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Longitudinal Useful Life Analysis and Replacement Strategies for LED Traffic Indicators

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<tr><td colspan="5">16. Abstract: The application of Light Emitting Diode (LED) lighting systems has experienced significant growth in the transportation sector over the past 10 years. LED indication lifespans have significantly greater durations than previous technologies, however, uncertainties in the duration of LED devices have unearthed challenges in developing a replacement schedule of LED traffic indications. This research evaluates two methods to approximate the useful life of LED traffic indicators. Previous research in LED indications used a lateral regression analysis to determine the lifetime of LED indications. A new methodology is used to incorporate longitudinal regression analysis as well as account for additional factors outside previous research methods. The findings of this report compare the results using the new methodology against previous research recommendations. A discussion on the impact of the updated results on transportation agencies' policies is also included. Findings indicate that useful life of the majority of LED indications is approximately two years longer than previously estimated.</td></tr>
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Executive Summary

The goal of this study is to recommend a replacement schedule of LED traffic indications to departments of transportation based on a longitudinal statistical analysis. Two main factors affect the recommended replacement schedule: the illuminance of the traffic signal indication when compared to ITE standards and the degradation rate of the illuminance output. The report details the data collection technique and methodology for this research. A comparison to a previous MoDOT project (TRyy1001) is included. Signal indication degradation rates are analyzed through a latitudinal (cross sectional) and longitudinal (time-varying) analysis. Finally, the lifetime estimates are calculated based on the combination of the previously calculated degradation rates and the recommended purchase specifications provided by the Institute of Transportation Engineers (ITE). Table 1 provides a comparison of estimated lifetime results between the previous MoDOT study (TRyy1001) and this study.

Table 1 – Estimated Lifetime Comparison Across MoDOT Traffic Signal Studies

Manufacturer	**Indication Type**	**Lifetime (years)**		
		2014 Study	**2011 Study**	**Useful Life Gain**
Dialight	Green Arrow	14.17	8.95	5.22
Dialight	Green Circular	***	8.45	***
Dialight	Red Circular	17.61	***	***
Dialight	Yellow Arrow	12.77	6.09	6.68
GE	Green Circular	6.63	4.61	2.02
GE	Green Arrow	9.79	7.63	2.16
GE	Yellow Arrow	7.45	5.85	1.60
GE	Yellow Circular	2.67	***	***
LTEK	Yellow Circular	5.06	***	***

Due to varying estimated lifetimes across both indication shape (arrow, circular) and manufacturer (GE, Dialight), the recommended replacement schedule separated these two variables. Table 2 provides the recommended replacement schedule cycle time based on these manufacturer and indication shape.

Table 2 – Recommended Replacement Schedule Cycle

Replacement Schedule Cycle		
	Dialight	**GE**
Arrow	13 years	9 years
Circular	9 years	7 year

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1.0 Introduction

The purpose of this study is to expand on previous findings from the MoDOT research project entitled Life Expectancy Evaluation and Development of a Replacement Schedule for LED Traffic Signals (MoDOT TRyy1001), which was completed in March 2011. This research seeks to expand on the findings of the previous report by providing an expanded and updated literature review, including data from over 5,000 observations, a much more robust statistical analysis, and updated traffic signal lifetime estimates.

1.1 Literature Review

1.1.1 Background of LEDs

In recent years, LED technology has replaced the incandescent lamps in the traffic signal indications due to greater product lifetimes and reduction in energy consumption. LED traffic indications were first introduced in early years of 1960's. Initially only red color LEDs had sufficient quality and performance outputs to be considered as a replacement for traditional lighting technologies. Later, companies such as Hewlett-Packard, Cree, Siemens, Toshiba, and Nichia made advances to improve efficiency in green, yellow, and blue color LEDs as well.

National Cooperative Highway Research Program (NCHRP) Project 05- 12 was the first major study to explore the feasibility and implementation of LED technology for use in traffic indications. The study objectives were to determine whether LED traffic indications met the applicable standards for color and intensity without adversely affecting the safety and operation of the roadways. Project results demonstrated that circular LED traffic indications, red arrow LED traffic indications, and orange pedestrian signals returned similar luminance output as incandescent signals [1]. Of greater note, the study detailed economic benefit. This led many DOT agencies to introduce LED technology into traffic signaling systems. The study did not detail a mechanism for determining useful life outside of laboratory conditions.

1.1.2 Drawbacks of LEDs:

There are many inherent drawbacks with LED traffic indications. The most critical is that they degrade over time instead of displaying catastrophic failure. Therefore, the degradation of LED signal indications must be evaluated through a regular maintenance and replacement strategy. The LED degradation usually occurs because of the abrasion of UV stabilized polycarbonate which gives protection from the sun rays, etc. The typical abrasion estimate of this polycarbonate is about 60 months of exposure in strong sunlight [2].

1.1.3 Standards Used For Purchase of LEDs:

In 1998 Institute of Transportation Engineers (ITE) released an LED traffic indication purchase specification Vehicle Traffic Control Signal Head part 2 (VTCSH part 2) to meet the needs of public agencies in their expansion of LEDs into traffic signaling systems. In 2005, ITE replaced the VTCSH part 2 with the name VTCSH –LED as a performance specification. VTCSH-LED is a standard for the public agencies stating all the specifications as a minimum performance specification or alternative requirements based on an engineering study. [5, 6] These standards were written considering the unique properties of LEDs and incorporated testing and performance requirements to ensure the overall safe performance of LED products.

1.1.4 Current MoDOT Traffic Signal Replacement Strategy:

Previous studies conducted in other states have measured intensity readings for individual signal heads only by color, rather than color, age, and manufacturer. In addition, these studies took readings either in a laboratory setting or at the signal head. The results from previous studies failed to determine detailed replacement guidelines that include recommendations based on:

1. Signal head intensity and ITE threshold compliance from the driver's perspective.
2. Differences by color, indicator type, and manufacturer.
3. Economic cost-benefit analysis of replacement of individual signal sections versus entire heads.

These studies recommended generic replacement schedules based largely on manufacturer warranty, typically five years plus one.

In 2010 a research team from Missouri University of Science and Technology conducted a study to provide a repeatable methodology that can be used by the Missouri Department of Transportation (MoDOT) and other DOTs to evaluate the life expectancy of LED traffic indications based on the realities of traffic flow, intersection geometrics in Missouri and the basic science of LED components, as well as provide guidelines for cost-effective replacement plans based on these findings [10]. The study used a combination of field testing and statistical analysis. Specifically, the project included:

1. An evaluation of the impact of the following variables: manufacturer, indicator type, color and directional view on the degradation of LED traffic signals.
2. The development of a comprehensive replacement plan for the LEDs based on the data collected.

Although the study findings did not recommend any one manufacturer over another, cross-sectional results suggest that useful life of LED signal indications meets or exceeds useful life warranty expectations for most indicator types and manufacturers. Pending longitudinal evaluation, the study recommended an implementation strategy that replaces circular green and green arrow indicators at approximately eight years of age. The study results suggested that the circular red indicators hover below the ITE threshold for a lengthy period following a rapid drop-off after installation. Based on limited observed degradation patterns, the study suggested that circular red signal indicators should be evaluated when circular green and green arrow indicators are replaced. If the luminous intensity continues to hover near threshold, the study suggested replacement at the ten year mark. If the intensity reading is significantly below ITE threshold, it should be replaced with circular green and green arrow signal indicators. This study had concerns over the intensity of circular yellow indicators which prevented them from making any recommendation; however, study findings supported a replacement plan of 6 years for yellow arrow indicators. A summary of findings by manufacturer and indication type is presented in Table 1.1.

Table 1.1 - Age of Recommended Replacement for all LED Signal Head Types

Type	*Age for replacement (yrs) (l,m)*
Circular, Green, GE	(4 years, 5 years)
Circular, Green, Dialight	(8 years, 9 years)
Circular, Red, Dialight	*++
Circular, Red, GE	**
Circular, Yellow, LTEK	*
Circular, Yellow, Philips	*
Circular, Yellow, Dialight	*
Arrow, Green, Dialight	(8 years, 9 years)
Arrow, Green, GE	(7 years, 8 years)
Arrow, Yellow, GE	(5 years, 6 years)
Arrow, Yellow, Dialight	(5 years, 6 years)

*Insufficient intersections available for study.
**Regression fit may not be very reliable due to insufficient age variability.
++ Although we have 68 records for Dialight circular red, data for older signals (except for age 12) is sparse. This impedes the recognition of a degradation pattern.

