Research & Technology Transfer

Alaska Department of Transportation & Public Facilities

Life-cycle Analysis and Replacement Strategy of LED Traffic Lights in Alaska

Prepared by:

Vinod Vasudevan, Ph.D., P.E.

Associate Professor of Civil Engineering

College of Engineering, University of Alaska Anchorage

Date:

April 24, 2023

Prepared for:

Alaska Department of Transportation & Public Facilities

Statewide Research Office

3132 Channel Drive

Juneau, AK 99801-7898

FHWA-AK-RD-4000(203)

REPORT DOCUMENTATION PAGE			Form approved OMB No.
Public reporting for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestion for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-1833), Washington, DC 20503			
1. AGENCY USE ONLY FHWA-AK-RD-4000(203)	2. REPORT DATE April 24, 2023	3. REPORT TYPE AND DATES COVERED February 21, 2020- March 30th, 2023	
4. TITLE AND SUBTITLE Life-cycle Analysis and Replacement Strategy of LED Traffic Lights in Alaska 6. AUTHOR(S) Vinod Vasudevan, Ph.D., P.E., Associate Professor of Civil Engineering			5. FUNDING NUMBERS FHWA 4000(203) DOT&PF HFHWY00202
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) College of Engineering University of Alaska Anchorage 2900 Spirit Drive, Anchorage, AK 99508			8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) State of Alaska, Alaska Dept. of Transportation and Public Facilities Research and Technology Transfer 3132 Channel Drive, Juneau, AK 99801-7898			10. SPONSORING/MONITORING AGENCY REPORT NUMBER FHWA-AK-RD-4000(203)
11. SUPPLENMENTARY NOTES: Performed in cooperation with Alaska DOT&PF and FHWA Alaska Division Office			
12a. DISTRIBUTION / AVAILABILITY STATEMENT No restrictions			12b. DISTRIBUTION CODE
13. ABSTRACT (Maximum 200 words): Over the last two decades, LEDs have replaced incandescent bulbs for traffic signal heads. The primary advantage of LEDs over incandescent bulbs is longevity and energy efficiency. LEDs continue emitting light that may not meet the minimum specifications for intensity and color. For this reason, 35 intersections in Anchorage and 16 intersections in Fairbanks were tested and analyzed using the ITE guidelines for luminous intensity and chromaticity. Under the luminous intensity specification, it was found that the average replacement period range for red lights was 7 to more than 12 years, and for green lights, it was 6 to 13 years at 95% confidence. Based on this range, the average replacement age for red lights is between 7 and 11 years. For green lights, the replacement age is between 6 and 10 years. Based on the chromaticity guidelines, the results showed that red signals improved chromaticity over time, whereas green signals displayed a reduction in chromaticity around the 15-year mark. These results show that luminous intensity is critical, and signals should be replaced based on those conditions.			
14- KEYWORDS : LED Traffic Signal, Life-Cycle Analysis, Asset Management, Chromaticity			15. NUMBER OF PAGES 54 16. PRICE CODE N/A
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT N/A

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4		mm
ft	feet	0.3048		m
yd	yards	0.914		m
mi	Miles (statute)	1.61		km
		AREA		
in^2	square inches	645.2	millimeters squared	cm^2
ft^2	square feet	0.0929	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
mi^2	square miles	2.59	kilometers squared	km^2
ac	acres	0.4046	hectares	ha
		MASS (weight)		
oz	Ounces (avdp)	28.35	grams	g
lb	Pounds (avdp)	0.454	kilograms	kg
T	Short tons (2000 lb)	0.907	megagrams	mg
		VOLUME		
fl oz	fluid ounces (US)	29.57	milliliters	mL
gal	Gallons (liq)	3.785	liters	liters
ft^3	cubic feet	0.0283	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3

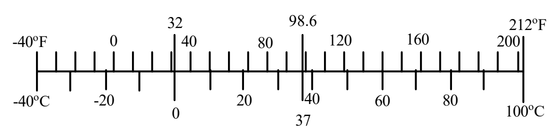
Note: Volumes greater than 1000 L shall be shown in m^3

Symbol	When You Know	Multiply By	To Find	Symbol
		TEMPERATURE (exact)		
ºF	Fahrenheit temperature	5/9 (ºF-32)	Celsius temperature	ºC
		ILLUMINATION		
fc	Foot-candles	10.76	lux	lx
fl	foot-lamberts	3.426	candela/m^2	cd/cm^2
		FORCE and PRESSURE or STRESS		
lbf	pound-force	4.45	newtons	N
psi	pound-force per square inch	6.89	kilopascals	kPa

These factors conform to the requirement of FHWA Order 5190.1A *SI is the symbol for the International System of Measurements

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	Miles (statute)	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
km^2	kilometers squared	0.39	square miles	mi^2
ha	hectares (10,000 m^2)	2.471	acres	ac
		MASS (weight)		
g	grams	0.0353	Ounces (avdp)	oz
kg	kilograms	2.205	Pounds (avdp)	lb
mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME		
mL	milliliters	0.034	fluid ounces (US)	fl oz
liters	liters	0.264	Gallons (liq)	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		TEMPERATURE (exact)		
ºC	Celsius temperature	9/5 ºC+32	Fahrenheit temperature	ºF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/cm^2	candela/m^2	0.2919	foot-lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	pound-force	lbf
kPa	kilopascals	0.145	pound-force per square inch	psi



Executive Summary

Over the last two decades, Light-Emitting Diode (LED) technology has advanced, and LEDs have been identified as a replacement for incandescent bulbs for a variety of applications, including in traffic signal heads. The primary advantage of LEDs over incandescent bulbs is that LEDs are extremely energy efficient and long lasting. LEDs also do not fail in the same manner as incandescent bulbs. Instead of complete and abrupt failure, which occurs when the filament in an incandescent bulb burns out or breaks, LEDs degrade gradually over time, causing the quality and intensity of the light emitted to decrease. However, the process of gradual failure has drawbacks. It is apparent when an incandescent bulbs fails and stops emitting light. LEDs, on the other hand, continue emitting light that may not meet the minimum specifications for intensity and color. These changes cannot always be distinguished by the naked eye, making it difficult to determine when LEDs must be replaced.

For this reason, 35 intersections in Anchorage and 16 intersections in Fairbanks were tested and analyzed using the ITE guidelines for luminous intensity and chromaticity with the goal of recommending a replacement period for LED signals and to determine whether factors like location and direction had an impact on the deterioration of the LEDs. Under the luminous intensity specification, it was found that the average replacement period range for red lights was 7 to more than 12 years and for green lights it was 6 to 13 years at 95% confidence. Based on this range, the average replacement age for red lights is between 7 and 11 years. For green lights, the replacement age is between 6 and 10 years. Based on the chromaticity guidelines, the results showed that red signals had an improvement in chromaticity over time whereas green signals displayed a reduction in chromaticity around the 15-year mark. These results show that luminous intensity is the critical condition and signals should be replaced based on those conditions.

Table of Contents

List of Figures

List of Tables

INTRODUCTION

Light-Emitting Diodes (LEDs) started replacing incandescent bulbs in traffic signal heads a couple of decades ago. However, the standard practice of replacing incandescent bulbs does not apply to LED bulbs for several reasons. Incandescent bulbs usually provide the amount of light required by regulations until they burn out. In contrast, LEDs degrade over time and may appear to work by having a color output, while the luminosity may fall below regulations. Although ITE guidelines mention the minimum luminance required for traffic lights, few reported studies are available discussing the performances of LED traffic signals. Studies by the Missouri DOT and the Louisiana DOT show that the useful lives of LED traffic lights are much longer than traditional incandescent lights. However, since these were conducted in the early 2000s, these studies did not include the entire life cycle of LED traffic lights, and the recommendations from these studies were conservative. Also, LED degradation is exponentially related to operating temperature. Therefore, applying scheduled replacement practices from other regions of the country may result in premature replacement and extra maintenance expenses.

OBJECTIVE

This study aimed to carry out a life-cycle analysis and reconnaissance of the "degradation rate" of LED traffic lights in Alaska by analyzing the performance over time of traffic signals based on luminance by installation date.

LITERATURE REVIEW

The literature review presents the prevailing guidelines and practices for measuring the performances of traffic lights. The State of Alaska started replacing incandescent lights with Light-Emitting Diodes (LEDs) in traffic signals in the early 2000s, following the ITE 1998 Traffic Signal Specification release. This section summarizes significant studies relevant to this project. The literature review was compiled through research of documents, articles, and similar information to learn about methods applied by various organizations, including universities and state departments, to study the performance of LEDs in traffic signals. Although performance measures of traffic lights are not well-researched, there is some documentation available. The resources include reports from various organizations, universities, equipment manufacturers, and businesses, all working for their local or state agencies to understand the performances of LED traffic lights.

Summary of Major Reported Studies

This section summarizes some of the relevant studies conducted across the US. Although a few studies were reported in the late 1990s, a majority were reported in the early 2000s.

In one of the earliest studies, Cohn et al. (1998) developed a quality index to compare the visual effect of various types of bulbs using heterochromatic flicker photometry. They compared the performance of various new types of bulbs with traditional bulbs. The study showed that LED traffic signals performed very similarly to incandescent traffic signals. Although several agencies had started to deploy LED traffic signals, this study helped to accelerate the process.

Suozzo (1999) explored the potential impacts of LED traffic lights on lowering maintenance and energy costs. This study showed that LED traffic light replacement had a payback period of about two years and would make considerable savings in the long run due to their longevity.

In a study based on a survey of maintenance practices of LED traffic lights, Behura (2007) reported that the use of LED traffic signals had been expected to reduce the lifetime cost per module compared with incandescent modules. This study reported that many agencies had not implemented appropriate maintenance programs for LED signal modules.

In the NCHRP synthesis, Urbanik (2008) reviewed a 2006 survey conducted by ITE of transportation agencies regarding their experience and practices with LED traffic signals. The study showed a consensus that agencies generally approved of the use of LED traffic lights. However, the report also mentions that agencies were concerned about long-term performance and the need to develop new standards for performance evaluation.

In their NCHRP report, Bullough et al. (2009) presented results from studying the photometric requirements, measurement, and maintenance of traffic signal modules using LEDs. The authors summarized that LEDs had reduced long-term costs. They also reported that the ITE specifications developed for incandescent lights were sufficient for LEDs. This study recommends group replacements combined with some recovery of replaced modules for necessary spot replacements.

Noble (2009) highlighted the maintenance of LED traffic lights and suggested some of the maintenance strategies according to the ITE standards. He concluded that phased replacement of signalized intersections is better than system-wide replacement due to budget and resource reasons.

Long et al. (2011, 2012) and Noll (2011) studied life expectancy and recommended a replacement schedule for LED traffic lights to the Missouri State Department of Transportation. These studies used a deterministic time regression model to calculate useful life. They focused on the unexpected behavior of red traffic lights. In these studies, the authors used cross-functional analysis for data collection with one data point for one light.

Digraskar (2014) tried to provide decision support for Missouri DOT on the judicious choice of manufacturer. This study analyzed the impact of distance, directional view, color, manufacturer, and temperature on the behavior of LED traffic lights. The author used three analysis methods on the obtained field data: 1) intensity analysis, 2) manufacturer analysis, and 3) temperature analysis. These analyses provide insights into the performance of red LEDs.

In summary, there are few relevant studies about life expectancy and replacement strategies for LED traffic lights. While the existing studies provide some useful insights, the lack of studies in cold regions make it impossible to generalize the results for Alaska.

Measuring Devices to Capture LED Light Output

The measuring devices to capture LED light output include factory-built photometers, spectroradiometers, and custom in-house devices. Photometers measure the luminance output of the light sources. Conversely, spectroradiometers measure both the luminance of LED light sources and the color output within the color spectrum visible to the human eye. Since color is an essential property of traffic lights, a spectroradiometer is more suitable to their study (Long et al., 2012).

Properties of Measuring Tool Devices

There are four major tools used in previous studies. Three of those, spectroradiometers, spectra colorimeters, and photometers, are commercially available. The fourth one is a custom-built Fresnel lens which captures luminous intensity, and it was developed by the Missouri University of Science and Technology. Aside from these four measuring devices, the literature also mentioned luminance meters, a device that measures a light source's luminance value (Finkle, 1997). A photometer captures the light being emitted by the source being measured (Wachtel, 2014). Spectra Colorimeter is a spectrally based colorimeter that performs complete photometric and colorimetric measurements for both steady-state and repetitively pulsed light sources (Jiang, 2004). The custom-built device included a commercial light meter, a range finder, a laser pen, and a Fresnel lens (Long et al., 2011).

Aperture Angle

The aperture angle on a measuring meter governs many properties of the measurements. These include the distance from the light source 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, 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 measured modules or parts of the module, depending on the type of study. As long as the "spot-size" circle captures light only from the measurement module and not the surrounding area, the meter will provide accurate readings of luminance (Wachtel, 2014). An example of a "spot-size" view to the user is shown in Figure 1.

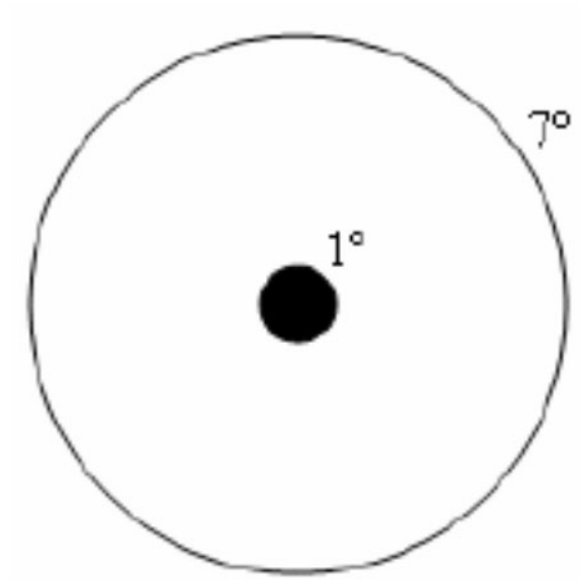


Figure 1. Aperture 1° capture circle within meter viewpoint (Jiang, 2004).

