	Geist Road / Fairbanks Street	2018	553.65	554.14	551.41	542.23	532.30
FAN	Geist Road / Fairbanks Street	2018	631.07	634.80	631.32	635.29	631.07
FAN	Geist Road / Fairbanks Street	2018	536.28	535.28	544.96	529.82	537.02
FAN	Geist Road / Fairbanks Street	2018	739.52	718.92	702.54	732.32	729.10
XAY	Fireweed / Spenard Rd	2018	788.28	736.10	752.63	720.86	816.48
XAY	Fireweed / Spenard Rd	2018	690.39	686.50	687.15	686.50	698.82
XAZ	Benson / Spenard Rd	2018	660.25	650.85	594.13	580.84	597.37
XAZ	Benson / Spenard Rd	2018	801.89	797.03	807.73	783.42	814.86
XAZ	Benson / Spenard Rd	2018	854.08	736.74	767.21	808.70	838.52
XAZ	Benson / Spenard Rd	2018	798.00	829.77	847.27	787.31	880.01
XAZ	Benson / Spenard Rd	2018	723.45	719.89	767.21	705.95	677.10
XAZ	Benson / Spenard Rd	2018	762.03	729.94	729.61	723.13	780.50
XAZ	Benson / Spenard Rd	2018	858.29	833.66	836.25	867.69	844.35
XAZ	Benson / Spenard Rd	2018	556.85	635.62	634.97	619.09	604.82
FAG	Airport Way / Peger Road	2020	812.27	810.65	804.81	757.81	804.49
FAG	Airport Way / Peger Road	2020	597.69	598.67	582.46	593.48	594.78
FAG	Airport Way / Peger Road	2020	792.17	796.06	779.53	761.38	783.42
FAG	Airport Way / Peger Road	2020	660.57	706.28	719.24	696.55	679.70
FAG	Airport Way / Peger Road	2020	866.72	866.07	865.10	876.77	860.24
FAG	Airport Way / Peger Road	2020	656.04	627.51	638.86	670.30	645.34
FAG	Airport Way / Peger Road	2020	798.00	798.33	808.38	784.71	801.89

FAG	Airport Way / Peger Road	2020	721.51	713.41	716.32	661.55	756.52
			AVG	667.89	Std. Dev.	106.17	

Table 10. Luminous Value Calculated Values Applied to Hypothesis Testing of Mean for Red Signal at Each Intersection Grouped in 5-year Increments, along with each Bins Average Value and Standard Deviation.

			Luminous Intensity				
Site Id	Site	Year of installation	1	2	3	4	5
XAA	15th / C St.	2001	181.98	181.58	181.50	180.64	180.24
XAA	15th / C St.	2001	140.51	140.91	141.00	138.95	140.93
XAA	15th / C St.	2001	225.16	225.23	225.90	225.31	225.90
XAA	15th / C St.	2001	239.08	238.04	240.10	244.07	243.55
XAB	15th / E St.	2001	182.30	181.23	179.42	183.64	181.83
XAB	15th / E St.	2001	168.87	163.04	167.93	163.22	162.62
XAB	15th / E St.	2001	254.86	244.91	243.82	244.26	245.41
XAB	15th / E St.	2001	168.58	166.44	168.77	166.14	167.48
FAA	Airport Wy/Cushman St	2002	133.41	92.22	94.43	86.58	121.77
FAA	Airport Wy/Cushman St	2002	89.76	79.73	80.58	93.43	87.97
FAA	Airport Wy/Cushman St	2002	119.17	120.21	118.15	116.21	117.80
FAA	Airport Wy/Cushman St	2002	102.86	98.22	105.89	101.62	101.20
FAF	Cowles Street / Kennicott Avenue	2002	154.01	145.37	136.66	134.45	147.16
FAF	Cowles Street / Kennicott Avenue	2002	133.21	134.33	131.25	124.65	133.11
FAF	Cowles Street / Kennicott Avenue	2002	146.64	150.44	148.50	141.97	147.26
FAF	Cowles Street / Kennicott Avenue	2002	98.40	101.85	102.34	99.76	99.98
FAO	Badger Road / Hurst Road	2002	169.27	202.70	183.12	163.44	200.64
FAO	Badger Road / Hurst Road	2002	184.61	183.12	182.17	180.07	184.26
FAO	Badger Road / Hurst Road	2002	170.59	170.31	177.19	171.68	174.04
FAO	Badger Road / Hurst Road	2002	138.80	142.97	137.08	138.52	138.25
FAO	Badger Road / Hurst Road	2002	199.37	179.10	183.37	177.46	173.19
FAO	Badger Road / Hurst Road	2002	141.38	137.31	136.98	135.47	124.40