The study raised questions as to why a second group of older LED indications had unusually high luminous intensity values. A shift in manufacturing design may be one possible explanation. The study results suggested that the older design degrades more slowly.

Additionally, the study results strongly indicated the need for additional laboratory and field study of circular yellow LEDs. The 2005 ITE *Vehicle Traffic Control Signal Heads Supplement* guidelines specify that circular yellow actually maintain the highest luminous intensity at a red to yellow to green ratio of (1: 2.5: 1.3). This was not observed during the study in either the laboratory or in the field.

Lastly, the study results indicated that circular red Dialight- LEDs degrade to the ITE minimum thresholds rather rapidly. The 2010 study main report shows the average light intensity value for all age groups of Dialight circular reds were also below the ITE minimum thresholds. This product should be subjected to further laboratory and field analysis.

No standard intersection management database currently exists at MoDOT or most other state DOTs based on the literature. Determining dates of manufacture, purchase, and installation, all of which are important pieces of information, was often time- and labor-intensive duties required by MoDOT personnel on top of regular responsibilities. The study had recommended the creation of a comprehensive intersection database to promote greater ease of tracking and replacement of LED signal indications.

LED technology is relatively young and there is no scientific methodology for scheduling the maintenance and replacement of LED signal indications. The study underscored the fact that LED performance depends on numerous factors that involve randomness, and, therefore a statistical approach was selected for the performance of measurement. [11]

1.1.5 Current LED Replacement Strategies Used by Various Other DOTs:

According to National Cooperative Highway Research Program (NCHRP) project 20-07 report it is recommended that group replacement is better than spot replacement from a cost perspective. The report further recommended that for a 10-year operating life, a replacement period of 8 years could minimize replacement costs, and every year twelve percent of LED traffic indications could be replaced. For a 7-year operating life, a replacement period of 6 years could minimize replacement costs, and 17% of the LED indications could be replaced every year.

From a cost perspective, NCHRP stated that the use of a proper replacement schedule would have advantages such as reduced power consumption, reduction in CO_2 emissions, better signal visibility, better signal uniformity, and reduction in emergency replacement outcalls for older LED traffic indications [3]. Based on the work documented by Behura (2007) and Urbanik (2008) many of the transportation agencies replaced the LED traffic lights based on spot visual inspections and changed them immediately if they failed the visual inspection. [3, 7]

In 2006 a survey of LED traffic indication policy and evaluation procedure was conducted by ITE [8] with public agencies and LED manufactures. The survey summarized that the usage of LED modules in traffic is predominant, most public agencies do not have a replacement program and that LED traffic indications are generally replaced after complaints from commuters. Most agencies use the 5-year warranty as a benchmark for replacement, but they tend to replace at the end of sixth year in use. The survey also ascertained that most agencies do not have adequate funding for monitoring the replacement program for LED traffic indications. In 2011 Sammat Engineering Services, LLC carried out research on the “Evaluation of life expectancy and development of the replacement schedule of LED’s for traffic signals in the District of Columbia” sponsored by DDOT, Washington D.C. Initially Sammat Engineering collected data of LED traffic signals from 30 intersections as identified by the DDOT (District Department of Transportation). A device (Spectra III LED Degradation tester) was used to measure the intensity of LED signals. Their research based on the analysis of the data and on the degradation rates compounded for each LED traffic signal indicator recommended an average replacement period of 7 to 9 years [9]. This is consistent with results from the previous MoDOT study (TRyy1001) [11].

2.0 Data Collection Locations

In order to estimate degradation rates, several traffic signal indications' illuminance were collected at 21 intersections throughout the state of Missouri. A list of these 21 intersections can be found below in Table 2.1.

Table 2.1 – Intersections Studied in Missouri

Region	Intersection
Jefferson City and Columbia, MO	763 X University
	763 X Paris
	763 X Big Bear
	63 X MO
St. Louis, MO	61 X Keller
	61 X Forder
	61 X Mehl
Union, MO	50 X 47 W
	50 X 47 E
	50 X Independence
	50 X Prairie Dell
Cape Girardeau and Jackson	Hwy D X Farmington
	34 X Main
	34 X Oklahoma
	74 X Silver Springs
	74 X Fountain
Rolla	72 X Rolla
	72 X Salem
	63 X Vichy
	63 X 72
	63 X University

2.1 Instrumentation

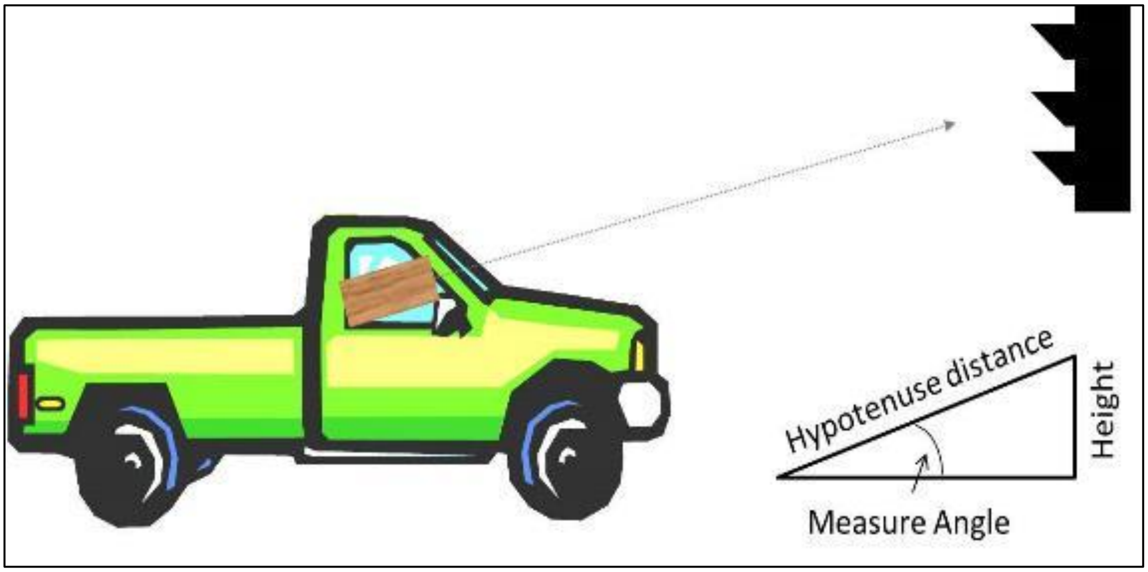
The data collection device described in the previous study was used again in this study. The device consists of a 12" tubular form, a 100x focusing Fresnel lens, and an attached illuminance meter. A separate device was used to record the distance between the data collection instrument and the traffic signal indication. A picture of the device is included in Figure 2.1 below.

Figure 2.1- Data Collection Device

An original field testing instrument was developed for collecting illuminance readings from the intersections across the state of Missouri by Missouri University of Science and Technology in the study provided to MoDOT in 2010 [**11**]. Illuminance is defined as the density of light falling into an particular area. Illuminance is measured in lux.The instrument consisted of a commercial light meter, distance meter, laser pen, and the custom made Fresnel lens. The instrument works on the technology of the Fresnel lens. The Fresnal lens was mounted inside a cylindrical casing and this blocked any ambient light [**11].** The Fresnel lens filtered the light emitted from the LED traffic indicators into a concentrated beam. The light meter used is HD450 Data logging light meter. It is placed behind the Fresnel lens at its focal length so that it effectively captures all the light emitted into the opening of the cylindrical casing. The light meter by itself would be incapable of measuring the illuminance of a LED traffic indicator from far out distances because the ambient light would impact the measured light output from the LED. The device also has a laser pointer to properly point at the maximum intensity capturing position of the LED traffic indicators. The distance was measured by a commerical distance meter. The output of the light meter is ported to the data recorder through a USB port. The interface software is provided by the light meter manufacturer.