INSTRUMENTS USED TO MEASURE LUMINOUS INTENSITY

Jadak

The Jadak PR-670 is one of the many PR modules provided by the company Jadak, also marketed as Photo Research. This instrument is equipped with multiple aperture angle settings to take measurements at 1°, $\frac{1}{2}°$, $\frac{1}{4}°$, and $\frac{1}{8}°$ aperture angles. As previously mentioned, a varying aperture angle setting allows for flexibility in measuring the light source from a distance. One may elect to measure the entirety of the module, half of the module, or a variety of points throughout the module. This instrument can 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 (ITE, 2005), which needs 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 spectroradiometer close to meeting ITE's specification.

Konica Minolta

The CS-200 is a colorimeter produced by Konica Minolta that allows the user to choose from either a 1º, $\frac{1}{5}$º, or $\frac{1}{10}$º aperture angle. This colorimeter can hold a maximum of 101 measurements. Those measurements need to be recorded onto a separate device and emptied from the colorimeter before taking new measurements. This instrument has a measuring uncertainty of 2.2%, which 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% (Konica Minolta, 2020).

Missouri S&T Fresnel Lens

The Missouri University of Science and Technology built a device for measuring the light output of a traffic signal module. They applied a Fresnel lens to capture light at a distance by drowning out the light output from the LED with the application of the surrounding ambient light (Long et al., 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 2 and 3, respectively. The instrument works by filtering light output emitted from the LED where it was then focused by the Fresnel lens into a concentrated beam. This allowed for a light meter to be placed behind the Fresnel lens to capture the light emitted from the tested traffic signal module.

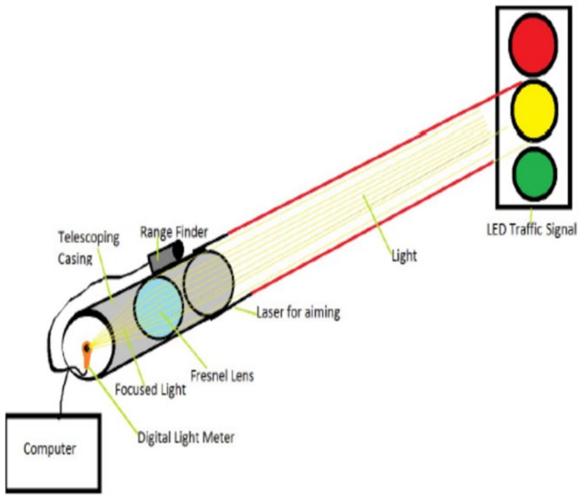


Figure 2. Illustration of Fresnel lens (Long et al., 2011)

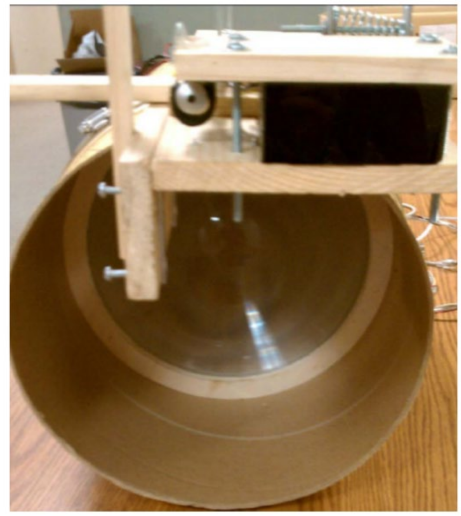


Figure 3. Fresnel lens (Long et al., 2011)

DATA COLLECTION PROCEDURE

When taking a field measurement for luminance, one needs to account for ambient daylight, the specific measurement geometry, angle position, and natural factors like wind, which will play a role in the accuracy of the measurements (Bullough et al., 2009). The 2005 Institute of Transportation Engineers' *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 (ITE, 2005). Additionally, those same modules shall include the nominal operating voltage and stabilized power consumption in watts and volt-amperes. 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 (ITE, 2005).

CHALLENGES IN TAKING MEASUREMENTS

The traffic signals have a casing around the light source. This means that measuring from a horizontal angle will not cover the full 12-inch or 8-inch traffic signal. Photo research meters are sensitive to their angle; therefore, they need to have a stable base or tripod when taking measurements (Jiang, 2004). When the measuring meter is pointed towards the light module, it provides an accurate reading so long as the “spot-size” within the aperture opening captures only the light being measured and not the surrounding area (Wachtel, 2014). Similarly, the “spot-size” within the measuring meter must capture and fill the possible area of the light module while keeping in mind that the area increases as the measuring meter becomes further away from the module, increasing the number of points contributing to the measurement (Finkle, 1997). When comparing measured values to various modules, one needs to note that the modules may differentiate in properties, which may result in the need to make adjustments (Cohn et al., 1998). For example, yellow, orange, and white lights will appear brighter than red, blue, and green lights (Wachtel, 2014).

Weather, Temperature, and Ambient Light

As mentioned in the ITE 2005 specification, when testing for luminance uniformity, the modules shall be compliance tested at a temperature of 25ºC or 77ºF (ITE, 2015). A study carried out by Florida State University in 2004 with a Photo Research measuring meter concluded that when the temperature was low the values of the traffic signal luminance were higher (Jiang, 2004). Similarly, the ITE 2005 specification states that the light output of LEDs diminishes as the ambient temperatures increase, and internal temperatures substantially reach a 74ºC (or 165ºF) upper limit, resulting in an unacceptable LED module performance (ITE, 2005).

When taking measurements in the presence of light, it is required to take luminance measurements 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 calculations for luminous intensity (Bullough et al., 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. Still, the measurement readings will result in a small percent error (Finkle, 1997).

Wachtel (2014) explains his experience with both nighttime and daytime measurements. He recommends nighttime measurements to ensure the readings are unobstructed by daylight. This study also mentions that the United States Sign Council prefers measurements to 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.

Angle of Measurement

The ITE 2005 Specification recommends measurements be taken from a range of 12.5º above to 22.5º below the horizontal plane and 27.5º right and 7.5º left on the vertical plane at 2.5º increments while keeping the two highest values (ITE, 2005). Within the exact specification, tables show the minimum accepted luminance for ranges of measurement angles.

Finkle (1997) states that as the meter is further away from the light module, the angle will be reduced. When the angle is at an extreme, the meter measures the effect of the inverse square law; as a result, the module will act as a point source (Finkle, 1997). Rea (2000) concluded that if the inverse square law was to be applied, then a percent error of less than 5% is required for calculations of the luminous intensity. Cohn et al. (1998) show that the values for luminous intensity decline when taken off-axis of the measured module by an extreme. Long et al. (2011) 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, and then they compared those values to the values presented in the ITE 2005 Specification (Long et al., 2011).

Distance of Measurement

Bullough et al. (2009) 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. Conversely, Wachtel (2014) suggests it does not matter at what angle or distance the measuring meter is from the light module; all that matters is that the “spot-size” falls only within the module itself and not its surrounding area.

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 (ITE, 2005). In the NCHRP Web-Only Document 146 report (Bullough et al., 2009), the authors mention how the luminous intensity of LED traffic signal modules degrade over time (Behura, 2007). They noted 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 (ITE, 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 the 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 $I=L\times A\times$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 et al., 2009).

EQUIPMENT USED IN THE STUDY

In this project, the PR-670 from JADAK was used. An image of the PR-670 and its accessories can be seen in Figure 4. The measuring unit includes an MS-75 Macro-Spectra camera lens that attaches to the measuring unit. The PR-670 is equipped with a 512MB memory digital card and a USB drive, along with a certificate of calibration. A digital card is capable of storing about three thousand luminance measurements.

IN-LAB TESTING

Before data collection in the field, the measuring unit required setup and testing on the University of Alaska Anchorage campus. Given the minimum distance equation Jadak provided and the size of the Student Innovation Center, the space used for testing, we were restricted to a 6-inch or 5-inch "spot-size" on a 1º aperture opening. The maximum workable distance in the lab was 30 ft, and the calculated minimum distance 6-inch "spot-size" was around 28 ft. Jadak recommends at least 80% of the LED is covered by the "spot-size" for an accurate measurement.

To setup the traffic model for testing, we inserted an LED signal inside of the traffic module's metal casing. We calibrated the PR-670 unit before testing. The traffic signal LED

Figure 4. PR-670 measuring unit with accessories.

module was raised to the level of actual traffic signal heights, 15-20 ft. The final setup is shown in Figures 5 and 6.

A required distance for a particular aperture angle and "spot-size" is calculated using Equation 1, provided by Jadak:

$$L = \frac{S \times z}{a} \qquad 1$$

$Where, S =$ Aperture spot-size diameter in meters, $z =$ max working distnace $(=$ 305m for Jadak PR $-$ 670, $a =$ max working distance per aperture size in meters

Values for a were provided by Jadak for various aperture values.

Aperture 1º = 5.32 meters, Aperture 0.5º = 2.66 meters, Aperture 0.25º = 1.33 meters, and 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.

Figure 6. Setting for lab testing using crane.

Figure 5. Red traffic signal module in lab setting.

Values for S are chosen depending on the size of the traffic signal. For example, if a 12-inch traffic signal is being measured, then a 10-inch "spot-size" is needed and chosen, therefore the value for S is 10 inches. "Spot-size" will vary with distance and the selected aperture angle. The ITE 2005 traffic signal specification calls for most 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" to 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. An example calculation for minimum horizontal distance is illustrated in Figure 7.

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 7. Distance calibrations for a Jadak PR-670 (Esteves, 2020).

DATA COLLECTION

Site Selection

Since the project aimed to analyze performance over time, sites with different deployment years were selected. We received a list of intersections and the year of deployments from the Alaska DOT&PF and the Municipality of Anchorage. After consultation with the DOT&PF, we finalized 51 sites for data collection. These included 35 sites in Anchorage and 16 in Fairbanks.

Scheduling

Data were collected in Anchorage and Fairbanks in October and November of 2020. We rented the main equipment, the PR-670, for three months, from August to November 2020. Existing reported studies recommend collecting data during the night. At the same time, the PR-670 has a range of recommended operating temperatures, making it challenging to collect data under cold conditions. These restrictions meant that the field data collection could be carried out only during a short timeframe.

Data Collection in the Field

Based on the data collection experience in the lab setting, we estimated the time taken for data collection as an hour at each site (4-lane, 4-way), including the set-up time. Therefore, we scheduled about eight intersections per night. We started data collection in Anchorage on October 19, 2020, to get familiar with the data collection process. Based on the experience, we modified our data collection process for higher efficiency. Then we collected data from

Fairbanks before completing the data collection in Anchorage. Tables 1 and 2 list the sites, year of deployment, and date of data collection. This section discusses the details of the data collection. Since PR-670 does not allow numbers to name files, Site IDs were used instead of site numbers. We also collected photo images of each signal head for our records. The DOT&PF staff helped with traffic control during the data collection in Anchorage and in Fairbanks. The following equipment was used during the data collection:

- PR-670 spectroradiometer and lens
- DSLR Camera and lens
- Tripods (2)
- Tripod mounts for precise adjustments (2)
- Power bank
- Laser distance measurement device

Since we focused on traffic signal heads from a distance, we had to use tripods and tripod heads with precise adjustments. A power bank was needed to power the PR-670. The laser distance measuring device was used to measure the distance from the signal head required to place the PR-670. The distance between the PR-670 and the signal head is dependent on the distance requirements of the desired "spot-size" per aperture setting. The available aperture settings for PR-670 are 1º, 0.5º, 0.25º, or 0.125º. The measurements were automatically saved onto an SD memory card. Figure 8 shows a photo of the PR-670 during data collection.

Due to cold weather below the operating threshold of the PR-670, we could not collect data at the last four sites in Anchorage scheduled on November 2nd. We tried to reschedule the data collection for a few more days. However, due to the extended cold wave, we had to cancel the data collection for these four sites after consultation with DOT&PF.