XAC	33nd / Denali	2003	83.70	71.57	82.17	70.55	87.20
XAC	33nd / Denali	2003	116.14	108.87	114.85	105.44	119.81
XAC	33nd / Denali	2003	138.28	224.14	257.59	253.87	252.63
XAC	33nd / Denali	2003	167.93	168.18	186.15	183.49	164.46
XAC	33nd / Denali	2003	175.87	178.75	171.36	164.98	168.80
XAC	33nd / Denali	2003	638.02	639.76	689.64	677.23	682.44
XAD	36th / Denali	2003	211.73	209.62	202.97	207.54	207.93
XAD	36th / Denali	2003	118.74	107.06	104.90	111.23	97.38
XAD	36th / Denali	2003	80.50	84.28	76.43	73.41	66.63
XAD	36th / Denali	2003	215.92	212.52	215.38	217.24	214.26
XAD	36th / Denali	2003	89.16	90.18	78.72	77.40	82.24
XAD	36th / Denali	2003	167.68	154.11	157.16	159.34	159.57
XAD	36th / Denali	2003	131.08	116.39	117.13	116.24	119.84
XAD	36th / Denali	2003	76.28	65.94	75.91	79.29	83.21
XAE	64th / C St.	2004	156.96	157.95	150.26	155.50	151.40
XAE	64th / C St.	2004	131.72	131.23	132.07	130.28	131.45
XAE	64th / C St.	2004	213.47	213.52	213.57	212.62	212.20
XAE	64th / C St.	2004	163.46	163.94	162.99	162.45	162.25
XAE	64th / C St.	2004	152.64	152.47	153.41	151.90	152.84
XAE	64th / C St.	2004	188.63	189.42	188.90	188.50	188.06
XAI	Old Seward / Tudor	2005	306.46	294.57	306.30	304.23	310.42
XAI	Old Seward / Tudor	2005	284.36	283.22	282.64	283.45	280.53
XAI	Old Seward / Tudor	2005	200.41	198.40	201.38	199.95	200.96
XAI	Old Seward / Tudor	2005	339.36	350.06	345.20	345.84	338.39
XAI	Old Seward / Tudor	2005	202.94	183.42	178.08	187.15	199.66
XAI	Old Seward / Tudor	2005	278.52	269.35	273.40	275.96	274.21
XAI	Old Seward / Tudor	2005	276.19	268.70	268.51	271.85	275.90
			AVG	180.13	Std. Dev.	93.40	
XAX	Minnesota / Northern Lights	2006	304.13	304.19	300.47	302.09	302.15
XAX	Minnesota / Northern Lights	2006	216.68	219.86	208.19	205.72	202.68
XAX	Minnesota / Northern Lights	2006	267.67	261.77	246.40	235.41	273.63
XAX	Minnesota / Northern Lights	2006	270.19	261.12	265.59	239.40	284.58
XAX	Minnesota / Northern Lights	2006	275.61	280.89	273.21	260.28	282.96
XAX	Minnesota / Northern Lights	2006	211.23	225.30	225.63	212.92	241.90
XAX	Minnesota / Northern Lights	2006	182.48	178.24	186.73	180.31	175.55