During data collection, an operator in the passenger seat of a vehicle, points the device at the traffic signal and locates the maximum reading for each indication. Using a distance meter, the driver then reads and records the hypotenuse distance between the traffic signal and the device. Data from the illuminance meter is then recorded, into an attached computer, for the duration of one traffic signal cycle. This process is completed five times for each traffic signal at each intersection at varying distances. Figure 2.2, below, depicts the relative locations between the vehicle and the traffic signal.

Figure 2.2 - Data Collection Image



Data was collected between January – November 2013. Within this time, three sets of data were collected at the 21 intersections listed in Table 2.1. The first set was collected between January – March, the second set of data was collected from April through August, and the third set of data was collected from August through November. Throughout the entire study, 5,076 points of data were collected and recorded into a database management system. Microsoft Access was chosen as the database management system because of its availability to the entire research team and minimal training required to use the program. For each observation, the following information was recorded:

- Season
- Date
- Intersection
- Hypotenuse Distance
- Direction
- Signal Number (Counting from Left)
- Indication Type (e.g. Circular Green)
- Illuminance Reading

Five example observations are shown below in Table 2.2.

Table 2.2 - Example Database Observations

Season	Date	Intersection	Distance	Direction	Light #	Color	Lux
WINTER	13-Jan-13	ROLLA X 72	137.20	SB	3	R	16.7
WINTER	13-Jan-13	ROLLA X 72	125.50	SB	3	R	19.2
WINTER	13-Jan-13	ROLLA X 72	118.50	SB	3	R	20.3
WINTER	13-Jan-13	ROLLA X 72	105.10	SB	3	R	27.9
WINTER	13-Jan-13	ROLLA X 72	92.30	SB	3	R	30.3

3.0 Data Analysis

Data analysis for the studied traffic signal indications required a series of data modifications and calculations in order to accurately estimate the lifetime of LED traffic signal indications. First, the illuminance reading values were corrected for the measurement angle. Then, a point estimate regression analysis was completed to ensure traffic indications are compared on a common measurement distance. These point estimates were then averaged based on their values and R^2 values from the point estimate regression. Then, the point estimates were grouped based on their operating lifetime. Finally, the degradation analysis was completed to estimate the lifetime of each studied LED traffic signal.

According to the Institute of Transportation Engineers purchase specifications for LED Vehicle Traffic Control Signal Heads [5] and the updated version covering arrow indications [6], the measurement angle greatly impacts illuminance measurements. To account for this, an angle correction factor is calculated and applied to each illuminance reading. The angle correction factor equation, seen below in Equation 3.1, originates from ITE's Vehicle Traffic Control Signal Heads: Light Emitting Diode (LED) Circular Signal Supplement [5]. Using the height of each traffic signal indication and the hypotenuse distance, collected for each point, the measurement angle was calculated for each observation.

Equation 3.1 - Angle Correction Factor

For $\theta_{Vert} \leq$ -2.5 degrees:

$$f\left(\mathrm{I}_{Vert}\right) = 0.26 + \left(\frac{\theta\mathrm{Vert}}{143}\right) + 0.76 * \left[e^{-0.02\left(\theta_{Vert}+2.5\right)^2}\right]^{\left(-0.07*\theta_{Vert}\right)}$$

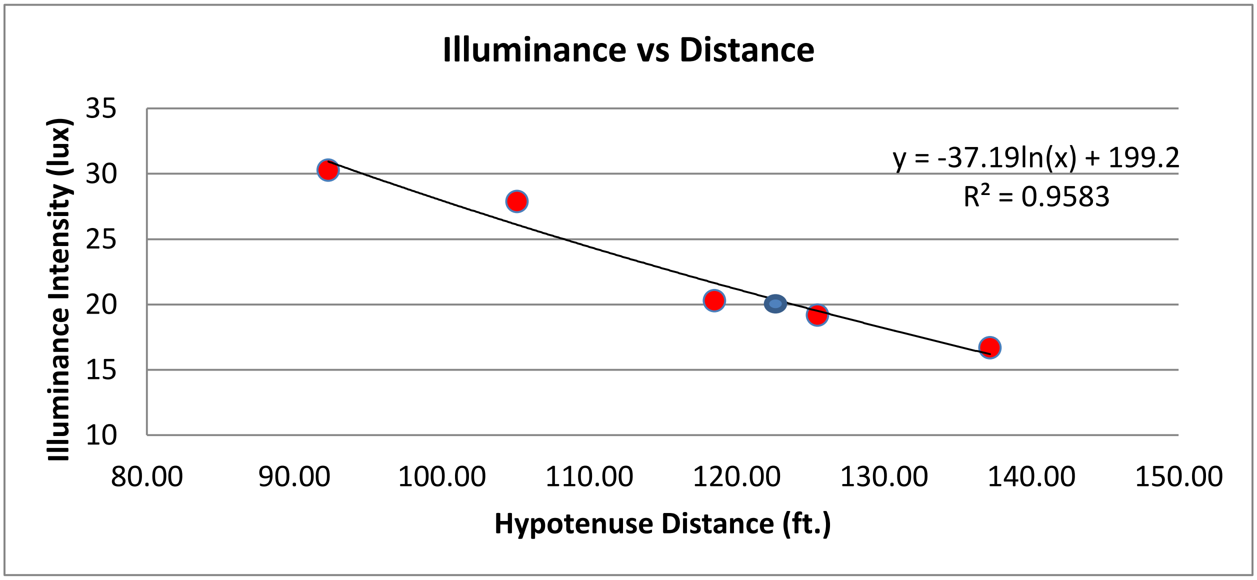
After the angle correction factor is applied to the illuminance reading for each observation, the data collected for each indication is ready to be analyzed. Across all hypotenuse distance measurements, the hypotenuse distance varied from 49.9 feet to 249.0 feet, which does not allow for common points of comparison. In order to complete a latitudinal comparison, a common hypotenuse distance, or measurement point, across all traffic indications must be measured. However, due to constraints within data collection, this was not feasible. Therefore, a linear regression is run on the logarithmic relationship for each traffic signal indication to estimate a common measurement point. The regression equation is presented in Equation 3.2 below. β_0 is the estimated intercept for each observational set (the five observations collected for each traffic signal indication), or the predicted illuminance at the point source. β_1 is the slope parameter, which is a linear estimate of the light diffusion, based on the natural log of the hypotenuse distance.

Equation 3.2 – Point Estimate Regression

$$\text{Illuminance (lux)} = \beta_0 + \beta_1 * \ln(\text{Hypotenuse Distance})$$

For example, in Figure 3.1, seen below, five measurements were completed in the winter set for a circular red traffic signal indication. After the angle correction factor was applied, a regression analysis was performed on each observation set. This allowed for a calculation of an illuminance point estimate, seen in blue, at 124.15 feet. The five observations in Table 2.2 were used in the Point Estimate regression analysis, which outputs β_0 and β_1 for these five observations. The β_0 (199.2) and β_1 (-37.19) were then used to calculate a point estimate at 124.15 feet. This same process was then applied to each traffic signal indication within each observational set. This process calculated an illuminance point estimate at 124.15 feet for all traffic signal indications.

Figure 3.1 – Point Estimate Regression Example



Once the point estimate regression analysis was completed, the results were filtered to exclude point estimates with negative values. The table below, Table 3.2, provides a count of point estimates of combinations of manufacturer and indication type.