Distance Between the Signal Head and PR-670

The distance between the signal head and PR-670 is one of the significant parameters of the data collection. The ITE guidelines list minimum recommended luminous intensity values based on the horizontal and vertical angle. Since we collected data on the middle of lanes for each traffic light, the horizontal angle was zero. Table 2 in the ITE guidelines (ITE, 2005) lists the minimum values at 2.5-degree increments of vertical angles. The values change significantly for each 2.5-

Table 1: Data Collection Schedule for Anchorage

Site ID	Intersection	Year of Installation	Data Collected on
AA	15th & C St.	2001	19-Oct-20
AB	15th & E St.	2001	19-Oct-20
AC	33nd & Denali	2003	19-Oct-20
AD	36th & Denali	2003	19-Oct-20
AE	64th & C St.	2004	19-Oct-20
AF	76th & Arctic	2001	19-Oct-20
AG	88th & Toloff	2002	19-Oct-20
AH	Debarr & Debarr Circle	2004	19-Oct-20
AI	Old Seward & Tudor	2005	27-Oct-20
AJ	Arctic & Tudor	2017	27-Oct-20
AK	Dowling & Raspberry	2015	27-Oct-20
AL	Arctic & Raspberry	2013	27-Oct-20
AM	Dowling & Old Seward	2012	27-Oct-20
AN	88th & Old Seward	2008	27-Oct-20
AO	Abbott & Lake ortiz	2017	27-Oct-20
AP	72nd & Lake Ortiz	2008	27-Oct-20
AQ	63rd & Lake Ortiz	2009	27-Oct-20
AR	Dowling & Elmore Rd	2009	27-Oct-20
AS	40th & Lake Ortiz	2011	29-Oct-20
AT	Northern Lights & UAA Drive	2014	29-Oct-20
AU	09th & Ingra	2013	29-Oct-20
AV	09th & C St.	2010	29-Oct-20
AW	06th & E St.	2009	29-Oct-20
AX	Minnesotta & Northern Lights	2006	29-Oct-20
AY	Fireweed & Spenard Rd	2018	29-Oct-20
AZ	Benson & Spenard Rd	2018	29-Oct-20
BA	Arctic & Benson	2007	29-Oct-20
BB	Arctic & Northern Lights	2007	29-Oct-20
BC	Golden Bear & Muldoon	2016	2-Nov-20

BD	6th & Muldoon	2010	2-Nov-20
BE	Creekside & Debarr	2007	2-Nov-20
~~**BF**~~	~~16th & Muldoon~~	~~2008~~	~~2-Nov-20~~
~~**BG**~~	~~Muldoon & Northern Lights~~	~~2011~~	~~2-Nov-20~~
~~**BH**~~	~~Boniface & Tudor Rd~~	~~2010~~	~~2-Nov-20~~
~~**BI**~~	~~Lake Ortiz & Tudor Rd~~	~~2010~~	~~2-Nov-20~~

Table 2: Data Collection Schedule for Fairbanks

Site ID	**Intersection**	**Year of Installation**	**Data Collected on**
FAA	Airport Way / Cushman Street	2002	23-Oct-20
FAB	Cushman Street / Gaffney Street	2016	23-Oct-20
FAC	Cushman Street / 10th Avenue	2014	23-Oct-20
FAD	Noble Street / 10th Avenue	2017	23-Oct-20
FAE	Noble Street / 3rd Avenue	2017	23-Oct-20
FAF	Cowles Street / Kennicott Avenue	2002	23-Oct-20
FAG	Airport Way / Peger Road	2020	23-Oct-20
FAH	Airport Way / Market Street	2018	23-Oct-20
FAI	Airport Way / Sportsman Way	2018	24-Oct-20
FAJ	Peger Road / Davis Road	2020	24-Oct-20
FAK	Illinois Street / Phillips Field Road	2013	24-Oct-20
FAL	College Road / Aurora Road	2015	24-Oct-20
FAM	Geist Road / Loftus Road	2018	24-Oct-20
FAN	Geist Road / Fairbanks Street	2018	24-Oct-20
FAO	Badger Road / Hurst Road	2002	24-Oct-20
FAP	Richardson Highway (south ramp) / Buzby Road	2010	24-Oct-20

Figure 8. Spectroradiometer in-field.

degree increment. Therefore, it is essential to estimate the actual vertical angle. To estimate the vertical angle, we need at least three parameters. As shown in Figure 9, we can create a right-angled triangle between the traffic signal head and PR-670. The height of the triangle can be calculated by fixing the height of PR-670 since the height of the signal head mast-arms was 20 ft. Therefore, the tripod was set at a height of 5 ft at all sites. Now, the height of the triangle was fixed at 15 ft. One more length is required to calculate the vertical angle, either the base or hypotenuse. Here the base of the triangle is the horizontal distance between the PR-670 and the traffic signal head, whereas the hypotenuse is the direct distance between PR-670 and the traffic signal head.

As discussed in the "In-lab Testing" section, the required distance for data collection is dependent on the aperture angle and spot-size, and it is calculated using Equation 1.

After the laboratory experiments, we finalized the aperture size as 0.250. The Photo Research recommends the "spot-size" to cover a minimum of 50% of the traffic signal for good measurements and at least 80% for the most accurate measurements. Therefore, we chose two

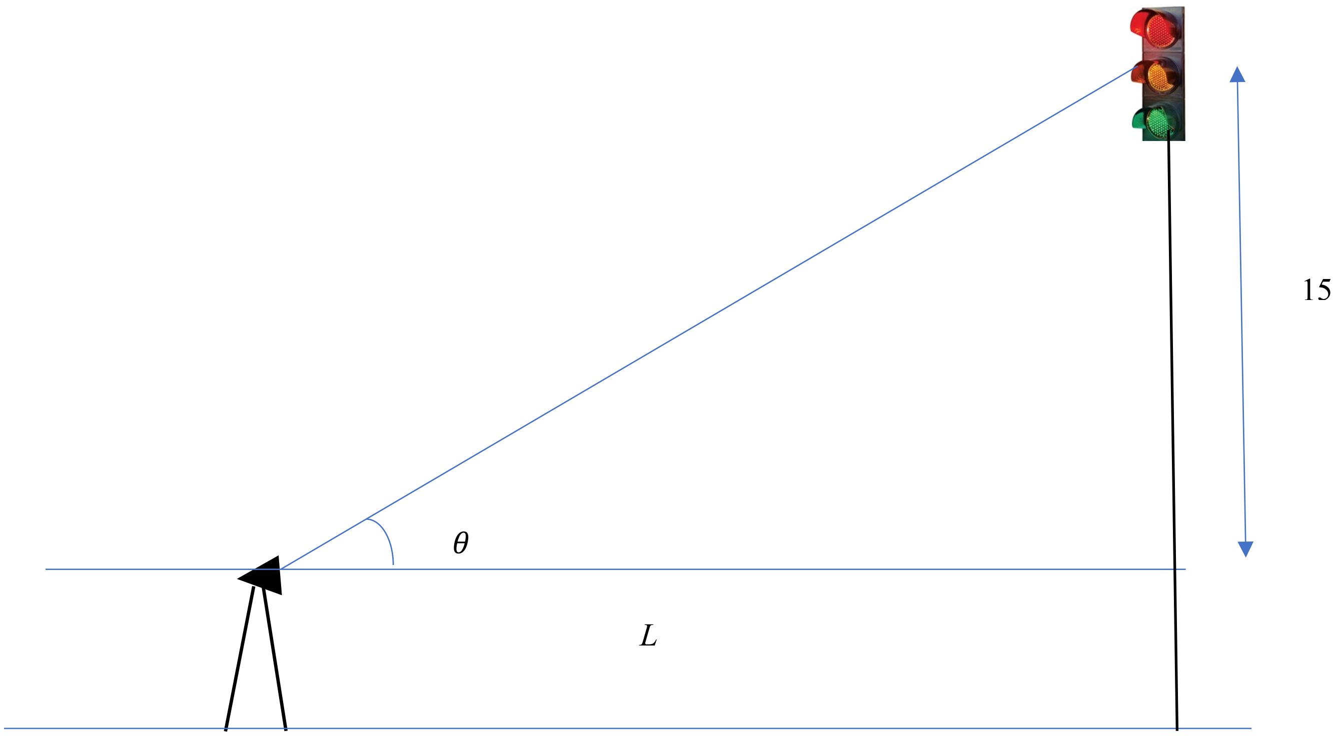


Figure 9. Schematic of data collection

spot sizes, 7-inch and 8-inch, to satisfy the criteria after a few experiments. We choose an 8-inch spot size wherever possible. However, wherever sight distance was an issue, we chose a 7-inch spot size. Corresponding values of L were 134 ft and 153 ft, respectively.

This distance represents the hypotenuse of the right-angled triangle shown in Figure 10. The vertical angle (θ) can be calculated using the properties of the triangle. To be precise, the height of the mast-arm (20 ft) represents the height of the center of the yellow traffic light. The center of the red traffic light is assumed to be at 1.1 ft above the mast-arm and that of the green traffic light 1.1 ft below the mast-arm. These adjustments are made for estimating vertical angles. The values of θ for red traffic lights for 7- and 8-inch spot sizes are 6.040, and 6.910 respectively. Corresponding values for green traffic lights are 5.960 and 5.220, respectively. The laser distance measuring unit was used to place PR-670 at the required distance. The ITE guidelines define the vertical angle as the angle measured above or below a horizontal plane perpendicular to the face of the module lens. Using the properties of triangles, we can see that the corresponding vertical angles are $-\theta$. We took five readings for each traffic signal head to avoid measurement errors.

DATA ANALYSIS

After capturing data with the PR-670, the data were exported from its SD card to CSV files using Spectrawin, software provided by Jadak. To convert luminance into luminous intensity, we multiplied the luminance value by the spot size. The spot size was converted to square meters before the conversion. These values were compared with the minimum values recommended by ITE. As mentioned before, the ITE guidelines list the minimum values at 2.5^0 intervals of vertical angle. As discussed in the previous section, the values of vertical angles in this study for red traffic lights for 7- and 8-inch spot sizes are -6.04^0 and -6.91^0, respectively. Corresponding values for green traffic lights are -5.96^0 and -5.22^0, respectively. The minimum values for red and green traffic lights for vertical angles -5.0^0 and -7.5^0 are given in Table 3. The differences in these values are significant. Therefore, since the vertical angles used in this study are between -5.0^0 and -7.5^0, linear interpolation was used to estimate the minimum values per the ITE guidelines. Table 4 shows the interpolation results, and these values are used along with the average luminous intensity for further analysis.

Table 3: Minimum Recommended Values of Luminous Intensity for 12-inch Heads (ITE, 2005).

Horiz. Angle	Verical Angle	Red	Green
0^0	-5.0^0	347	451
0^0	-7.5^0	288	375

Table 4: Interpolated Minimum Values of Luminous Intensity

Horiz. Angle	Verical Angle	Red	Green
0^0	-6.91^0	301.9	--
0^0	-6.04^0	322.3	--
	-5.96^0	--	421.7
	-5.22^0	--	444.4

As discussed in the data collection section, five readings were taken for each traffic signal. The average and standard deviation of these values were calculated. Tables A1 and A2 in Appendix A show the values of all intersections by approach for red and green traffic signals, respectively.

Comparison with the ITE Minimum Values

In the first part of the analysis, the obtained values were compared with the minimum values listed in Table 4. Tables A3 and A4 show the results. The primary summary for red traffic lights is given in Table 5. Table 6 shows the same data for green traffic signals. Table 5 shows that for the installation years before 2010, most red signals did not satisfy the ITE minimum criteria. A similar trend can be observed for green traffic lights, but there was more variability for 2011 through 2015.

Table 5: Summary of Comparison (Overall - Red)

Installation Year	Satisfied	Not Satisfied	% Satisfied	% Not Satisfied
2001	0	12	0%	100%
2002	0	18	0%	100%
2003	1	13	7%	93%
2004	0	12	0%	100%
2005	1	6	14%	86%
2006	0	7	0%	100%
2007	4	10	29%	71%
2008	5	7	42%	58%
2009	3	7	30%	70%
2010	11	5	69%	31%
2011	6	0	100%	0%
2012	6	0	100%	0%
2013	12	2	86%	14%
2014	4	4	50%	50%
2015	7	2	78%	22%
2016	10	1	91%	9%
2017	15	8	65%	35%
2018	36	4	90%	10%
2019	-	-	NA	NA
2020	8	0	100%	0%
Overall	129	118		

Table 6: Summary of Comparison (Overall - Green)

Year	Satisfied	Not Satisfied	% Satisfied	% Not Satisfied
2001	1	11	8%	92%
2002	2	16	11%	89%
2003	1	13	7%	93%
2004	2	10	17%	83%
2005	0	7	0%	100%
2006	3	4	43%	57%
2007	2	12	14%	86%
2008	5	7	42%	58%
2009	1	9	10%	90%
2010	2	14	13%	88%
2011	3	3	50%	50%
2012	3	3	50%	50%
2013	8	6	57%	43%
2014	4	4	50%	50%
2015	4	5	44%	56%
2016	10	0	100%	0%
2017	22	1	96%	4%
2018	38	1	97%	3%
2019	-	-	NA	NA
2020	8	0	100%	0%
Overall	119	126		

Since the red traffic signals are more crucial for safety than the green ones, they were analyzed city-wide. Table 7 shows the summary of red traffic lights in Fairbanks and Table 8 shows the same for Anchorage.

Table 7: Summary of Comparison (Fairbanks - Red)

Year	Satisfied	Not Satisfied	% Satisfied	% Not Satisfied
2001	-	-	NA	NA
2002	0	14	0%	100%
2003	-	-	NA	NA
2004	-	-	NA	NA
2005	-	-	NA	NA
2006	-	-	NA	NA
2007	-	-	NA	NA
2008	-	-	NA	NA
2009	-	-	NA	NA
2010	0	3	0%	100%
2011	-	-	NA	NA
2012	-	-	NA	NA
2013	3	0	100%	0%
2014	4	0	100%	0%
2015	3	2	60%	40%
2016	5	0	100%	0%
2017	2	5	29%	71%
2018	26	4	87%	13%
2019	-	-	NA	NA
2020	8	0	100%	0%
Overall	51	28		

Table 8: Summary of Comparison (Anchorage - Red)

Year	Satisfied	Not Satisfied	% Satisfied	% Not Satisfied
2001	0	12	0%	100%
2002	0	4	0%	100%
2003	1	13	7%	93%
2004	0	12	0%	100%
2005	1	6	14%	86%
2006	0	7	0%	100%
2007	4	10	29%	71%
2008	5	7	42%	58%
2009	3	7	30%	70%
2010	11	2	85%	15%
2011	6	0	100%	0%
2012	6	0	100%	0%
2013	9	2	82%	18%
2014	0	4	0%	100%
2015	4	0	100%	0%
2016	5	1	83%	17%
2017	13	3	81%	19%
2018	10	0	100%	0%
2019	-	-	NA	NA
2020	-	-	NA	NA
Overall	78	90		

Detailed Analysis

Tables 5 to 8 show, as expected, that the luminous intensity values deteriorate over time. However, because failure tends to occur over a wide range of years, it is difficult to develop a replacement strategy based on these findings. Therefore, a detailed analysis was required to develop replacement strategies. Here, we followed the process outlined by Long et al. (2011) for the Missouri DOT. In this study, signal heads were measured for variations in color, age, and manufacturer. After calculating the average light intensity vs age of the signal head, the study applied a deterministic regression model to predict average intensity as a linear function of age. The age for replacement was found by determining the intersection of the function with the minimum ITE intensity threshold. After this value was determined, an optimistic and pessimistic replacement age was determined by simply rounding off the value found to the nearest year. The analysis in the current study improved on this process and will be discussed in detail in the following sections.