XAN	88th / Old Seward	2008	170.04	137.69	154.35	140.74	181.58
XAN	88th / Old Seward	2008	296.48	298.39	303.58	304.06	294.31
XAN	88th / Old Seward	2008	342.93	334.18	340.01	346.82	340.66
XAN	88th / Old Seward	2008	247.15	248.51	228.15	245.95	262.71
XAN	88th / Old Seward	2008	313.72	316.19	312.49	315.41	314.31
XAN	88th / Old Seward	2008	192.05	197.36	193.12	194.80	200.44
XAQ	63rd / Lake Otis	2009	173.54	191.01	191.88	183.94	174.51
XAQ	63rd / Lake Otis	2009	154.12	158.34	165.53	152.86	163.07
XAR	Dowling / Elmore Rd	2009	523.14	495.92	532.22	383.44	439.52
XAR	Dowling / Elmore Rd	2009	377.93	375.34	371.45	370.80	367.24
XAR	Dowling / Elmore Rd	2009	499.48	472.58	476.79	507.91	510.50
XAW	06th / E St.	2009	320.30	322.05	321.05	315.64	319.62
XAW	06th / E St.	2009	329.64	321.63	318.62	316.38	323.19
XAW	6th / E St.	2009	239.86	238.43	239.53	242.03	238.20
XAW	6th / E St.	2009	70.66	70.27	69.30	69.66	69.78
XAW	6th / E St.	2009	177.69	178.69	176.10	176.88	178.17
FAP	Richardson Highway (south ramp) / Buzby Road	2010	144.33	141.20	143.96	143.51	145.79
FAP	Richardson Highway (south ramp) / Buzby Road	2010	263.55	263.05	257.34	259.33	259.58
FAP	Richardson Highway (south ramp) / Buzby Road	2010	183.91	176.02	181.21	181.23	178.38
XAV	09th / C St.	2010	491.38	489.76	489.76	486.84	486.52
XAV	09th / C St.	2010	541.94	535.78	520.55	516.66	575.65
XAV	9th / C St.	2010	440.17	438.87	439.52	432.71	437.57
XAV	9th / C St.	2010	508.23	514.07	511.80	503.05	513.74
XAV	9th / C St.	2010	664.79	641.45	653.44	664.14	655.06
XAV	9th / C St.	2010	522.17	518.28	516.34	514.72	513.74
XAV	9th / C St.	2010	474.52	478.74	480.68	473.55	480.68
			AVG	311.75	Std. Dev.	140.68	
XAS	40th / Lake Otis	2011	363.67	354.27	352.00	362.38	348.76
XAS	40th / Lake Otis	2011	641.77	633.35	638.21	642.10	679.05
XAS	40th / Lake Otis	2011	684.56	693.96	673.54	684.24	667.06
XAS	40th / Lake Otis	2011	561.07	541.62	526.71	543.89	545.83
XAS	40th / Lake Otis	2011	538.70	549.07	576.62	559.12	573.38
XAS	40th / Lake Otis	2011	377.61	378.91	374.69	358.81	373.40
FAK	Illinois Street / Phillips Field Road	2013	357.10	359.34	357.85	355.86	361.32

FAK	Illinois Street / Phillips Field Road	2013	388.37	396.06	397.31	415.67	414.68
FAK	Illinois Street / Phillips Field Road	2013	363.31	350.40	361.32	348.67	360.83
XAL	Arctic / Raspberry	2013	385.71	424.28	398.03	411.97	478.41
XAL	Arctic / Raspberry	2013	392.84	392.84	403.54	405.81	401.27
XAL	Arctic / Raspberry	2013	373.40	379.23	367.56	370.80	385.06
XAL	Arctic / Raspberry	2013	458.64	470.31	450.86	461.56	472.26
FAC	Cushman St./10th Ave	2014	479.69	478.21	491.61	475.48	464.81
FAC	Cushman St./10th Ave	2014	387.88	411.20	371.00	381.17	380.18
FAC	Cushman St./10th Ave	2014	360.83	369.76	376.96	372.99	367.77
FAC	Cushman St./10th Ave	2014	404.50	394.58	367.28	344.94	332.54
XAT	Northern Lights / UAA Drive	2014	193.80	194.48	186.34	224.59	234.77
XAT	Northern Lights / UAA Drive	2014	225.01	223.94	223.58	219.14	239.76
XAT	Northern Lights / UAA Drive	2014	283.26	252.79	255.12	244.07	346.17
XAT	Northern Lights / UAA Drive	2014	303.84	292.59	279.79	271.65	332.23
FAL	College Road / Aurora Road	2015	375.47	374.97	367.77	381.92	384.40
FAL	College Road / Aurora Road	2015	358.84	359.83	345.69	352.14	364.55
FAL	College Road / Aurora Road	2015	371.99	371.00	368.02	365.04	366.29
FAL	College Road / Aurora Road	2015	271.98	272.73	273.23	258.34	277.20
FAL	College Road / Aurora Road	2015	236.87	234.34	233.82	231.58	233.89
XAK	Dowling / Raspberry	2015	395.44	392.20	395.44	398.68	388.95
XAK	Dowling / Raspberry	2015	359.78	340.33	343.58	346.82	346.82
XAK	Dowling / Raspberry	2015	402.57	408.73	410.67	403.22	399.33
XAK	Dowling / Raspberry	2015	337.09	342.28	336.12	338.71	340.98
			AVG	387.80	Std. Dev.	109.02	
FAB	Cushman St./Gaffney St.	2016	436.76	424.35	411.95	367.28	364.80
FAB	Cushman St./Gaffney St.	2016	471.51	496.32	481.43	481.43	478.95
FAB	Cushman St./Gaffney St.	2016	364.80	372.24	367.28	377.20	384.65
FAB	Cushman St./Gaffney St.	2016	352.39	354.87	352.39	349.91	357.35