Table 3.2 – Count of Point Estimates by Manufacturer and Indication Type

Indication Types	DIAL	GE	LTEK	PHILIPS	Grand Total
Circular Green	60	71			131
Green Arrow	63	41			104
Circular Red	176	68		4	248
Circular Yellow	142	26	33		201
Yellow Arrow	35	12			47
Grand Total	**476**	**218**	**33**	**4**	**731**

After an illuminance point estimate is calculated for each traffic indication signal in each season, then the illuminance point estimate versus indication age regression analysis is ready to be completed. Indication age is defined as the operational running time for each traffic signal indication. Each traffic signal indication's age was grouped into age groups by the nearest integer. For example, a traffic signal indication with an indication age of 1.6 years would be grouped into the 2 year age group. Once all traffic signal indications were grouped, a weighted average was calculated for each age group. Each illuminance point estimate was grouped by the R^2 value of the previous point estimate regression analysis. The R^2 value is an estimate of the strength of the correlation within a regression analysis. Therefore, the less accurate point estimates have less of an influence on the weighted average within each age group. The weighted average illuminance point estimates for each manufacturer's type of indication, e.g. Dialight Green Arrow, are measured against the grouped indication's age through a linear regression analysis. A weighted linear regression analysis comparing weighted average illuminance point estimates and indication age group was completed for each combination of manufacturer and signal type. Each age group's weighted point estimate was again weighted by the number of points averaged within each group. For example, if a traffic signal's weighted average illuminance equals 20, and that average was calculated using 7 estimated points, then the illuminance point estimate versus indication age regression analysis uses the weighted average value of 20 with a weight of 7 for that specific indication type. The equation below, Equation 3.3, presents the regression analysis completed for each combination of manufacturer and signal type.

Equation3.3 – Degradation Regression Equation

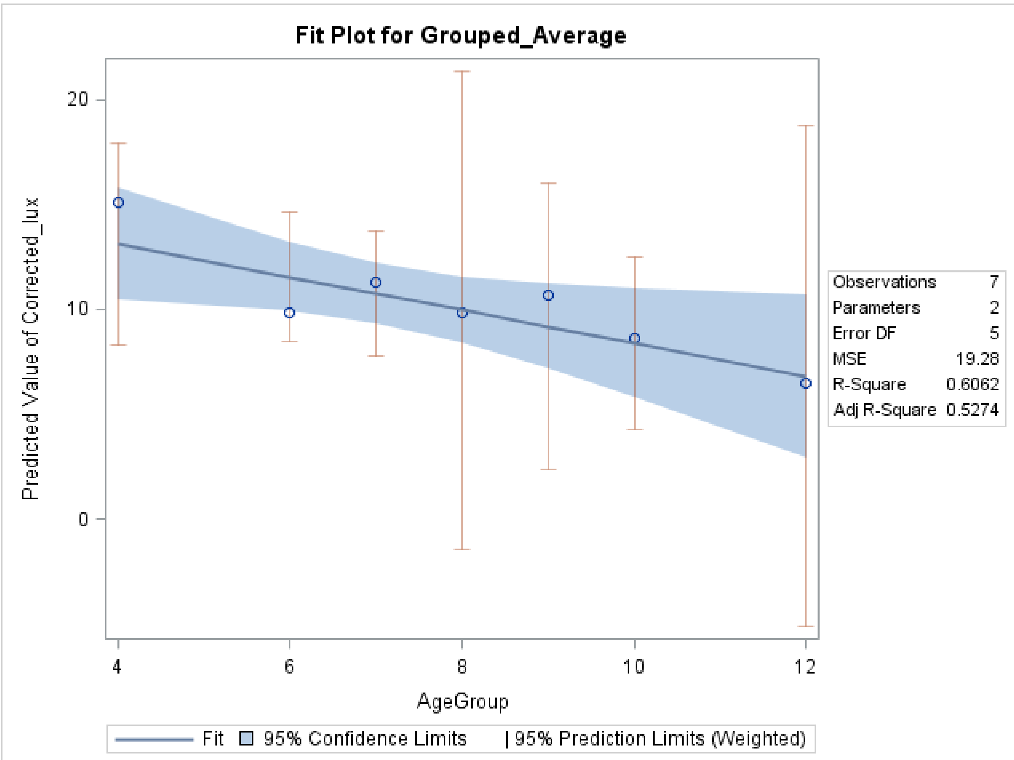
$$\text{Weighted Average Point Estimate (lux)} = \beta_0 + \beta_1 * (\text{Indication Age Group})$$

This regression equation calculates an estimation of the illuminance at age 0, or the intercept (β_0), and the estimation of the rate of degradation (β_1) for each combination of manufacturer and indication type. The linear fit plot for each combination of manufacturer and indication type is shown below in Figures 3.2 – 3.11.

3.1 Degradation Analysis for Dialight Green Arrow

The degradation rate for the Dialight Green Arrow shows a strong decreasing trend. The R^2 value of 0.6062 for this indication has a moderately strong correlation between the age and weighted average point estimate illuminance value. The area within the confidence limit, shown in light blue in Figure 3.2, is shown to be close to the trend line. In addition, the area enclosed by the 95% confidence limits is relatively small, which supports the accuracy of the degradation regression model for this indication.

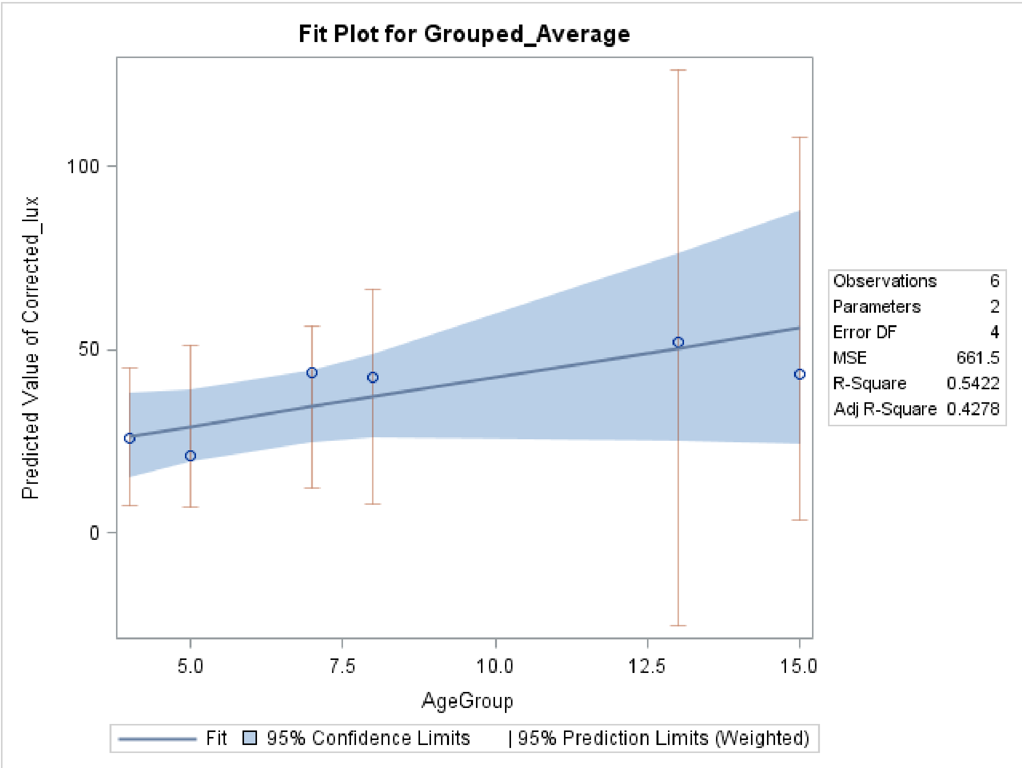
Figure 3.2 - Fit Plot for Dialight Green Arrow



3.2 Degradation Analysis for Dialight Circular Green

The degradation rate for the Dialight Circular Green shows a strong increasing trend. The R^2 value of 0.5422 for this indication has a moderately strong correlation between the age and weighted average point estimate illuminance value. The area within the confidence limit, shown in light blue in Figure 3.3, varies in width across ages. The higher age group values have larger confidence limits, which indicate imprecision for indications within the 13 and 15 year age groups. Based on the increasing trend line, which is inconsistent with degradation models, the Dialight Circular Green indication is excluded from the Lifetime Estimate Analysis.