The various measurements for each individual traffic light were grouped together by the year they were installed and the average luminous intensity of the traffic signals for each year were determined. Because there were different guidelines for the various spot sizes as discussed above, the evaluation of the results had to be completed for each spot size and corresponding vertical angle. The average luminous intensities for traffic signals by age are summarized in Tables 9 through 12. These average intensities were then used to develop a statistical analysis and propose a replacement life.

LUMINOUS INTENSITY FINDINGS

As discussed in the data analysis section, the average luminous intensities for both red and green signals at both 7- and 8-inch spot sizes were calculated and fitted with a simple linear regression model. The values for the 95% confidence interval, ŷ, is given by Equation 2:

$$\hat{y} = y \pm t_{95} SE \sqrt{\frac{1}{n} + \frac{(X - X_m)^2}{SS_{xx}}} \qquad 2$$

Where, y = the luminous intensity given by the linear regression model, $t_{95\%}$ = two-tailed inverse of the student's t-distribution at 95% confidence, SE = standard error, n = the number of values in the data set, X = given signal age, X_m = mean of all signal ages in the data set, and SS_{xx}= sum of the squares of the deviations.

Table 9: Average Luminous Intensity of Red Traffic Signals at a Vertical Angle of -6.04°

Year Installed	Age	Vertical Angle (°)	Avg luminous intensity
2001	19	-6.04	-
2002	18	-6.04	-
2003	17	-6.04	-
2004	16	-6.04	-
2005	15	-6.04	266.86
2006	14	-6.04	244.72
2007	13	-6.04	-
2008	12	-6.04	320.69
2009	11	-6.04	281.13
2010	10	-6.04	517.91
2011	9	-6.04	526.61
2012	8	-6.04	472.94
2013	7	-6.04	398.02
2014	6	-6.04	251.35
2015	5	-6.04	371.39
2016	4	-6.04	418.79
2017	3	-6.04	448.89
2018	2	-6.04	507.29
2019	1	-6.04	-
2020	0	-6.04	555.69

Table 10: Average Luminous Intensity of Red Traffic Signals at a Vertical Angle of -6.91°

Year Installed	Age	Vertical Angle (°)	Avg luminous intensity
2001	19	-6.91	196.09
2002	18	-6.91	156.17
2003	17	-6.91	176.81
2004	16	-6.91	157.42
2005	15	-6.91	-
2006	14	-6.91	-
2007	13	-6.91	229.65
2008	12	-6.91	-
2009	11	-6.91	-
2010	10	-6.91	287.20
2011	9	-6.91	-
2012	8	-6.91	-
2013	7	-6.91	372.54
2014	6	-6.91	400.67
2015	5	-6.91	321.28
2016	4	-6.91	413.63
2017	3	-6.91	325.19
2018	2	-6.91	457.73
2019	1	-6.91	-
2020	0	-6.91	-

Table 11: Average Luminous Intensity of Green Traffic Signals at a Vertical Angle of -5.22°

Year Installed	Age	Vertical Angle (°)	Avg luminous intensity
2001	19	-5.22	286.24
2002	18	-5.22	301.55
2003	17	-5.22	278.98
2004	16	-5.22	272.02
2005	15	-5.22	-
2006	14	-5.22	-
2007	13	-5.22	345.66
2008	12	-5.22	-
2009	11	-5.22	-
2010	10	-5.22	306.16
2011	9	-5.22	-
2012	8	-5.22	-
2013	7	-5.22	473.46
2014	6	-5.22	502.89
2015	5	-5.22	462.36
2016	4	-5.22	586.19
2017	3	-5.22	561.88
2018	2	-5.22	580.13
2019	1	-5.22	-
2020	0	-5.22	-

Table 12: Average Luminous Intensity of Green Traffic Signals at a Vertical Angle of -5.96°

Year Installed	Age	Vertical Angle (°)	Avg luminous intensity
2001	19	-5.96	-
2002	18	-5.96	-
2003	17	-5.96	-
2004	16	-5.96	-
2005	15	-5.96	312.15
2006	14	-5.96	427.75
2007	13	-5.96	-
2008	12	-5.96	393.74
2009	11	-5.96	348.06
2010	10	-5.96	393.08
2011	9	-5.96	457.11
2012	8	-5.96	433.21
2013	7	-5.96	414.78
2014	6	-5.96	354.01
2015	5	-5.96	376.78
2016	4	-5.96	667.79
2017	3	-5.96	741.89
2018	2	-5.96	755.92
2019	1	-5.96	-
2020	0	-5.96	736.64

This process was repeated for both signal colors and spot sizes as seen in Figures 10 to 13.

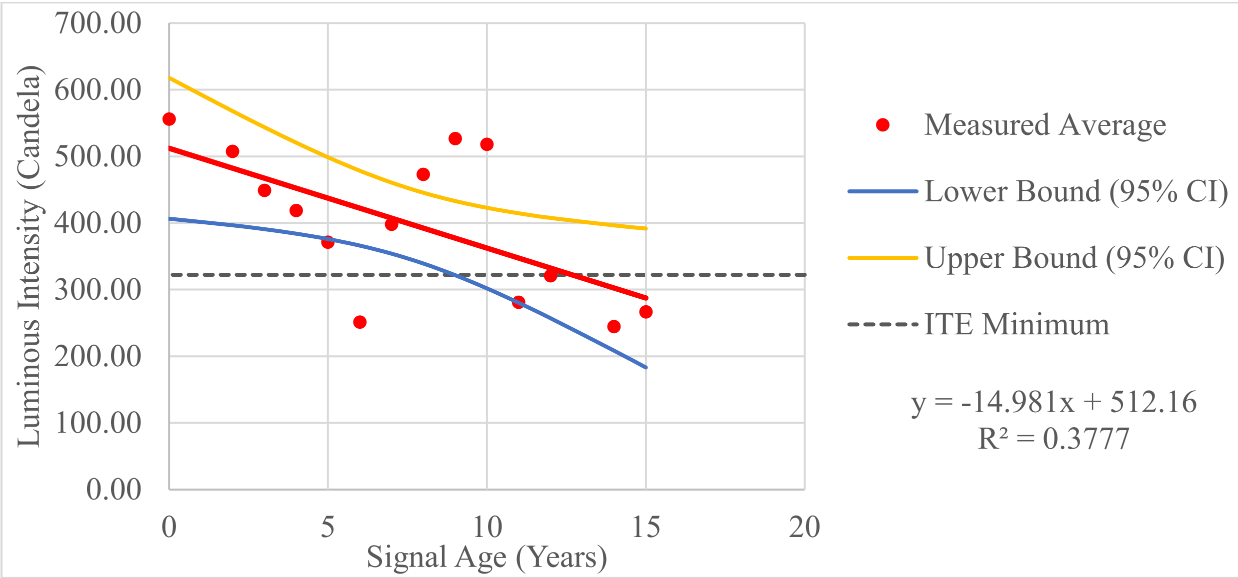


Figure 10. Average luminous intensity of red traffic signals at vertical angle of -6.04°.

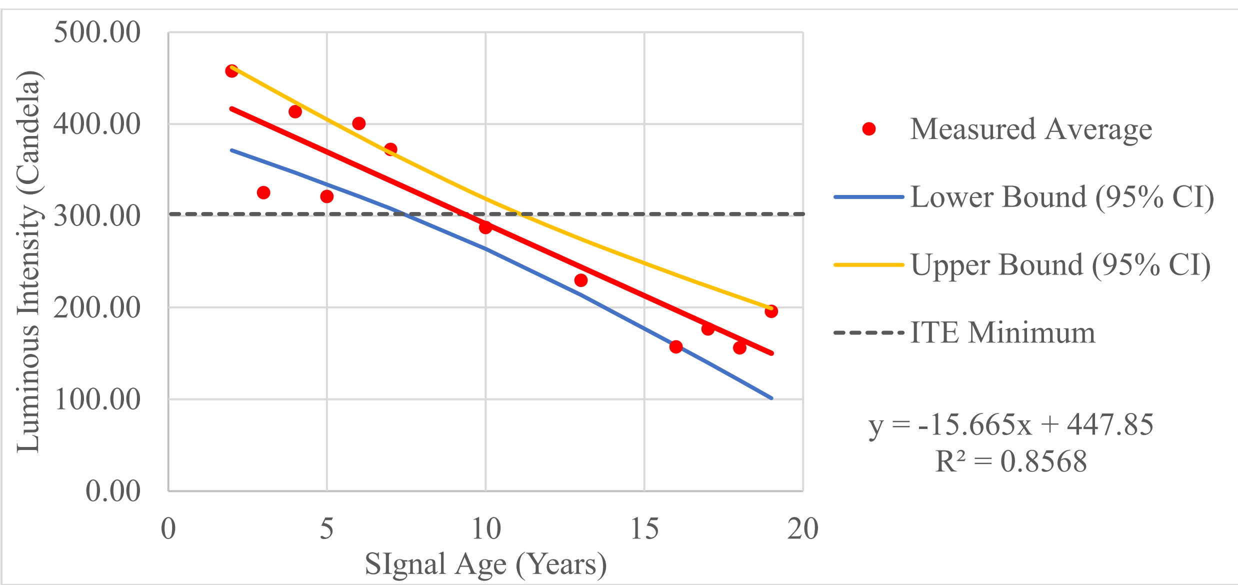


Figure 11. Average luminous intensity of red traffic signals at vertical angle of -6.91°.

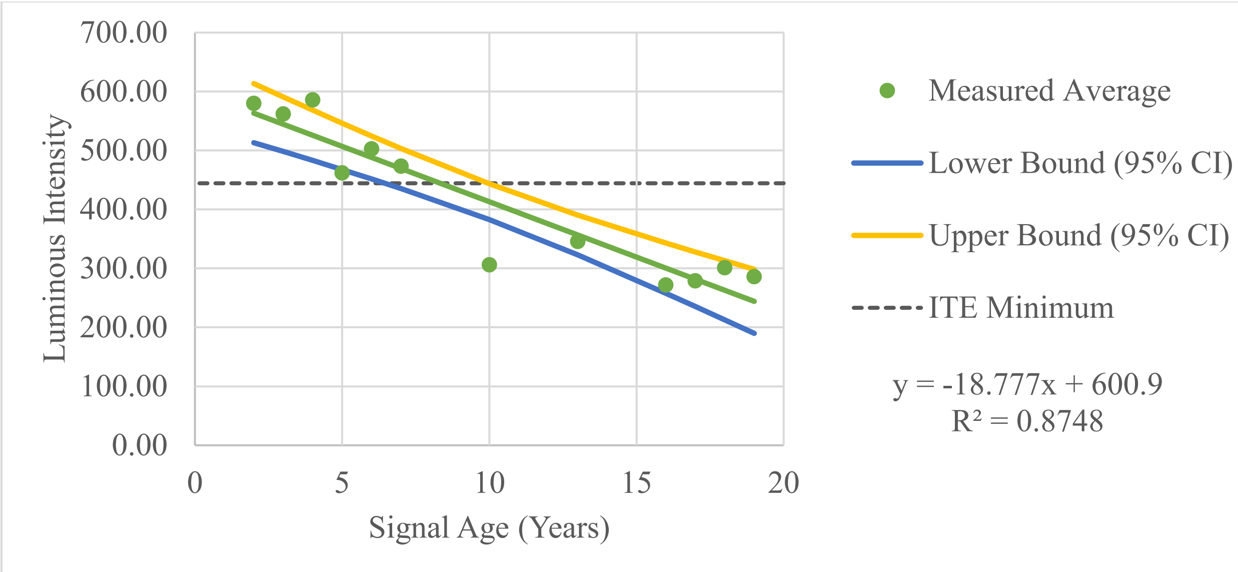


Figure 12. Average luminous intensity of green traffic signals at vertical angle of -5.22°.

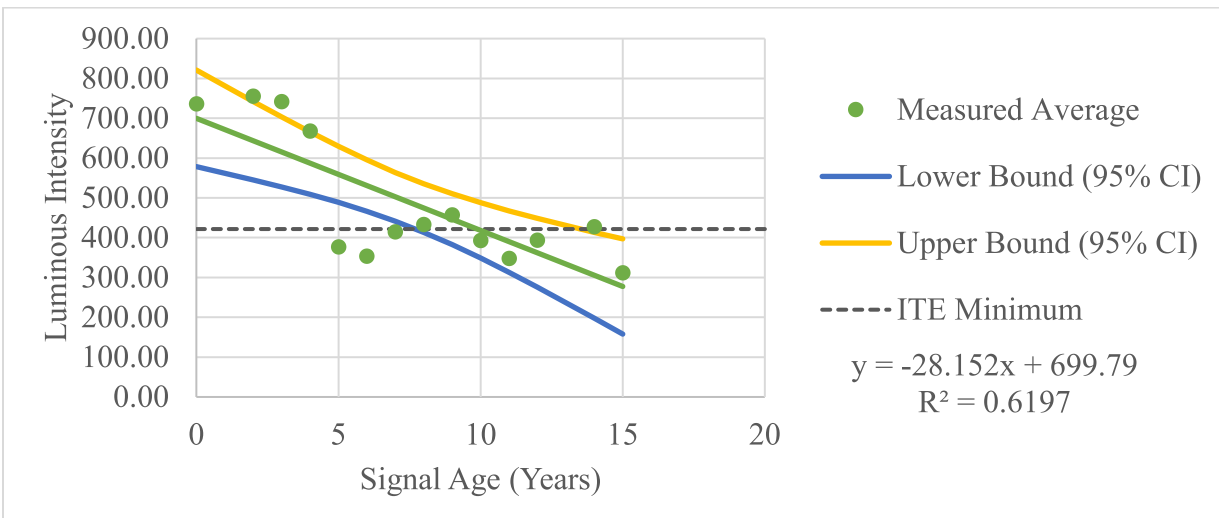


Figure 13. Average luminous intensity of green traffic signals at a vertical angle of -5.96°.