FAB	Cushman St./Gaffney St.	2016	456.62	456.62	454.13	461.58	464.06
XBC	Golden Bear / Muldoon	2016	396.81	398.79	383.66	427.58	409.22
XBC	Golden Bear / Muldoon	2016	377.20	376.71	381.67	373.48	403.76
XBC	Golden Bear / Muldoon	2016	475.72	465.05	456.86	432.54	474.98
XBC	Golden Bear / Muldoon	2016	312.68	312.68	312.19	307.47	302.01
XBC	Golden Bear / Muldoon	2016	259.58	254.12	244.81	237.61	241.96
XBC	Golden Bear / Muldoon	2016	473.88	471.28	472.26	478.74	491.05
XBC	Golden Bear / Muldoon	2016	447.30	437.90	439.52	438.22	454.43
XBC	Golden Bear / Muldoon	2016	435.63	413.59	410.67	371.78	444.70
XBC	Golden Bear / Muldoon	2016	488.14	490.08	498.83	496.24	490.73
XBC	Golden Bear / Muldoon	2016	285.38	289.11	275.95	298.04	285.63
XBC	Golden Bear / Muldoon	2016	401.27	392.52	399.97	394.46	396.41
FAD	Noble St./10th Ave.	2017	416.91	392.84	402.76	408.22	406.49
FAD	Noble St./10th Ave.	2017	63.21	63.33	64.45	64.27	63.65
FAD	Noble St./10th Ave.	2017	260.82	267.02	259.82	261.56	270.74
FAD	Noble St./10th Ave.	2017	263.05	260.57	260.57	255.61	260.57
FAE	Noble St./3rd Ave.	2017	323.60	326.33	327.82	320.13	318.89
FAE	Noble St./3rd Ave.	2017	294.82	285.88	279.18	287.62	284.64
FAE	Noble St./3rd Ave.	2017	241.46	245.53	239.25	252.88	251.39
XAO	Abbott / Lake Otis	2017	308.15	289.74	287.73	281.25	347.14
XAO	Abbott / Lake Otis	2017	478.41	498.51	496.24	493.32	460.59
XAO	Abbott / Lake Otis	2017	479.39	492.35	486.84	495.59	486.84
XAO	Abbott / Lake Otis	2017	547.45	549.07	558.47	559.45	565.28
XAO	Abbott / Lake Otis	2017	446.65	444.06	443.73	412.29	430.12
XAO	Abbott / Lake Otis	2017	313.40	312.78	311.49	314.31	308.83
XAO	Abbott / Lake Otis	2017	504.02	489.11	495.27	497.86	504.02
XAO	Abbott / Lake Otis	2017	513.42	518.28	509.53	503.70	520.87
FAN	Geist Road / Fairbanks Street	2018	346.93	360.83	357.35	357.35	356.86
FAN	Geist Road / Fairbanks Street	2018	251.14	262.55	268.76	268.26	269.75
FAN	Geist Road / Fairbanks Street	2018	447.93	451.65	441.48	447.93	439.49
FAN	Geist Road / Fairbanks Street	2018	442.47	440.49	429.07	442.72	442.47
FAN	Geist Road / Fairbanks Street	2018	380.93	381.92	377.70	377.70	376.71
FAN	Geist Road / Fairbanks Street	2018	352.14	341.72	341.97	345.69	342.71
XAY	Fireweed / Spenard Rd	2018	583.43	587.32	583.76	580.19	594.45
XAY	Fireweed / Spenard Rd	2018	611.31	604.82	609.69	611.31	613.90
XAZ	Benson / Spenard Rd	2018	541.94	542.27	546.80	516.01	569.49
XAZ	Benson / Spenard Rd	2018	528.33	525.41	515.69	523.79	532.54