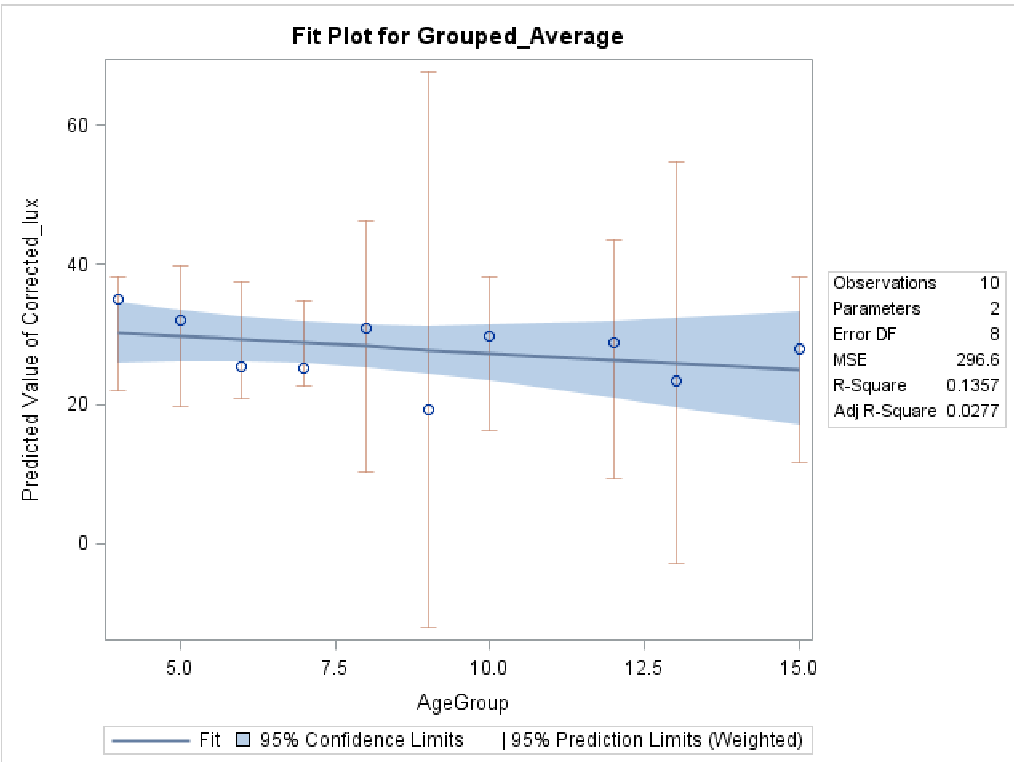
Figure 3.3 - Fit Plot for Dialight Circular Green



3.3 Degradation Analysis for Dialight Circular Red

The degradation rate for the Dialight Circular Red shows a small decreasing trend. The R^2 value of 0.1357 for this indication has a weak correlation between the age and weighted average point estimate illuminance value. However, the area within the confidence limit, shown in light blue in Figure 3.4, remains tightly bound around the trend line, which indicates a small variance around the predicted trend line. The small negative slope value also indicates a small degradation value over time. The slight annual degradation value and the large intercept value provide a high estimated lifetime value for the Dialight Circular Red indication.

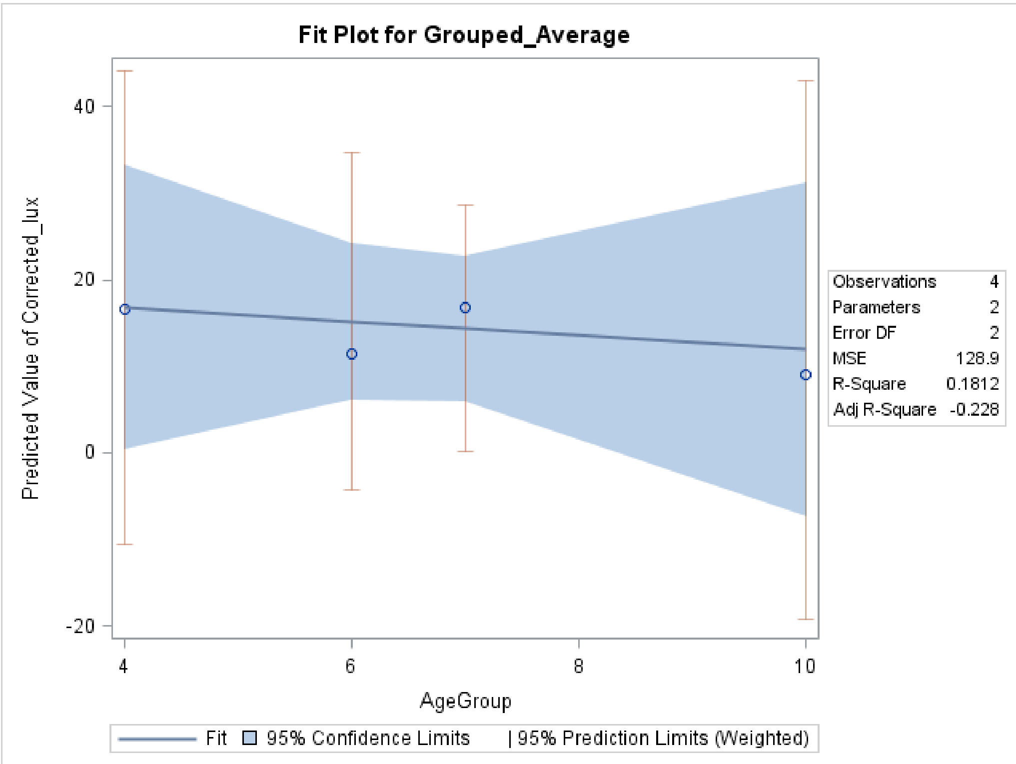
Figure 3.4 - Fit Plot for Dialight Circular Red



3.4 Degradation Analysis for Dialight Yellow Arrow

The degradation rate for the Dialight Yellow Arrow shows a small decreasing trend. The R^2 value of 0.1812 for this indication has a weak correlation between the age and weighted average point estimate illuminance value. In addition, the area enclosed by the confidence limits, shown in light blue in the Figure 3.5, is quite large and varies greatly from point to point. The large confidence interval and the weak R^2 value indicate there is uncertainty within the predicted trend line. However, a large portion of this uncertainty is due to the relatively few number of observations collected for this indication. The small negative slope value also indicates a small degradation value over time. The slight annual degradation value and low ITE threshold provide a high estimated lifetime value for the Dialight Yellow Arrow indication.

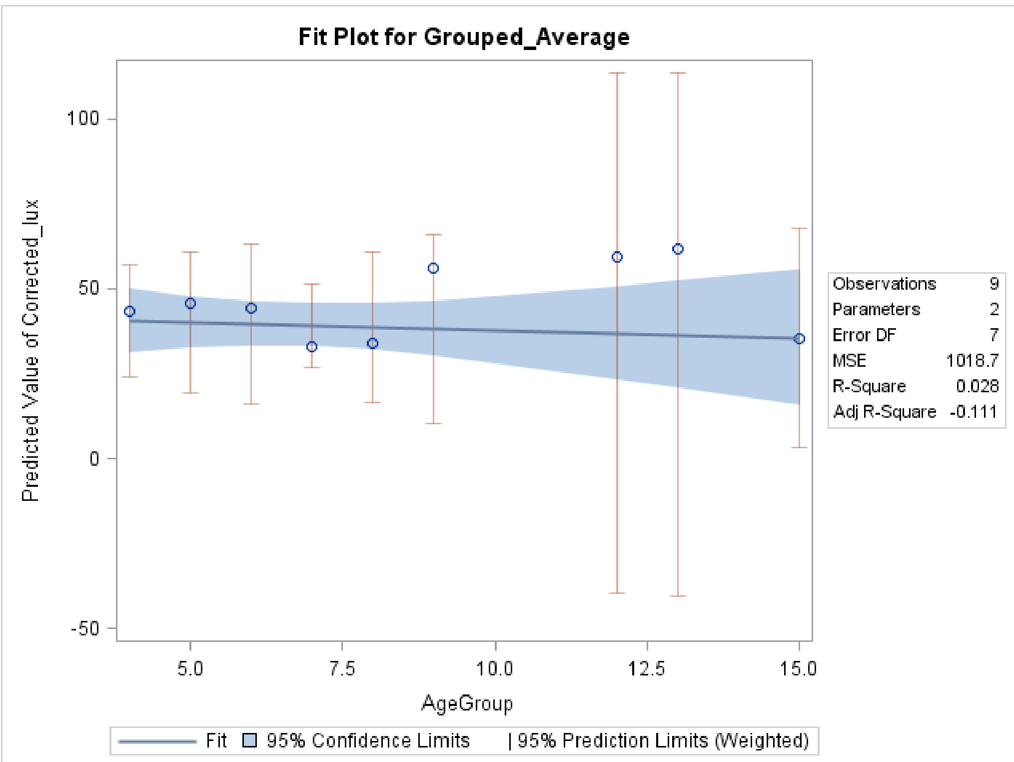
Figure 3.5 - Fit Plot for Dialight Yellow Arrow