Using the average values as well as the lower and upper bounds of the resulting regression model, the replacement age of the traffic signals are summarized in Table 13. Even though there should theoretically be no difference between the spot size utilized during measurement of luminous intensity and replacement age, there is a difference between the spot sizes for both the red and green signals. This is likely due to the relatively small sample size considering the number of years covered by the study. This is also apparent in the red, 7-inch spot size results as the upper bound for the replacement age could not be found with the available data. At the same time, the average values are close to each other. These results, after rounding off, indicate that the average replacement age for red lights is between 7 and 11 years. For green lights, the replacement age is between 6 and 10 years. It is important to note that replacing all lights at once is economically efficient. Since the performance of red lights are more critical than that of green lights from a safety perspective, we can exclusively use the replacement age for red lights to replace all lights.

Table 13: Replacement Period of Red and Green Traffic Signals

Color	Spot Size (Inch)	Lower Bound (95% CI)	Average	Upper Bound (95% CI)
Red	7	8.97	12.67	-
	8	7.43	9.32	11.08
Green	7	7.72	9.88	13.51
	8	6.47	8.33	9.94

CHROMATICITY FINDINGS

In addition to luminous intensity measurements, the PR-670 also can measure the chromaticity of a light source. Per the ITE specifications, chromaticity is the color of the light emitted by a module, specified by the x and y chromaticity coordinates as graphed on the 1931 Commission Internationale d'Eclairage (CIE) chromaticity diagram as shown in Figure 14.

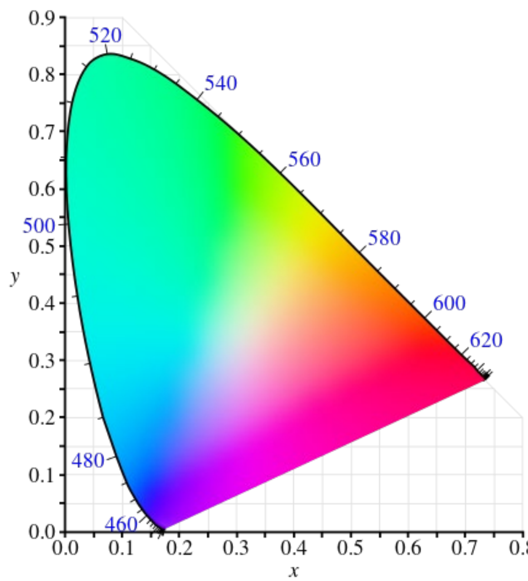


Figure 14. The 1931 CIE color space chromaticity diagram.

The ITE specification states that traffic signals must conform to their respective color regions as identified in the specification. This ensures that the drivers can see the signal and interpret the appropriate message even in low light or adverse weather conditions. Chromaticity is important for there to be uniformity across the nation as well as a clear definition of what red, yellow, and green lights are when it comes to traffic signals.

Using the measured chromaticity values, each signal was plotted against the ITE color region to determine whether the signal satisfied the color requirements. The evaluation of red and green traffic signals is shown in Figures 15 and 16, respectively. As shown in the figures, the red chromaticity values tend to move toward failure in a linear fashion, while the green chromaticity values are more scattered. Additionally, there were several red traffic signals that appeared to be outliers, whereas the green traffic signals did not have outliers, though this could be the result of a fairly small sample size.

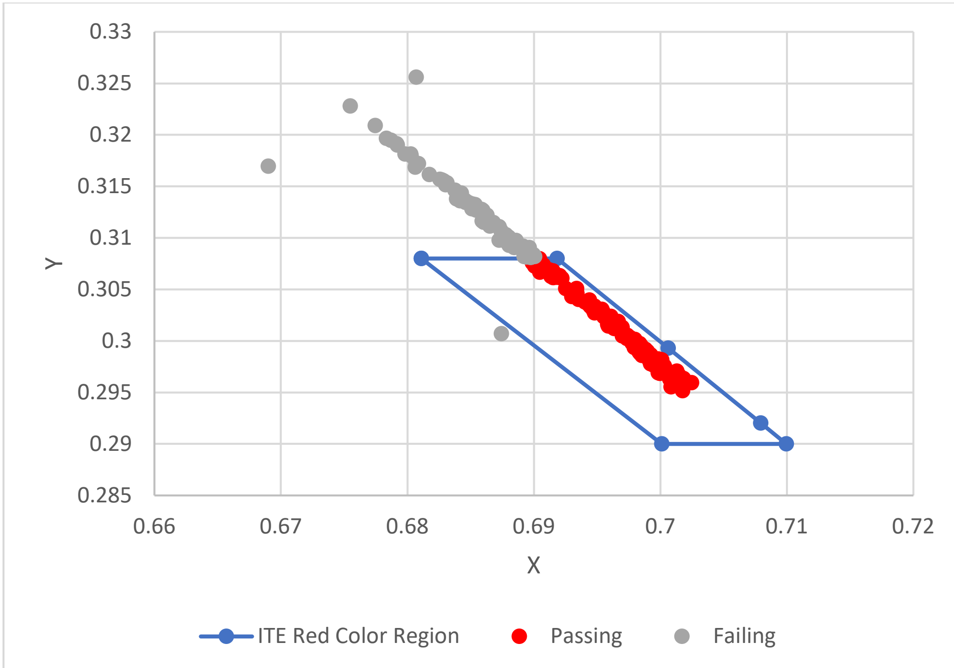


Figure 15. Red traffic signal chromaticity evaluation.

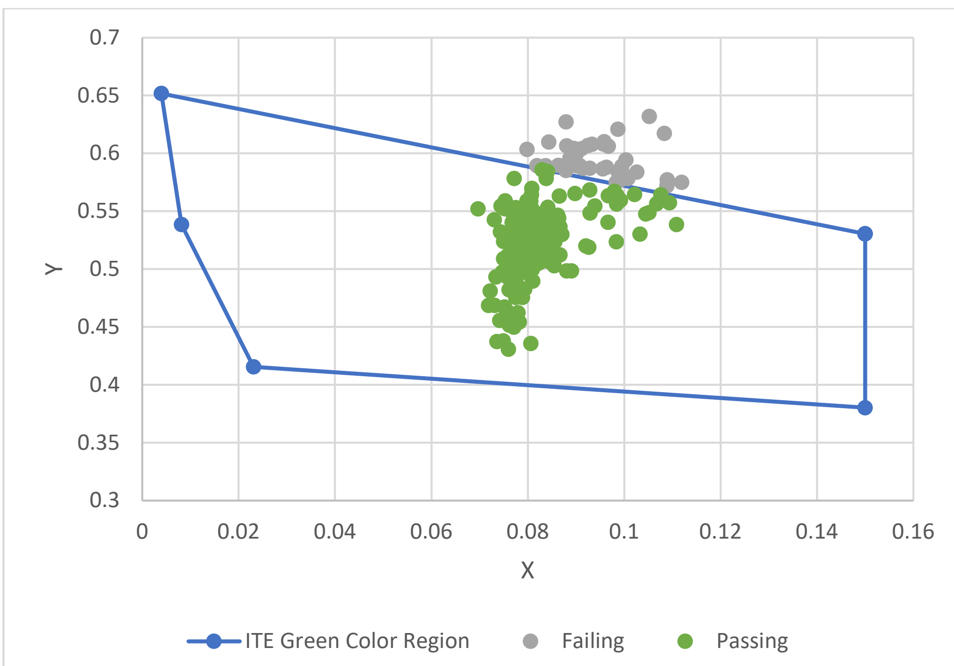


Figure 16. Green traffic signal chromaticity evaluation.

To evaluate the age at which the signals fail, the percent of signals passing for both the green and red traffic signals were plotted against the year they were installed. The resulting plot is shown in Figure 17. Again, the results showed drastic differences between the green and red traffic signals. The green signals appear to follow an expected trend where the new signals had a high passing rate with a decrease in percent passing around the 15-year mark. On the other hand, the red traffic signals appeared to have a low passing rate for new signals with some years having 0% satisfaction and the overall percent passing increasing as time went on. This is not what was expected and appears to show that when the red traffic signals are installed, they do not satisfy ITE guidelines for chromaticity, but as they age, they experience a chromaticity shift that places them within the ITE red color region. The green traffic signals appear to satisfy ITE chromaticity guidelines when they are installed, and then they gradually shift outside of the green color region.

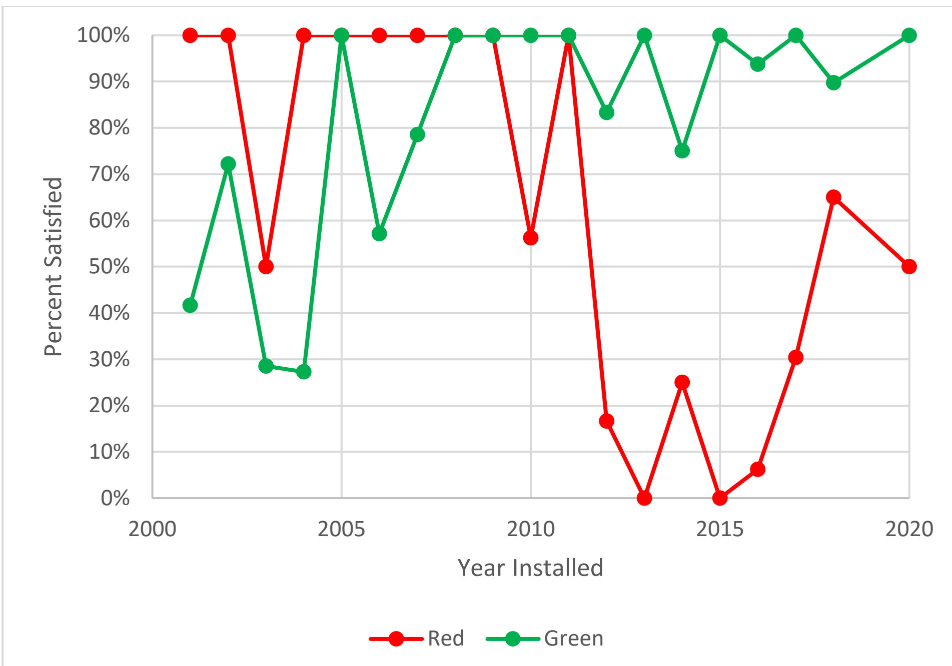


Figure 17. Percent of traffic signals satisfying chromaticity condition by installation year.

To further investigate the trend of red signals moving toward the ITE specs and green signals moving away from the specs, the newest signals (2018-2020) were compared to the oldest signals (2001-2005), as shown in Figures 18 and 19. Again, the red signals displayed a shift towards the ITE color region identified in the specifications whereas the green traffic signals displayed a shift away from the ITE color region.

Because of this seemingly backwards trend for red traffic signals and the inverse relationship between red and green signals, chromaticity is not the best measure for determining when to replace traffic signals. Particularly since red traffic signals are more critical for safety than green signals, the chromaticity measure would encourage premature replacement, which would incur unnecessary expenses.

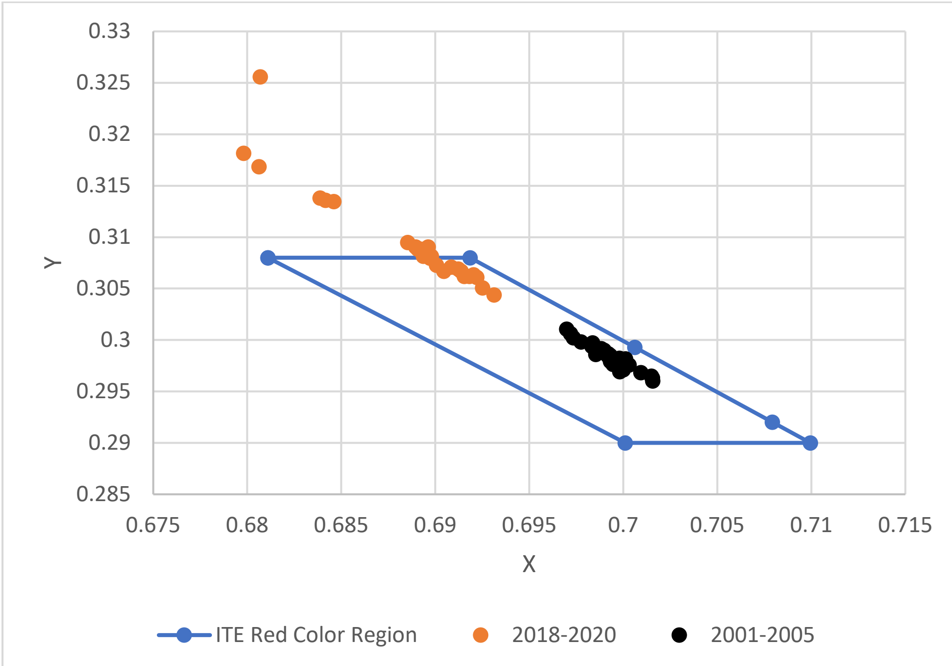


Figure 18. Comparison of “new” and “old” red traffic signals.