XAZ	Benson / Spenard Rd	2018	550.69	542.92	537.40	535.14	552.31
XAZ	Benson / Spenard Rd	2018	585.70	542.27	581.81	582.78	600.29
XAZ	Benson / Spenard Rd	2018	621.35	620.06	618.76	621.03	608.39
XAZ	Benson / Spenard Rd	2018	520.87	541.62	546.48	515.36	575.33
XAZ	Benson / Spenard Rd	2018	558.80	560.74	525.41	526.71	569.49
XAZ	Benson / Spenard Rd	2018	436.28	458.32	443.08	434.33	478.74
FAG	Airport Way / Peger Road	2020	408.08	364.00	400.30	366.91	384.09
FAG	Airport Way / Peger Road	2020	516.98	506.94	504.67	510.83	512.77
FAG	Airport Way / Peger Road	2020	594.45	603.20	609.36	596.40	602.88
FAG	Airport Way / Peger Road	2020	598.02	592.18	595.10	592.83	594.78
FAG	Airport Way / Peger Road	2020	572.41	566.90	565.93	576.62	572.09
FAG	Airport Way / Peger Road	2020	631.40	634.32	628.81	628.48	623.95
FAG	Airport Way / Peger Road	2020	556.53	539.03	556.85	545.83	549.07
FAG	Airport Way / Peger Road	2020	615.52	599.96	593.15	612.93	603.20
			AVG.	437.14	Std. Dev.	121.26	

Appendix B

Testing Questions Risen During Preliminary Testing

Multiple tests were conducted in the Engineering and Industrial Building, room 101, at the University of Alaska Anchorage, to troubleshoot some concerns which presented themselves during the first rounds of testing for luminance with the PR-670 spectro-radiometer. The topics of concentration were the following;

- FOCUS: The accuracy of measurements when the measuring unit is out of focus, compared to when it is in focus. It is important to measure the difference between out of focus and in focus, because when on the field taking measurements there will be an adjustment to distance and aperture size, therefore it is important to recognize if any changes to the way readings are being taken are compromised by the lens focal status. The PR-670 has two locations to adjust the focus, the MS-75 lens and the eye-piece (which shows the “spot-size”). Tests were done to differentiate between measurements taken when the lens was in focus and out of focus, and similarly when the eyepiece was in focus and out of focus. A variation of focus settings were accomplished for both the lens and eyepiece, for example the lens fully focused and the eyepiece fully out of focus.
- SAVE: All tests were done while the measuring meter was on auto-save. After a measurement is taken, the PR-670 screen shows a “save” option to be clicked if the user so chooses. This test is to confirm the auto-save function within the meter, and if

measurements are being saved without the need to press the “save” button after each reading.

- ABORT: Similar to the “save” button appearing on the screen, an “abort” button appears while a measurement is in process. This test is to confirm the functions of the “abort” button and verify the reading is being aborted without saving onto the SD card.
- FREEZE: While in the process of taking a measurement, the PR-670 measuring meter froze twice on one of the first preliminary testing days. It is suspected that the freeze occurred due to the “measure” button being pressed while a measurement was in-progress. This test was conducted to determine a reason why the measuring meter freezes. As a result, to un-freeze the measuring meter, it was determined the battery will need to be removed. Additionally, this gave reason to perform an additional test to check if measurements taken prior to the freeze were kept saved within the SD memory card, or if the measurements were deleted in cause of the freeze.

In-Lab Set-up

Properties of Equipment and Test Set-Up
Meter height on tri-pod = 3 feet
Signal height = 3 feet
Measuring meter aperture degree = 1º
“Spot-size” = 5 inches
Required distance from the signal to meter for a 5-inch “Spot-size” = 24 feet

Focus Study

Four test will need to be conducted to fully measure the accuracy of readings for a variety of focus setting both on the MS-75 lens and the measuring meter’s eyepiece. Test for the lens and eyepiece both in focus, lens in focus and eyepiece out-of-focus (all the way to the left), lens in focus and eyepiece half-way its turning capacity, and lens out of focus and eyepiece turn all the way to the right. Five measurements per each stage will be needed. It was determined that the when the lens and eyepiece were both in focus, the average value for each five readings was 7040 cd/m^2. Table 11 shows the average readings for each of the three stages attempted,

Table 11. Average of five reading per focus of Lens and Eyepiece

Lens: In-Focus Eyepiece: In-Focus	Lens: In-Focus Eyepiece: Out-of-Focus	Lens: In-Focus Eyepiece: Half-Way	Lens: Out-of-Focus Eyepiece: Full right
7040 cd/m^2	7733 cd/m^2	7095 cd/m^2	6786 cd/m^2

When the lens is in focus and the eyepiece is either in focus completely or half-way, the resultant values for both cases is about the same. We see discrepancies when either the lens is out of focus, the values decrease, or when the eye-piece is completely out-of-focus, the values increase, respectively.