3.5 Degradation Analysis for Dialight Circular Yellow

The degradation rate for the Dialight Circular Yellow shows a negligibly small decreasing trend. The R^2 value of 0.028 for this indication has an extremely weak correlation between the age and weighted average point estimate illuminance value. In addition, the area enclosed by the confidence limits, shown in light blue Figure 3.6, is quite large and varies greatly from point to point. The large confidence interval and the weak R^2 value indicate there is uncertainty within the predicted trend line. In addition, the intercept calculated in this regression model is lower than the ITE Threshold for yellow circular indications. Because the apparent uncertainty in the degradation regression model and the intercept is less than the ITE threshold for circular yellow indications, the Dialight Circular Yellow indication was excluded from the estimated lifetime analysis.

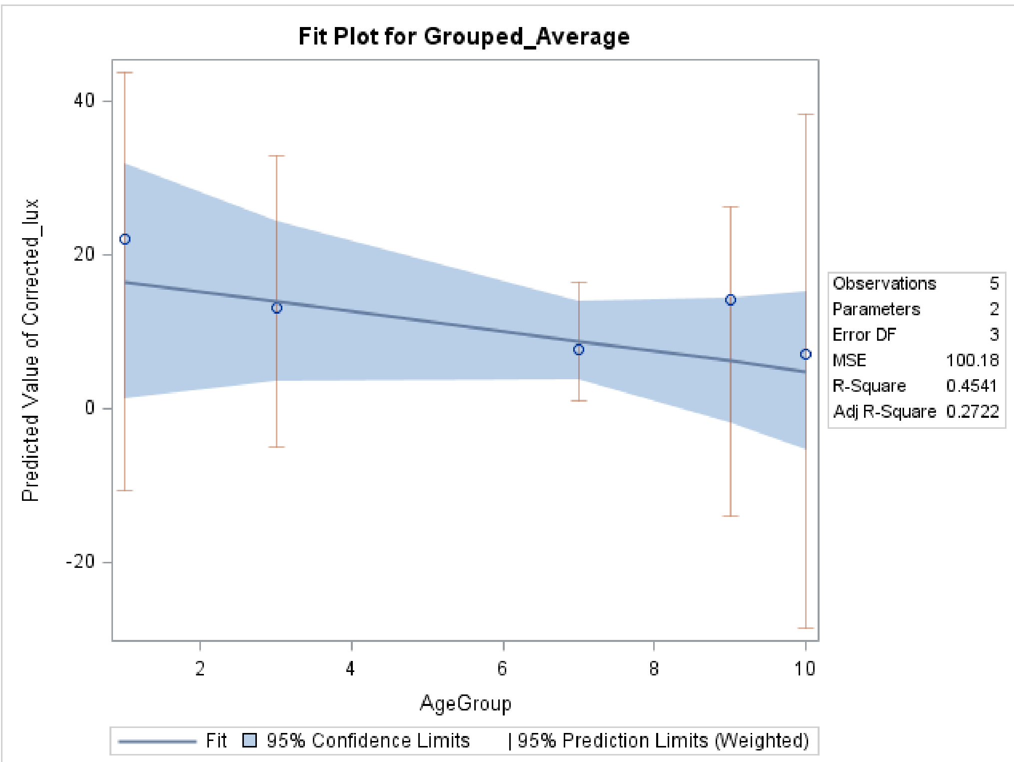
Figure 3.6 - Fit Plot for Dialight Circular Yellow



3.6 Degradation Analysis for GE Green Arrow

The degradation rate for the GE Green Arrow shows a strong decreasing trend. The R^2 value of 0.4541 for this indication has a moderate correlation between the age and weighted average point estimate illuminance value. The area within the confidence limit, shown in light blue in Figure 3.7, is shown to vary widely in relation to the trend line. However, the predicted trend line shows a distinctly negative slope, which supports a small degradation over time. The high intercept value, small annual degradation value, and lower ITE Threshold for arrow indications will provide a moderate lifetime estimate for GE Green Arrows.

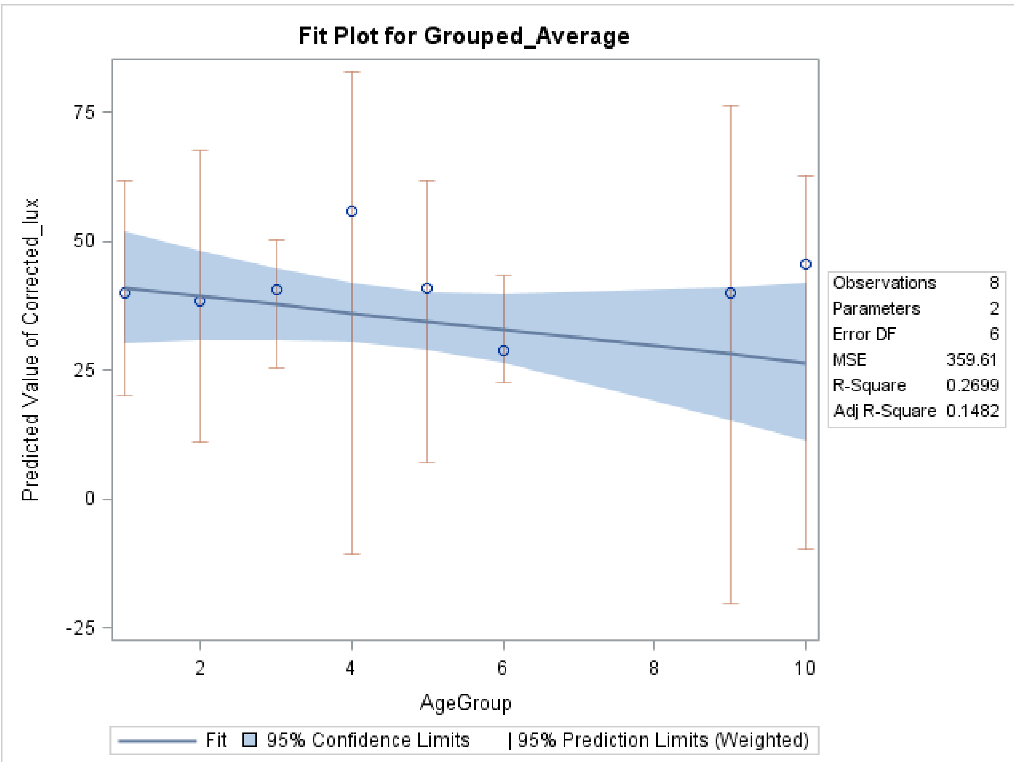
Figure 3.7 - Fit Plot for GE Green Arrow



3.7 Degradation Analysis for GE Circular Green

The degradation rate for the GE Circular Green shows a strong decreasing trend. The R^2 value of 0.2699 for this indication has a weak correlation between the age and weighted average point estimate illuminance value. The area within the confidence limit, shown in light blue in Figure 3.8, is shown to tightly follow the trend line. Despite the weak R^2 value, the trend line shows a distinctly negative slope, which supports a small degradation over time.