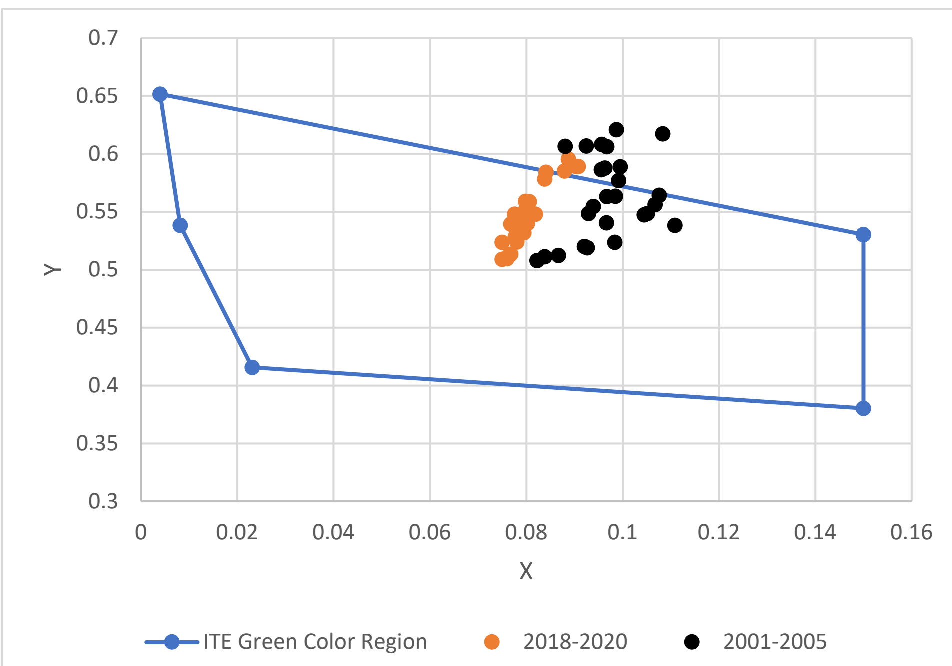


Figure 19. Comparison of “new” and “old” green traffic signals

Correlation Between Luminous Intensity and Chromaticity Failure

To determine the nature of failure of LED traffic signals in Alaska, both the luminance and chromaticity were recorded for several traffic signals across Anchorage and Fairbanks. The lifespan of these traffic signals was proposed in previous sections, but the research also sought to determine whether there was a relationship between failures in luminous intensity and failures in the chromaticity. If the number of signals failing both criteria were high, it may be an indication that the degradation of the LED luminance and chromaticity are connected to one another.

As mentioned in previous sections, the luminous intensity and chromaticity measurements for each of the traffic signals was measured then compared to the ITE guidelines and each signal was designated as “failing both in luminous intensity and chromaticity,” “failing only in luminous intensity,” “failing only in chromaticity,” or “satisfying both criteria.” The results were then tallied for each location separately and also combined to portray the nature of the failures. Tables 14 and 15 show the results for red and green traffic signals, respectively, and Figures 20 and 21 represent these results in a graphical format.

Table 144: Failure Comparison of Red Traffic Signals

Location		Both Failing	Luminous Intensity Fail	Chromaticity Fail	Both Passing
Anchorage	#	17	82	39	29
	%	10.18	49.10	23.35	17.37
Fairbanks	#	11	22	25	21
	%	13.92	27.85	31.65	26.58
Total	#	28	104	64	50
	%	11.38	42.28	26.02	20.33

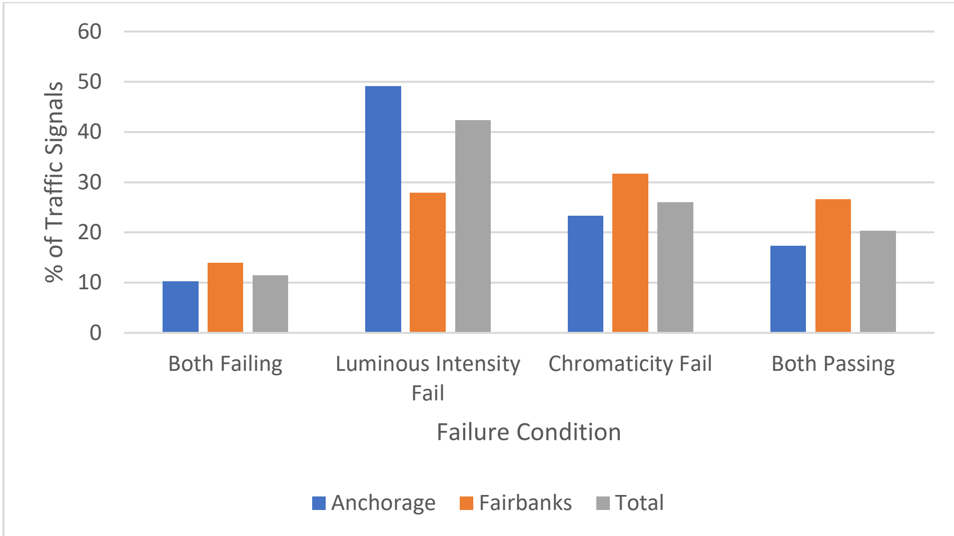


Figure 20. Failure comparison of red traffic signals.

Table 155: Failure Comparison of Green Traffic Signals

Location		Both Failing	Luminous Intensity Fail	Chromaticity Fail	Both Passing
Anchorage	#	27	76	4	54
	%	16.77	47.20	2.48	33.54
Fairbanks	#	4	13	3	57
	%	5.19	16.88	3.90	74.03
Total	#	31	89	7	111
	%	13.03	37.39	2.94	46.64

Ultimately, only about 11.38% of the red traffic signals and 13.03% of the green traffic signals failed both the luminance and chromaticity criteria. The percentage of red signals satisfying both luminous intensity and chromaticity criteria was 20.33%, while it was 46.64% for the green signals. A large percentage of red signals failed only one criterion: 42.28% failed only luminance and 26.02% failed only chromaticity. On the other hand, the percentage of green signals that failed only luminous intensity was 37.39%, and only 2.94% of all green signals failed only chromaticity. This supports the conclusion that the green signals failed mostly in luminous intensity, which could be due to the nature of the chromaticity shift of the LEDs. It is also evident that traffic signals are not often failing both the luminous intensity and chromaticity criteria, which could point to the fact that the two failure mechanisms are not related, and that failure in one criterion does not automatically result in failure of the other criterion.

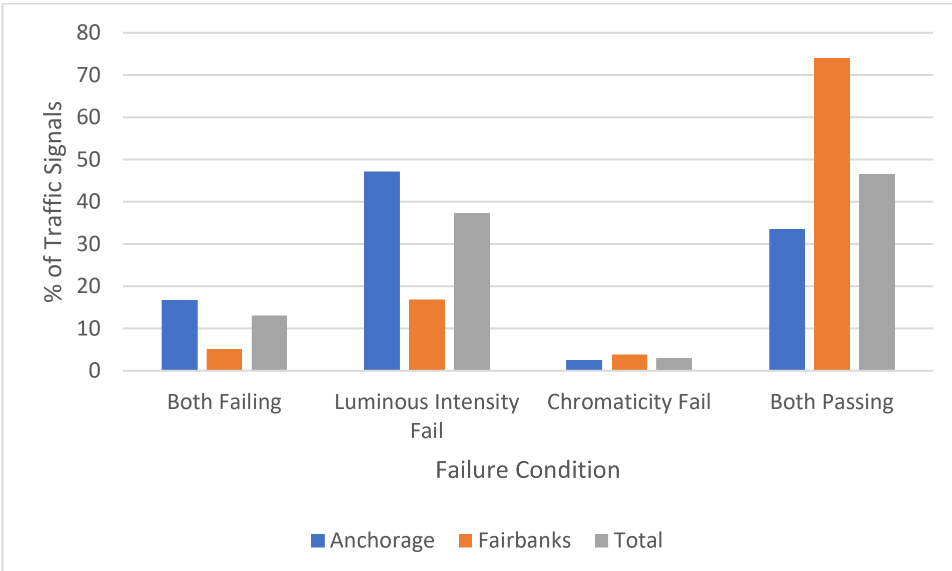


Figure 21. Failure comparison of green traffic signals.

SOME ADDITIONAL ANALYSES

After carrying out the basic analyses, we wanted to test whether the location of the lights (Fairbanks Vs Anchorage) and direction of the signal head (North. South, East, or West) have any influence in the rate of deterioration of performance. We analyzed the luminous intensity data of Anchorage and Fairbanks separately and compared them over time. The same process was carried out to test whether the direction of signal head had any influence on the rate of deterioration. However, the analysis did not show any significant differences in the rate deterioration based on location or direction of the signal head. Appendix A shows the detailed analysis.

Luminance meters like the Jadak PR-670 are effective in measuring the luminance of a given source, but they are also resource intensive, both in terms of cost and the time required to operate them. In some cases, modern digital cameras have been shown to effectively replace luminance meters as a quicker and cheaper alternative. We explored the option to use digital photos to extract luminous intensity and chromaticity. There are numerous methodologies and methods for this process; however, there are also issues, like the high intensity of the LED traffic signals, that may prevent this process in practice. Therefore, additional study is required to determine if digital cameras can be used to measure the luminance of LED traffic signals accurately. Appendix B shows the details of the process.

CONCLUSION

As LEDs continue to replace incandescent bulbs, it is important to modify policies to address these changes. The use of LEDs in traffic signals has concrete benefits, including greater energy efficiency and longer lifespans, but their gradual failure mechanism makes it more difficult to determine an appropriate replacement lifespan that meets the guidelines outlined by ITE. Because the light emitted by LEDs decreases in intensity over time, rather than failing abruptly like an incandescent bulb, LED traffic signals may continue emitting light without meeting the minimum specifications for intensity and color. The objective of this study, therefore, was to determine the lifespan range for LED traffic signals in Alaska. While the primary method in this study of using a luminance meter was effective, it was also resource intensive. Thus, we also explored the effectiveness of using digital cameras to evaluate the luminance and chromaticity of traffic signals, a method which may be more cost-effectively replicated for the continual evaluation and maintenance of traffic signals.

Based on the ITE guidelines for luminous intensity and Chromaticity, 35 intersections in Anchorage and 16 intersections in Fairbanks were analyzed and tested with the goal of recommending a replacement period for LED signals and to determine whether factors like location and direction had an impact on the deterioration of the LEDs. Under the luminous intensity specification, it was found that for red lights, the average replacement time is 9 years with the 95% confidence interval ranging between 7 and 11 years. For green lights, the average replacement time is 8 years with the 95% confidence interval ranging between 6 and 13 years. When looking at chromaticity, the red lights actually improved over time and failure tended to occur in green lights at around the 15 year mark, which is well beyond the replacement period on the grounds of luminous intensity.

When comparing whether luminous intensity and chromaticity failures were related, both criteria were examined concurrently. Ultimately, only about 11.38% of the red traffic signals and 13.03% of the green traffic signals failed both the luminance and chromaticity criteria. The percentage of red signals satisfying both criteria was 20.33%, while 46.64% of green lights met both. A large percentage of red signals failed only one criterion, with the percentage failing only the luminous intensity criterion being 42.28% and failing only the chromaticity criterion being 26.02%. On the other hand, the percentage of green signals that failed only in luminous intensity was 37.39%, and only 2.94% of all green signals failed only in chromaticity. This supports the conclusion that luminous intensity is the primary failure concern for LED traffic signals. Additionally, it does not appear that direction had a significant impact on the deterioration of the traffic signals.

REFERENCES

Behura, N. S. (2007). A survey of maintenance practices of light-emitting diode traffic signals and some recommended guidelines. ITE Journal, Vol.77, No.4.

Bullough, J. D., Snyder, J. D., Smith, A. M., & Klein, T. R. (2009). Replacement Processes for Light Emitting Diode (LED) Traffic Signals. Troy, NY: NCHRP.

Cohn, T. E., Greenhouse, D., & Knowles, R. (1998). Alternative Traffic Signal Illumination Traffic Signal Human Factors Study. Berkeley, California: University of California, Berkeley.

Craine, E., (2008). Preliminary experiments using a digital camera to measure commercial light sources. *International Dark-Sky Association, Inc.*

Digraskar, S. S. (2014). Analysis of Factors Responsible for Life Degradation of LED Traffic Indicators in the State of Missouri. Ann Arbor: UMI.

Elvers US. (2020). Percentage Points of Student's t Distribution.

Esteves, J. (2020, July). Personal Communication. (M. Quinonez, Interviewer)

Finkle, M. (1997). Luminance-to-intensity Measurement Method. Journal of the Illuminating Engineering Society.

Hiscocks, P., (2011). Measuring luminance with a digital camera. *Advanced Test Equipment Rentals.*

Institute of Transportation Engineers. (2005). Vehicle Traffic Control Signal Heads: - Institute of Transportation. Retrieved from Yumpu: https://www.yumpu.com/en/document/view/27283197/vehicle-traffic-control-signal-heads-institute-of-transportation-

Jiang, Z. (2004). Luminous Intensity Measurements for LED Related Traffic Signals and Signs. Tallahassee: Florida State University.

Long, S., Gosavi, A., Qin, R., & Noll, C. (2012). Evaluating Useful Life and Developing Replacement Schedules for LED Traffic Signals: Statistical Methodology and a Field Study. Engineering Management Journal, 15-23.

Long, S., Qin, R., Gosavi, A., & Wu:, C. (2011). Life Expectancy Evaluation and Development of a Replacement Schedule for LED Traffice Signals. Missouri University of Science and Technology.

Noble, D.E. (2009). LED Maintenance Strategies: Lessons from Professional Practice and Recent Research, in ITE Technical Conference, Phoenix, Arizona.

Noll, C. (2011). Life Expectancy Evaluation and Replacement Schedule Development for LED Traffic Signals. Rolla, USA: Missouri University of Science and Technology.

Photo Research. (2016). PR-655, PR-670, PR-680 and PR-680L Spectra Scan Spectroradiometers. North Syracuse, New York.

Rea, M. (2000). IESNA lighting Handbook: reference and application, 9th. New York, New York: Illuminating Engineering Society of North America.