Save Study

Two tests were taken while the PR-670 was on auto-save; one test required the “save” button to be pressed, and the other went without pressing the “save” button. Measurements were saved on a file name “SAVE” within the measuring meter’s SD memory card. The setting chosen for each single measurement was five measurements to be averaged to provide one measurement. The first measurement was calculated to be 6948 cd/m^2 when going without pressing the save button after the measurement completed. The second reading was determined to be 6894 cd/m^2 when the save button was pressed after the measurement completed. To confirm both readings were saved, the two values were checked on the SpectraWin2 software, provided by JADAK as included with the PR-670. In conclusion, measurements will be saved when "auto-save" is on, if the save button is pressed or is without being pressed.

ABORT Study

When taking a measurement with the PR-670 measuring meter, the screen on the meter shows the resulting measured value. This same screen will present an "abort" button while a measurement is in-progress. The measuring meter takes about 2-4 seconds for a measurement to be complete, depending on the surrounding light. During those 2-4 seconds, the screen on the PR-670 measuring meter highlights an "abort" button, and dims out all other buttons. Clicking the "abort" button is assumed to cancel a measurement before it saves onto on the SD memory card. Five measurements were taken, and for each measurement the "abort" button was pressed. In conclusion, upon checking the SpectraWin2 software to confirm if the measurements were aborted, it was determined that the files went without saving.

FREEZE Study

This study is to determine if data will be saved or deleted if a "freeze" occurs while taking a measurement with the PR-670 measuring meter. A freeze brings the measuring meter to a state of being unable to turn be turned off by the usual methods, unable to take measurements, or unable to press any buttons on its screen. The only way to un-freeze the PR-670 will be by removing its battery. To test for a "freeze," a few measurements are to be taken, and while those measurements are taken, the measure button will need to be pressed multiple times during the time a measurement is in progress. A freeze was challenging to create and so the study was done without achieving a freeze. Removing the battery will shut the PR-670 measuring meter off completely. After replacing the battery and turning on the measuring meter, another set of measurements were taken and save onto the same file in which the earlier measurements were saved. This reason is to determine if the measurements taken prior to the freeze and battery removal were deleted or remained stored on the SD memory card. In conclusion, upon checking the measurements on the SpectraWin2 software, the files taken prior to removing the battery were kept saved on the SD memory card, along with the new measurements taken after the battery removal.

EIB 103 DAY 2 Crane Lift LED Traffic Signal Light Measurements

Measurements were taken on the second day of testing in the Engineering Industrial Building (EIB) room 103 following the first set of measurements. Minimum distances were calculated for various potential field test traffic signal heights, and potential height locations for the measuring meter. Calculations were done for traffic signal heights of 16-18 feet, along with 3-6 feet measuring heights for the measuring meter. Figures 17 and 18 show the crane hook and the mount-lock assembly on the traffic signal module. Additionally, these required distances were calculated for each of the four aperture angle settings on the PR-670. With these required measuring distance values, we are able to choose an appropriate elevation for the traffic signal and measuring meter keeping in mind our testing area. Testing then followed by keeping track of the required distances from the generated required distance tables.

Test were done on a 4-foot tri-pod. The tri-pod held the PR-670 with the ability to maneuver it left, right, up, and down to our needs. It is recommended to have a firm standing tri-pod, since lots of shaking can be encountered while taking measurements. However, any tri-pod works better than holding the measuring unit by hand due to the instability.

The PR-670 measuring meter may freeze while taking measurements if the "measure" button on top of the PR-670 is pressed quickly, while the previous measurement is being processed. When this happens, open the battery compartment and remove the battery to take away the measuring unit's power source. The PR-670 will then shut off, and once it is off, insert the battery back into its compartment and turn it back on. If auto-save was selected on the measuring properties screen, then all the data taken prior to the measuring unit freezing will remain saved on the memory card.

Four new traffic signals were measured on the second day of testing in room 103 of the EIB; a new green LED signal, a used green LED signal, a used red LED signal, and a new yellow LED signal. To collect data, have a writing utensil and paper available and create a table showing the aperture degree at which the measurement was taken, the "spot-size," the distance at which the measurement was taken, and the number of taken readings per the selected measurement properties. Apply this table to each of the LED signals that are measured and title the table with the type of LED light along with its manufacturer. Keep in mind that the PR-670 will be saving copies of the luminance readings along with the time and date of when the measurement was taken. Once the measurements have been completed, the table can be compared to the measurements stored on the measuring unit's memory card at a later time. Conversely, a good reminder is to re-focus the measuring unit's lens for each of the measurements taken at varying distances, aperture degree openings, and "spot-size." For example, if the measuring unit was moved twenty-feet forward, re-focus the lens. If the aperture angle was made 0.5-degrees from originally being 1-degree, re-focus the lens.