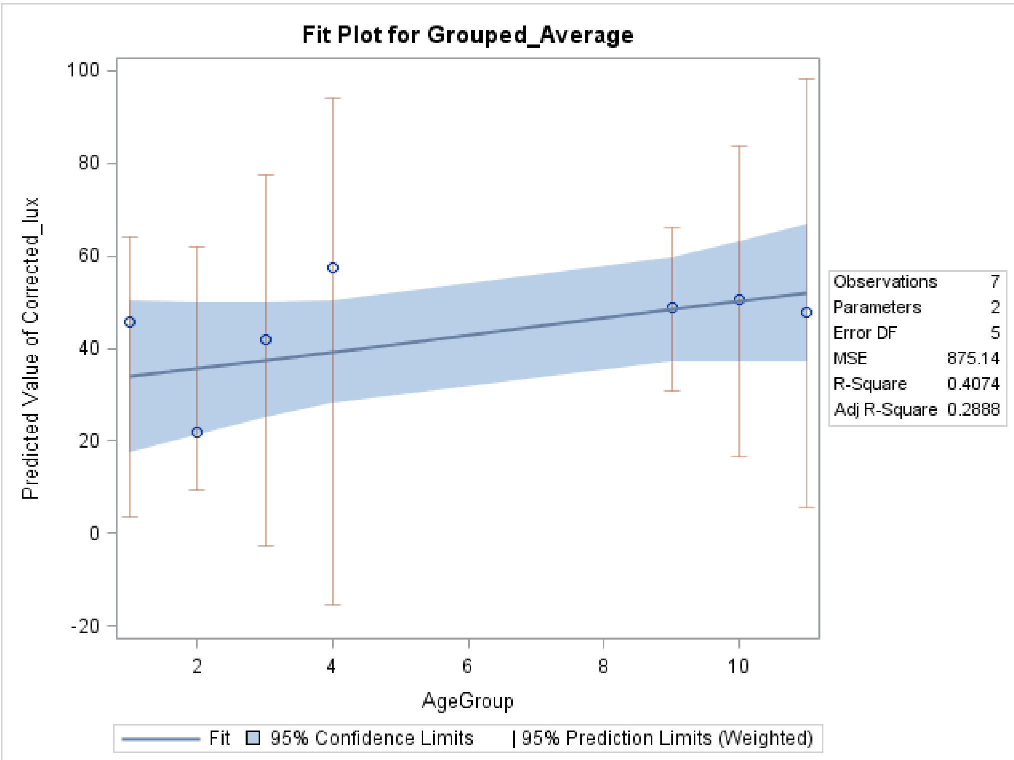
Figure 3.8 - Fit Plot for GE Circular Green



3.8 Degradation Analysis for Dialight Yellow Arrow

The degradation regression model rate for the Dialight Yellow Arrow has an increasing trend line. Based on the increasing trend line, which is inconsistent with degradation models, the Dialight Yellow Arrow indication is excluded from the Lifetime Estimate Analysis.

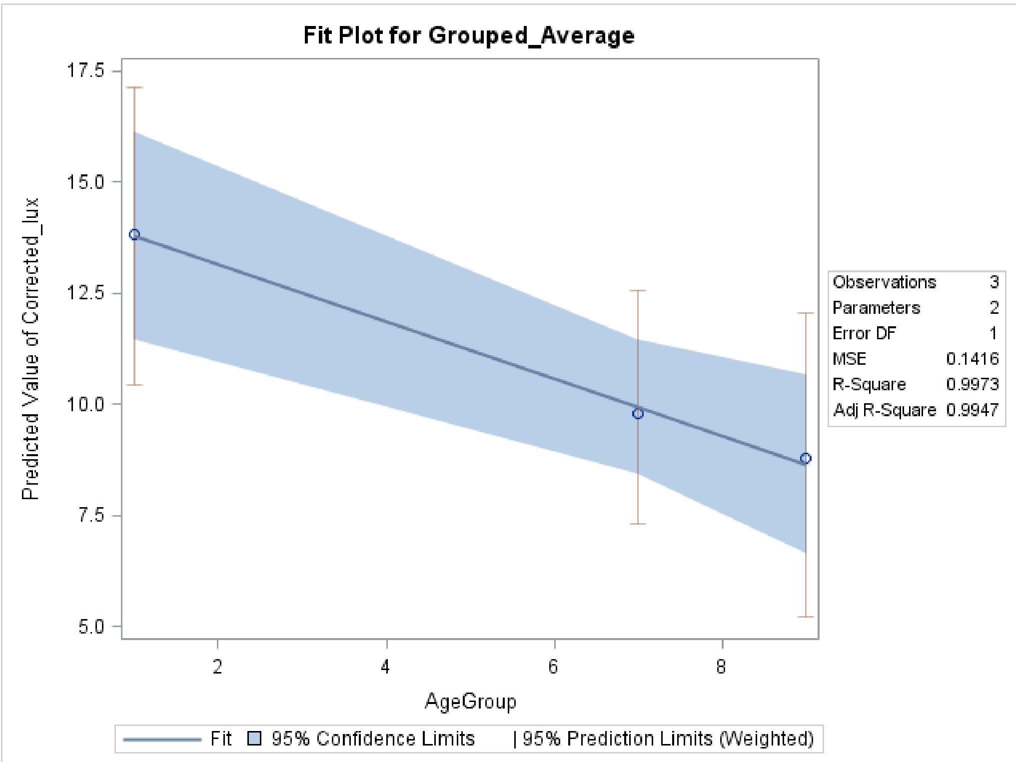
Figure 3.9 - Fit Plot for Dialight Yellow Arrow



3.9 Degradation Analysis for GE Yellow Arrow

The degradation rate for the GE Yellow Arrow shows a strong decreasing trend. The R^2 value of 0.9973 for this indication has an extremely strong correlation between the age and weighted average point estimate illuminance value. The area within the confidence limit, shown in light blue in Figure 3.10, is shown to vary consistently across all age groups in relation to the trend line. However, the predicted trend line shows a distinctly negative slope, which supports a small degradation over time. The high intercept value, small annual degradation value, and lower ITE Threshold for arrow indications will provide a moderate lifetime estimate for GE Yellow Arrows.

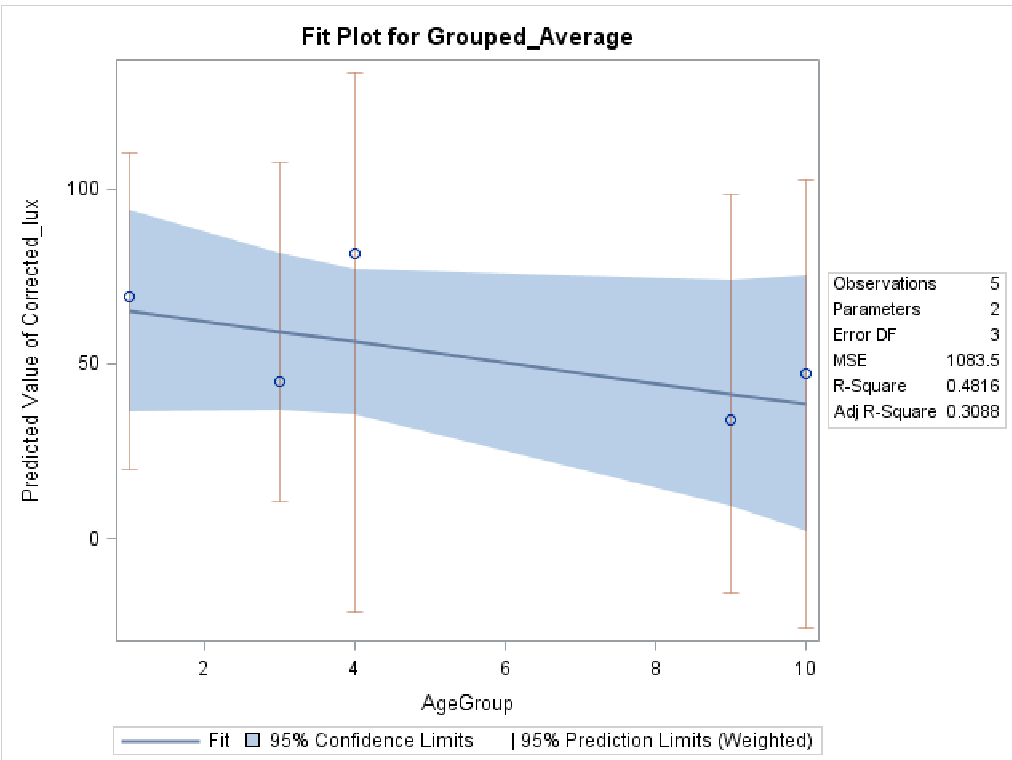
Figure 3.10 - Fit Plot for GE Yellow Arrow



3.10 Degradation Analysis for GE Circular Yellow

The degradation rate for the GE Circular Yellow shows a strong decreasing trend. The R^2 value of 0.4816 for this indication has a moderate correlation between the age and weighted average point estimate illuminance value. The area within the confidence limit, shown in light blue in Figure 3.11, is shown to vary greatly across all age groups in relation to the trend line. However, the predicted trend line shows a distinctly negative slope, which supports degradation over time. The R^2 value and the distinctly negative slope do not rule the GE Circular Yellow indication from exclusion in the Lifetime Estimate Analysis.