Suozzo, M. (1999). Case Studies of Successful LED Traffic Signal Installations and Documentation of a Three-Color Signal Demonstration, American Council for an Energy-Efficient Economy, Washington D.C.

Urbanik, T. (2008), LED Traffic Signal Monitoring, Maintenance, and Replacement Issues. A Synthesis of Highway Practice, Transportation Research Board, Washington, DC, NCHRP Synthesis 387.

U.S. Department of Energy, Office of Energy Efficiency & Renewable Resources. Lumen and Chromaticity Maintenance Behavior of Light-Emitting Diode (LED) Packages Based on LM-80 Data (2020).

Singh, P., & Tan, C. M. (2016). Degradation physics of high power leds in outdoor environment and the role of phosphor in the degradation process. *Scientific Reports*, *6*(1). https://doi.org/10.1038/srep24052

Wachtel, J. (2014). Report on Digital Sign Brightness. Bereley: The Veridian Group, Inc.

Wüller, D., & Gabele, H. (2007). The usage of digital cameras as luminance meters. *Digital Photography III*. https://doi.org/10.1117/12.703205

APPENDIX A

FAILURE COMPARISON AND IMPACTS OF TRAFFIC LIGHT DIRECTION AND LOCATION

One of the major benefits of LEDs is the way in which they fail. Compared to incandescent bulbs which fail catastrophically when the interior filament breaks or burns out, LEDs degrade gradually and grow dimmer over time. As discussed in the previous section, LEDs also experience gradual chromaticity shifts. Both factors matter when determining the performance of LED bulbs.

An LED is a type of semiconductor device that emits light when an electric current passes through it. The color of the light emitted by the LED is controlled by the material of the semiconductor. Different semiconductor materials produce different wavelengths, and, as a result, different colors. The main semiconductor materials used to make LEDs and the colors they produce are presented in Table 14.

Table 166: LED Semiconductor Materials

Semiconductor Material	**LED Type**
Indium Gallium Nitride (InGaN)	Blue, green, and ultraviolet high-brightness LEDs
Aluminum Gallium Indium Phosphide (AlGaInP)	Yellow, orange, and red high-brightness LEDs
Aluminum Gallium Arsenide (AlGaAs)	Red and infrared LEDs
Gallium phosphide (GaP)	Yellow and green LEDs

The differences in semiconductor materials used to produce various LED colors also impact the performance of LEDs. One of the most important performance differences is the varying degradation mechanisms and rates of different LED colors. Singh and Tan (2016) found that the degradation mechanisms of blue LEDs (those without phosphor) and white LEDs (those with phosphor) were different under both powered and unpowered conditions. The differences in the coefficient of thermal expansion between the material as well as the heat generated by the phosphor layer were found to account for most of the difference in the degradation mechanisms observed.

The United States Department of Energy (DOE, 2020) published research showing the results of analysis of LM-80 testing datasets of 223 separate packaged LEDs to determine component behavior over time in regard to lumen maintenance and chromaticity shift. The research considered four different LED types including mid-power, high-power, chip-on-board (COB), and chip-scale package (CSP). Ultimately, the analysis revealed relatively predictable luminance degradation for all LED types, but vastly different chromaticity shift patterns. It was found that mid-power LEDs tend to shift toward the blue color region and high-power LEDs shift toward the yellow color region, while COB and CSP LEDs shifted in a variety of directions depending on the manufacturer.

Effects of Location and Direction on Deterioration

The traffic signals were organized by location and direction and were sorted based on whether they had not failed any criteria, failed only the chromaticity criteria, failed only the luminous intensity criteria, or had failed both criteria. The results of this analysis are shown in Table 17 for all red traffic signals and in Table 18 for all green traffic signals. The results show that each location had similar trends in failures but had different rates of failures. This is likely because the traffic signals sampled were all a certain age and the traffic signals in Fairbanks were installed, on average, more recently than the traffic signals in Anchorage. The passing rates for the Fairbanks traffic signals were higher than the Anchorage traffic signals for both red and green lights.

To determine whether the location played a role in the deterioration rate of the signals, the age of the signals had to considered. The average luminous intensity of the traffic signals was plotted against the signal age and the results are shown in Figure 22 for red traffic signals and an 8-inch measurement spot size and in Figure 23 for green traffic signals and an 8-inch measurement spot size. As shown in the figures, the slope of the best fit line could be described as a measure of the deterioration rate and the slopes are similar in both cases. Unfortunately, there was not a sufficient number of data points from Fairbanks to compare the 7-inch spot size measurements for the red and green traffic signals but the measurements of the 8-inch spot sizes provide a general trend for the signals.

Table 17: Location and Direction Failure Comparison for Red Traffic Signals

Location/Direction			Both Failing	Luminous Intensity Fail	Chromaticity Fail	Both Passing
Anchorage	E	#	5	21	13	5
		%	11.36	47.73	29.55	11.36
	N	#	3	21	6	14
		%	6.82	47.73	13.64	31.82
	S	#	2	22	9	8
		%	4.88	53.66	21.95	19.51
	W	#	7	18	11	2
		%	18.42	47.37	28.95	5.26
Fairbanks	E	#	1	5	12	3
		%	4.76	23.81	57.14	14.29
	N	#	3	5	7	6
		%	14.29	23.81	33.33	28.57
	S	#	3	6	4	4
		%	17.65	35.29	23.53	23.53
	W	#	4	6	2	8
		%	20.00	30.00	10.00	40.00

Table 18: Location and Direction Failure Comparison for Green Traffic Signals

Location/Direction			Both Failing	Luminous Intensity Fail	Chromaticity Fail	Both Passing
Anchorage	E	#	8	22	0	12
		%	19.05	52.38	0.00	28.57
	N	#	9	15	1	17
		%	21.43	35.71	2.38	40.48
	S	#	5	21	3	11
		%	12.50	52.50	7.50	27.50
	W	#	5	18	0	14
		%	13.51	48.65	0.00	37.84
Fairbanks	E	#	0	3	2	16
		%	0.00	14.29	9.52	76.19
	N	#	0	4	0	17
		%	0.00	19.05	0.00	80.95
	S	#	4	2	0	10
		%	25.00	12.50	0.00	62.50
	W	#	0	4	1	14
		%	0.00	21.05	5.26	73.68

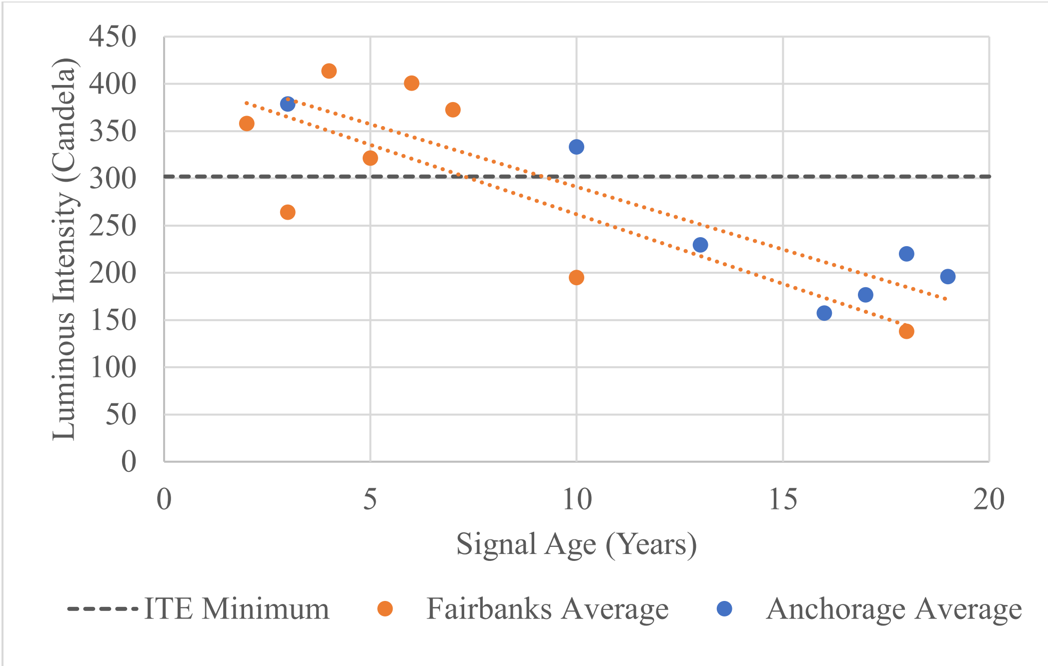


Figure 22. Location-based luminous intensity deterioration comparison for red traffic signals and 8-inch measurement spot size.

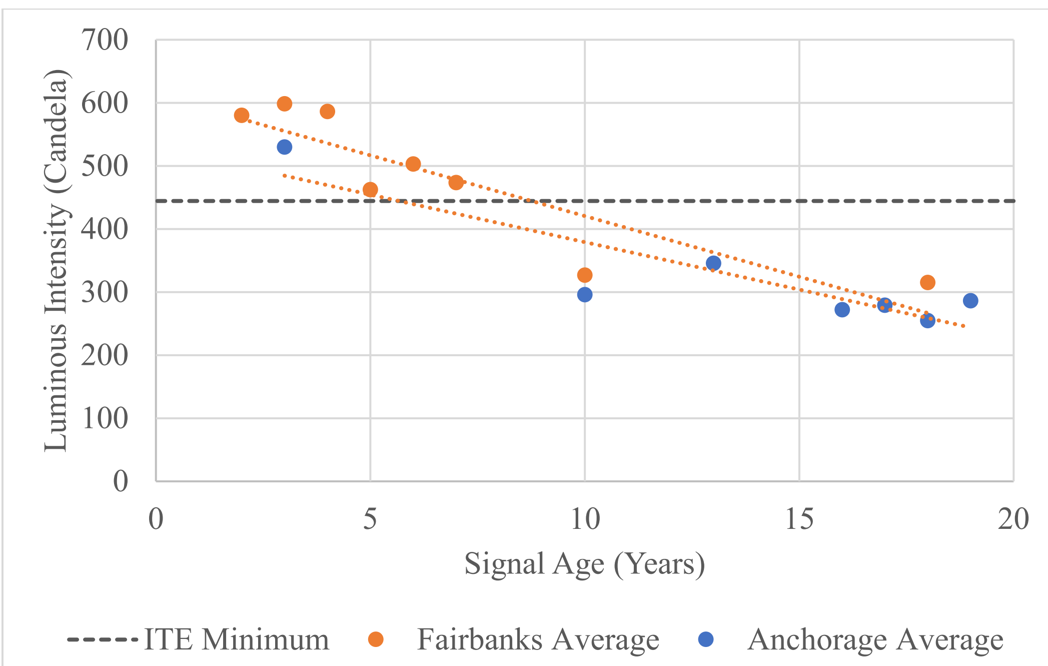


Figure 23. Location-based luminous intensity deterioration comparison for green traffic signals and 8-inch measurement spot size.

To test the slopes, Equation 3 was used to determine the range of the slopes at 95% confidence. The value of t depends on the confidence, degrees of freedom, and whether the test was one or two-tailed. The Anchorage slopes were tested against the Fairbanks slopes and the results demonstrate that the hypothesis that the Anchorage and Fairbanks slopes were not different could not be rejected at 95% confidence, as shown in Table 19.

$$m \pm t_{95\%} SE_m \qquad (3)$$

Where m=slope, $t_{95\%}$=value from the t distribution, and SEm=standard error of m.

Table 19: Statistical Evaluation of Location Based Luminous Intensity Deterioration

Light	Anchorage Slope	Lower Bound, 95% CI	Upper Bound, 95% CI	Fairbanks Slope
Red	-13.26	-20.11	-6.41	-14.72
Green	-15.04	-23.44	-6.65	-19.23

Additionally, an analysis was conducted to determine whether the direction of the traffic signal influenced the deterioration of the signal. For this, the luminance data were sorted by the direction they faced, north, east, south, and west, and these measurements were plotted against the signal age. These plots are shown in Figures 24 and 25 for red and green traffic signals, respectively. It was hypothesized that the northbound slope would be greater than the other directions, signifying a greater deterioration rate due to the prolonged exposure to sunlight experienced by the traffic signals. Similar to the location analysis, the slopes of the best-fit lines were compared to determine approximate deterioration rates. Again, Equation 3 was used to test the hypothesis that the northbound deterioration slope was greater than the other directions. The results are shown in Table 20. For the red traffic signals, the hypothesis can be rejected at 95% confidence since all the slopes fall within the confidence interval. For the green traffic signals, the hypothesis can be rejected for all but the westbound slope, direction does not appear to have a significant impact on the deterioration of the signals.