Figure 17. Crane Hook

Figure 18. Back of Traffic Signal

Out-door Testing at the Cross-Section of Seawolf Drive and Providence Drive

Testing on Day 1, material is gathered inside of the Engineering and Industrial Building (EIB) room 103. The PR-670 will need to be checked for completion prior to taken out for field work. To check the PR-670 for completion, verify that all its accessories are located and functional. This was done by taking a few tests inside the EIB room 101 prior to going out for out-door measurements. The PR-670 accessories include the MS-75 lens, battery block, tripod, surveyors measuring tape, measuring meter carrying case, and its SD memory card. In addition to gathering the PR-670 accessories, it is recommended to take a notepad and a writing utensil to note down the temperature and weather, the heights of the tripod and traffic signals, the date and time, and any other pertinent information to the study.

Testing for the sound bound traffic signal began immediately after the test for the west bound traffic signal had concluded. The tripod was relocated about 15 feet behind the cross-walk pedestrian curve entrance along the sidewalk where the traffic signal main post is location, when facing south. The tripod will need to be placed in an area where, if any, pedestrians can freely maneuver in any given direction around traffic, and have a clear path forward in their direction of walking or bicycling. In addition, the tripod will need to be placed at the required distance away from the traffic signal of focus by first measuring the required distance with the surveyor measuring tape, and marking the spot. It is recommended to have two people working when setting the measuring tape and marking the required distance. The distance measured required two measurements, due to the measuring tape’s 100-foot maximum length, at which then those two length were added to one another. Once the distance is determined, set the tripod in place and continue with selecting all of the appropriate measuring properties within the measuring unit such as the selected “aperture degree” and the number of measures per single measurement. If applying a surveyor measuring tape to measure the required distance, be careful with measuring the height of the traffic signal. The measuring tape was tossed and hooked onto one of the traffic signal’s mounting metal post to measure the traffic signals height. It is recommended to have another form of measure to determine all required distances, such as a distance measuring laser pointer to complement the surveyor measuring tape and to assist with measuring the challenging heights and distances.

On Day 2, the PR-670 was mounted on the tripod and positioned at a location horizontal to the traffic signal of interest. Measurements were taken at two locations facing in the south direction for two traffic signal modules consisting of a green, yellow, and red traffic signal. Two sets of measurements were taken at each location, one for the traffic signal horizontal to the measuring meter, and the second for the second traffic signal at an angle from the horizontal position. This was by rotating the PR-670 measuring meter either to the left or right. The goal for this approach was to compare the results for each signal and to determine if data values remained accurate with a small amount of distance adjustment, or if there was to be a large percentage error as a result of this adjustment. It is important to ensure measurements are being saved onto the SD memory card of the measuring meter. Measurements were taken in the evening with the weather outside being at 50ºF and cloudy. Figure 19 shows a drawn image on the layout of the test site and includes the estimated location for each traffic signal along with the estimated locations for the measuring meter’s positions. Figure 20 shows the surrounding area at the testing site.

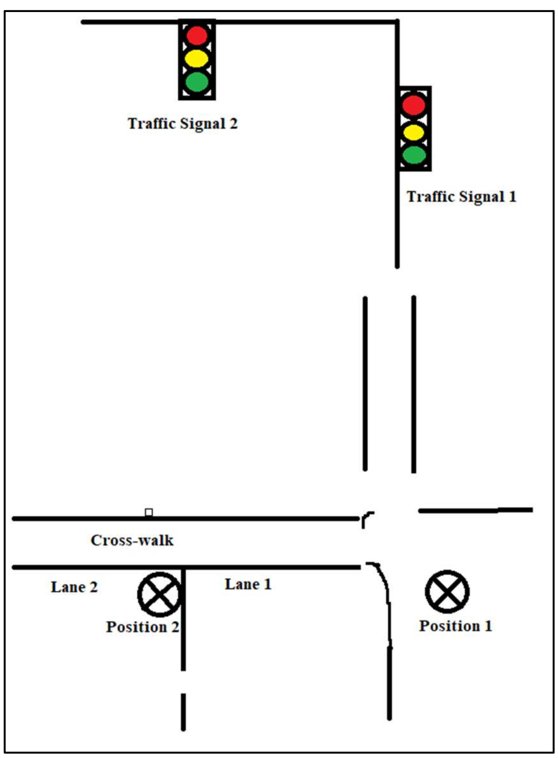

Figure 19. Position Drawing

Figure 20. Facing West at Seawolf Drive

On Day 3, an additional day to measure the same two traffic signals from the same positions as Day 2 was accomplished that following week. Two traffic signal modules were measured for green, red, and yellow luminance at a horizontal to one of the traffic signals, then the angled at the same position to measure the other. Temperature during measurements was 50ºF. The data collected and percent errors calculated are presented in Tables 12-15. Equation 7, as seen in the Introduction, was applied to calculate the percentage error,