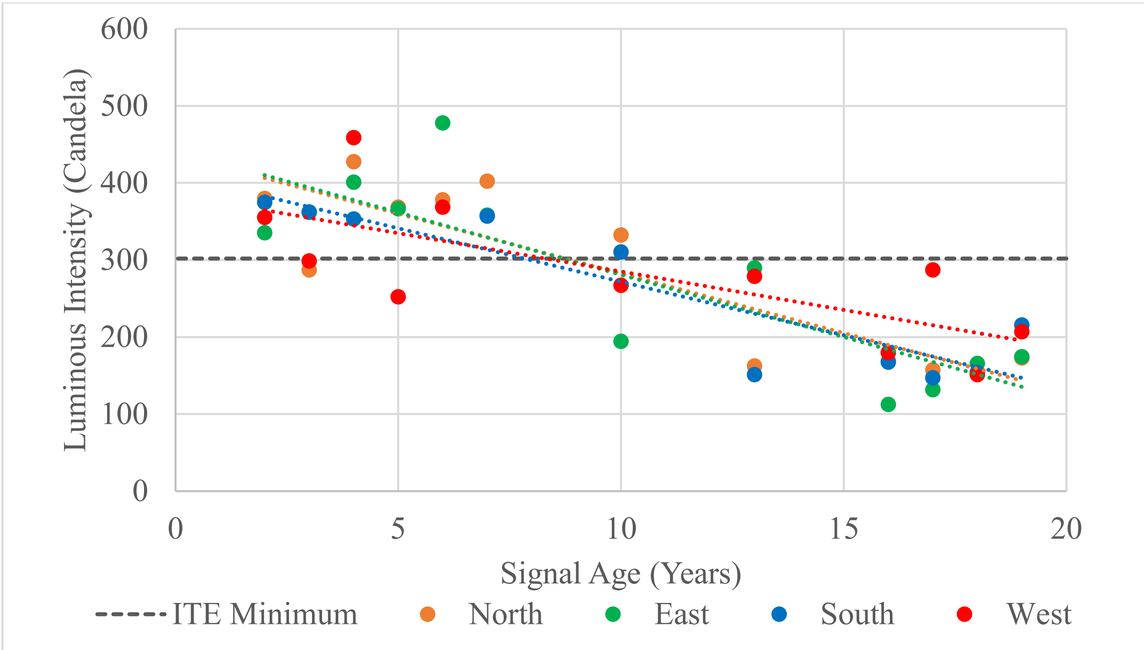


Figure 24. Direction-based luminance deterioration comparison of red traffic signals and 8-inch measurement spot size.

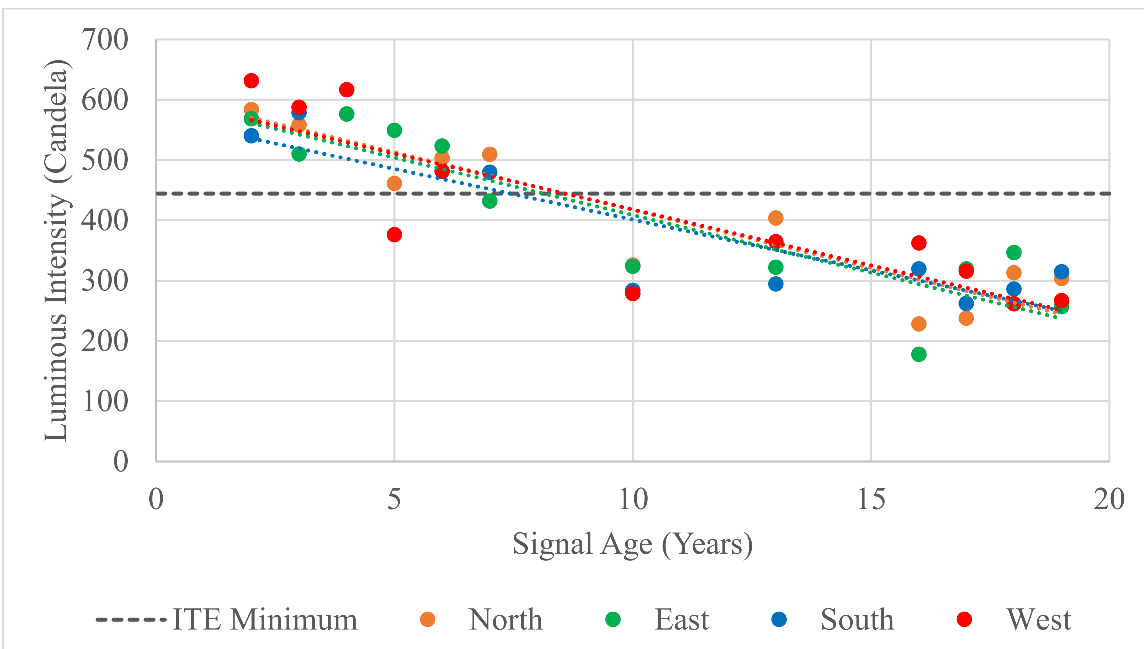


Figure 25. Direction-based luminance deterioration comparison of green traffic signals and 8-inch measurement spot size.

Table 20: Statistical Evaluation of Direction Based Luminous Intensity Deterioration

Light	NB Slope	95% Confidence Interval	EB Slope	SB Slope	WB Slope
Red	-15.48	-∞ to -10.75	-16.16	-13.87	-9.96
Green	-19.19	-∞ to -14.5	-19.08	-16.82	-18.54

APPENDIX B

MEASURING LUMINANCE WITH A DIGITAL CAMERA

Luminance meters like the Jadak PR-670 are effective in measuring the luminance of a given source, but they are also resource intensive, both in terms of cost and the time required to operate them. In some cases, modern digital cameras have been shown to effectively replace luminance meters as a quicker and cheaper alternative.

According to Hiscocks (2011), there are some significant benefits to using a digital camera for measuring luminance. For one, a digital camera can capture an entire scene, including multiple light sources in a single photograph, which greatly reduces the number of measurements. Second, the surroundings are also recorded, which puts the measurement into context. Lastly, for luminance measurements, the field of view of the sensor must be smaller than the source, and the field of view of a typical luminance meter is 1° whereas the field of view of a digital camera is on the order of 150 times smaller. As a result, a digital camera can measure small area light sources or can be used to measure from a much greater distance than would be possible with a luminance meter.

Numerous studies have demonstrated the validity of using a digital camera as a measuring tool. Craine (2008) found that it was possible to use a digital single-lens reflex (DSLR) camera to accurately measure the luminance levels of light sources as long as the calibrations of the camera at the specific exposure are known and that the images are neither under exposed nor saturated. Additionally, families of calibration curves must be made for each light source to camera distance for which photographs are to be taken and must also take into account the field of view of the calibrating luminance meter. Ultimately, the results showed that it was possible to calculate luminance of a light source with 10% or less error using calibrated DSLR photographs. However, the results also showed that at high luminance levels, the camera will saturate regardless of exposure settings which will not give an accurate measure of the luminance.

Wüller and Gabele (2007) analyzed whether it was possible to measure luminance with digital still cameras (DSCs). The cameras were calibrated according to the standard for the determination of the opto-electric conversion function (OECF), which assigned digital output values to different input luminance values. Then images were analyzed to determine the luminance of the light source. The resulting luminance values of the cameras were compared with the measured values of the luminance meters. The difference in the two values depended on the camera and whether or not the image was colored or monochrome. In some cases, when measuring colored objects, the error was found to be over 30%. Ultimately the study concluded that digital cameras are not exact luminance measuring instruments, however, there are many applications where the luminance results of a digital camera could be sufficient.

A guide detailing the process of measuring luminance with a digital camera was also reviewed by Hiscocks (2011). In this guide, the selection of the luminance standard, camera calibration, and interpretation of image data are presented for the measurement of the luminance of an LED array. The guide presented Equation 1, which could be used to relate the digital number of a selected pixel in a photograph to the luminance and specific specifications of the camera the photo was taken on.

$$N_d = K_c \left(\frac{t\,S}{f_s^2} \right) L_s \qquad 3$$

Where N_d = Digital number (value) of the pixel in the image, K_c = Calibration constant for the camera, t = Exposure time in seconds, f_s = Aperture number (f-stop), S = ISO sensitivity, L_s = Luminance of the scene in candela/m^2

Hiscocks (2011) stated:

> "In theory, to calibrate the camera one photographs a known luminance, plugs values for luminance, exposure time, film speed and aperture setting into equation 4, and calculates the calibration constant Kc.
>
> It should then be possible to use the camera at other settings of exposure time, film speed and aperture setting. One determines the pixel value in the image and then runs equation 4 in the other direction to calculate an unknown luminance."

To test this procedure and evaluate whether digital cameras could be used to measure the luminance of LED traffic signals, photographs were taken of each traffic signal that was measured by the luminance meter, and the relevant photograph specifications and measured traffic signal luminance values were used to determine the camera calibration constant. The images taken during the study were then analyzed in *ImageJ* to determine the digital number or pixel number, as shown in Figure 26.

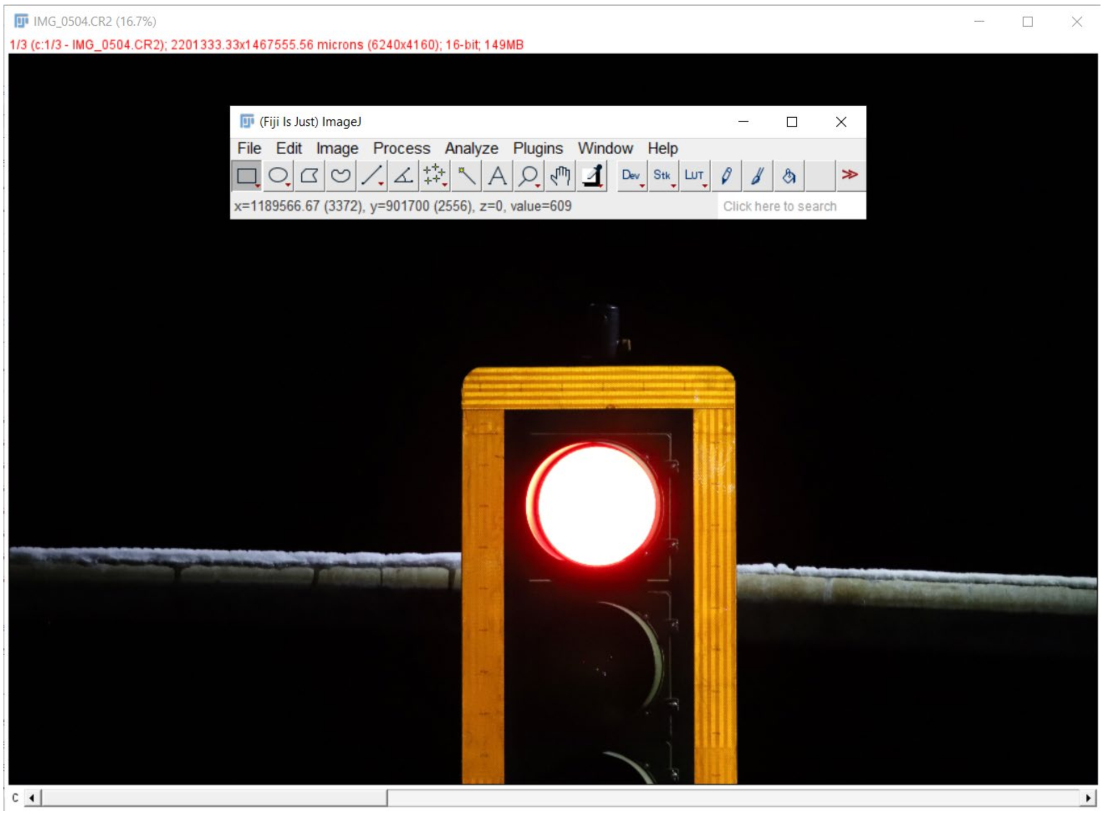


Figure 26. Using ImageJ to determine the pixel value of the traffic signal.

Using the luminance values measured by the luminance meter and the process outlined in Hiscocks (2011), the calibration constant of the camera was evaluated using Equation 3 and the results are shown in Table 21.

Table 21: Determination of the Camera Calibration Constant

Image	Traffic Light	Digital Number, N_d	Calibration Constant, K_c	Exposure Time, t	Aperture Number, f_s	ISO Sensitivity, S	Luminance of the Scene, L_s
IMG_0504	FAA_E Red	609	0.1418	1/320	6.3	12800	4258.6
IMG_0504 Monochr.	FAA_E Red	255	0.0594	1/320	6.3	12800	4258.6
IMG_0503	FAA_E Red	609	0.2837	1/5	6.3	100	4258.6
IMG_0500	FAA_E Green	609	0.2240	1/500	6.3	4000	13484
IMG_0499	FAA_E Green	609	0.1792	1/10	6.3	100	13484
IMG_0507	FAA_N Red	609	0.2780	1/4	6.3	100	3477.4
IMG_0508	FAA_N Red	609	0.4344	1/500	6.3	8000	3477.4
IMG_0510	FAA_N Green	609	0.2501	1/10	6.3	100	9661
IMG_0511	FAA_N Green	609	0.1250	1/500	6.3	10000	9661
IMG_0490	FAA_S Red	609	0.2028	1/4	6.3	100	4767.4
IMG_0491	FAA_S Red	609	0.3219	1/500	7.1	10000	4767.4
IMG_0493	FAA_S Green	609	0.3473	1/13	6.3	100	9047
IMG_0494	FAA_S Green	609	0.3339	1/500	6.3	4000	9047
IMG_0517	FAA_W Red	609	0.1176	1/2	6.3	100	4108.6
IMG_0518	FAA_W Red	609	0.3736	1/500	7.1	10000	4108.6
IMG_0519	FAA_W Green	609	0.1266	1/6	6.3	100	11452
IMG_0520	FAA_W Green	609	0.1319	1/500	6.3	8000	11452

The digital number, N_d, was obtained from the ImageJ program by measuring in the center of the traffic light. The exposure time, aperture number, and ISO were given in the photograph. The luminance value was the reading obtained with the luminance meter. Using these values, the camera calibration constant was obtained. As shown in Table 21, the digital number for all photographs analyzed was 609, except for the monochrome photograph. This may have been the result of an over saturated photograph as mentioned by Craine (2008). The calibration constant of the camera ranged from a low of .0594 to a high of .4344 for the various exposures, aperture numbers, and ISO sensitivities. The camera photograph settings aside from aperture number were not kept constant as initially believed which likely impacted the range of the camera calibration constant.

The use of digital cameras to measure the luminance of LED traffic signals would help save both time and resources in the evaluation of traffic signal luminance per the ITE specifications. The review of the existing literature showed that the measurement of luminance from light sources is indeed possible using a digital camera. There are numerous methodologies and methods for this process; however, there are also issues, like the high intensity of the LED traffic signals, that may prevent this process in practice. Ultimately, additional study is required to determine if digital cameras can be used to measure the luminance of LED traffic signals accurately.