Where *Actual* value within the equation was the average of the five measurements taken at a horizontal to the traffic signal of interest, and *Approximate* was the average of the five measurements taken at an angle to the same traffic signal. Same traffic signal for compared values, at a varying location of where the measurement was taken.

Table 12. Measurements for Traffic Signal 1 Taken from Positions 1 and 2

Luminance (cd/m^2) Position 1 on Traffic Signal 1			Luminance (cd/m^2) Position 2 on Traffic Signal 1		
Red	Yellow	Green	Red	Yellow	Green
2651	27225	12146	2770	25557	12639
2657	30434	12913	2683	23015	13692
2324	-	13847	2355	-	13465
2082	-	11961	2085	-	11133
2373	-	14079	1855	-	11467

Table 13. Measurements for Traffic Signal 2 Taken from Positions 1 and 2

Luminance (cd/m^2) Position 1 on Traffic Signal 2			Luminance (cd/m^2) Position 2 on Traffic Signal 2		
Red	Yellow	Green	Red	Yellow	Green
3818	12865	6438	4959	27907	9493
3986	12296	6484	4393	28771	9624
3923	-	6575	4211	-	9659
4076	-	6551	4357	-	10117
3858	-	6355	4281	-	9678

Table 14. Percent Error for Traffic Signal 1 Taken from Position 1 and Position 2

Red	Yellow	Green
2.8 %	10.5 %	3.9 %

Table 15. Percent Error for Traffic Signal 2 Taken from Position 1 and Position 2

Red	Yellow	Green
11.4 %	55.6 %	66.7 %

The highest percent error was seen at 66.7 %, and that was for the green signal on traffic signal 2. The lowest percent error was seen at 2.8 %, being for the red signal on traffic signal 1. It is uncertain as to the reason for the high percent errors.

On Day 4 of testing, the same procedure as test day 2 and 3 to collect day was followed. The test taken occurred during the night on a Tuesday at 8:00 p.m. with the temperature being at 40ºF. A light change was made to the tripod on which the PR-670 measuring meter was attached onto. The new tripod was able to achieve a taller height and provided a stronger balance to measuring meter for ground stability. This test day went without measuring the luminance of the yellow traffic signal since it provides 1-2 seconds to take a measurement, therefore it was decided to take only the red and green traffic signal measurements. The data collected and percent errors calculated are presented in Tables 16-19.

Table 16. Measurements for Traffic Signal 1 Taken from Positions 1 and 2

Luminance (cd/m^2) Position 1 on Traffic Signal 1			Luminance (cd/m^2) Position 2 on Traffic Signal 1		
Red	Yellow	Green	Red	Yellow	Green
6677	-	17638	5019	-	16198
6630	-	17394	4995	-	16195
6578	-	17387	5054	-	16190
6531	-	17201	5214	-	16011
6503	-	17175	5174	-	16261

Table 17. Measurements for Traffic Signal 2 Taken from Positions 1 and 2

Luminance (cd/m^2) Position 1 on Traffic Signal 2			Luminance (cd/m^2) Position 2 on Traffic Signal 2		
Red	Yellow	Green	Red	Yellow	Green
4378	-	6719	4628	-	9979
4373	-	6712	4613	-	9996
4369	-	6703	4593	-	11006
4358	-	6700	4567	-	11054
4375	-	6680	4561	-	10044

Table 18. Percent Error for Traffic Signal 1 Taken from Position 1 and Position 2

Red	Yellow	Green
22.6 %	-	6.8 %

Table 19. Percent Error for Traffic Signal 2 Taken from Position 1 and Position 2

Red	Yellow	Green
4.8 %	-	35.6 %

There seems to be a high percentage error for both day-time measurements compared to night-time measurements. The only consistent percentages were seen for the green signal on module 1. All others show high amounts of percentage change when compared to one another. I recommended taking measurements in the night-time over the day-time, because as seen on Tables 12, 13 and 16, 17, values for night-time readings were higher than the day-time.