Figure 3.11 - Fit Plot for GE Circular Yellow



3.11 Estimated Lifetime Analysis

As the duration of operation increases, traffic signal indications are expected to decrease in illuminance. Using the ITE recommended thresholds for LED traffic signal indications, seen in Table 3.3, the operational lifetimes were calculated using the intercept and slope of the regression results shown in Figures 3.2 – 3.11. The expected lifetimes for each combination of manufacturer and indication type were calculated using Equation 2.4, seen below. The ITE Threshold is multiplied by 100 to account for the 100x magnification factor of the Fresnel lens within the data collection device.

Equation 3.4 – Expected Lifetime Equation

$$Expected\ Lifetime = \frac{Intercept - ((Converted\ ITE\ Threshold) * 100)}{-Slope}$$

The ITE Thresholds, or standards, were converted from candela (cd), which is a measurement of light output at a point source, to lux (lx), which is a measurement of illuminance over area. The ITE Thresholds were converted using the common distance of 124.15 feet, the common point distance used in the degradation regression analysis. Equation 3.5, below, converts the ITE Threshold from candela (I_v) to lux (E_y) using the hypotenuse distance value (D) of 124.15 feet.

Equation 3.5 – Candela to Lux Conversion Equation

$$E_v = I_v / D^2$$

Table 3.3 – Original and Converted ITE 12” LED Indication Illuminance Thresholds

Indication Type	ITE Threshold (cd)	Converted Threshold (lux)
Circular Red	365	0.237
Circular Yellow	910	0.6012
Circular Green	475	0.3182
Yellow Arrow	146	0.0964
Green Arrow	76	0.0509

Because the calculations indicate the degradation rates of the Dialight Circular Green indication and the GE Circular Red indication are non-negative, these two indications were excluded from the expected lifetime analysis. In addition, the Dialight Circular Yellow was excluded due to its extremely low R^2 value.

4.0 Results, Discussion, and Recommendations

4.1 Lifetime Estimate Results

The results from the estimated lifetime analysis are shown below in table 4.1. Due to significant uncertainties within the analyzed data, the lifetimes for Dialight Circular Green, GE Circular Red, and Dialight Circular Yellow were excluded from the estimated lifetime analysis.

Table 4.1 - Estimated Indication Lifetimes

Manufacturer	Indication Type	Estimated Lifetime (years)
DIAL	Green Arrow	14.1719
DIAL	Circular Red	17.6077
DIAL	Yellow Arrow	12.7728
GE	Circular Green	6.6339
GE	Green Arrow	9.7866
GE	Yellow Arrow	7.4503
GE	Circular Yellow	2.6718
LTEK	Circular Yellow	5.0582

4.2 Discussion of Results

The results provide values for green and yellow arrow indications for both GE and Dialight, which is an improvement from the previous analysis. Also, the results for the Circular Red lifetime estimate show a significantly longer lifetime than the 2010 MoDOT study.

Again, the Circular Yellow indication show troublesome results. Accurate data for circular yellow indications is extremely difficult to collect due to the short duration the indication operates within each traffic cycle, in most cases between 3-6 seconds. Therefore, the lifetime analysis results for the GE and LTEK yellow circular indications should be considered with caution.

Based on the overall analysis presented within this paper, the Dialight traffic signal indications have a significantly higher lifetime estimate over GE traffic signal indications for the Green Arrow and Yellow Arrow indication types.

4.2.1 Comparison of Results Between 2011 and 2014 Study

With increased R^2 values and reduced confidence intervals in the degradation analysis, this longitudinal and latitudinal study provides more accurate results for the estimated lifetimes than the previous study. A comparison of results of the two studies is presented in Table 4.2. Indications are sorted by both manufacturer and indication type. The difference column in Table 4.2 is calculated by subtracting the lifetime estimate from the previous study from the lifetime estimate from this study. Due to differences in results, some values within Table 4.2 are not shown, and these values are marked with “***”.

Table 4.2 – Lifetime Estimate Results for 2010 and 2014 MoDOT Studies

Manufacturer	Indication Type	Lifetime (years)		
		2014 Study	2011 Study	Useful Life Gain
Dialight	Green Arrow	14.17	8.95	5.22
Dialight	Circular Green	***	8.45	***
Dialight	Circular Red	17.61	***	***
Dialight	Yellow Arrow	12.77	6.09	6.68
GE	Circular Green	6.63	4.61	2.02
GE	Green Arrow	9.79	7.63	2.16
GE	Yellow Arrow	7.45	5.85	1.60
GE	Circular Yellow	2.67	***	***
LTEK	Circular Yellow	5.06	***	***

***Indicates Missing or Excluded Data

Based on the information in Table 4.2, significant improvement is shown across all arrow indications. The lifetime estimates for Dialight Arrow indications have increased by at least 5 years for both Green Arrow and Yellow Arrow indication types. Lifetime estimates for GE Arrow indications have improved also, although their indications have improved by 1.6 years for the Yellow Arrow indication and 2.15 years for the Green Arrow indication.

5.0 Temperature Analysis:

In addition to the degradation analysis, a temperature analysis was performed for two sets of data collected in different seasons. The purpose of this temperature analysis is to study the effect of temperature on the behavior of the same lights, of same age, and belonging to same manufacturer. For this analysis, temperatures were recorded at the time of data collection. Tables 5.1 and 5.2 provide the sample data of the temperature recordings for set 1 and set 2.

Table 5.1 – Location, Date, and Temperature Information for Set 1

Location	Date	Temperature
Rolla		
63 X 72	1/14/2013	-11^{o} C
63 X University	2/3/2013	-9^{o} C
Rolla X 72	1/14/2013	-11^{o} C
Salem X 72	1/13/2013	-12^{o} C
63 X Vichy	3/3/2013	-13^{o} C
Union and Washington		
50 X Prairie Dell	1/15/2013	-8 ^{o} C
50 X Independence	1/14/2013	-8 ^{o} C
47 X 50 E	1/14/2013	-8 ^{o} C
47 X 50 W	1/14/2013	-8 ^{o} C
Columbia		
763 X University	2/17/2013	-2 ^{o} C
763 X Paris	2/17/2013	-2 ^{o} C
763 X Big Bear	2/17/2013	-2 ^{o} C
Jefferson City		
63 X MO	2/15/2013	-8 ^{o} C
Cape Girardeau		
74 *Silver Springs	3/14/2013	-6^{o} C
74 *Fountain	3/15/2013	-2^{o} C
Jackson		
D X 34	3/13/2013	-3^{o} C
34 X Main	3/14/2013	-6^{o} C
St. Louis		
Keller X61	3/31/2013	8^{o} C
Forder X 61	1/4/2013	3^{o} C
Mehl X 61	1/4/2013	3^{o} C

Table 5.2 – Location, Date, and Temperature Information for Set 2

Location	Date	Temperature
Rolla		
63 X 72	7/15/2013	20^{o} C
63 X University	7/31/2013	16^{o} C
Rolla X 72	4/19/2013	1^{o} C
Salem X 72	6/13/2013	16^{o} C
Union and Washington		
50 X Prairie Dell	6/30/2013	18^{o} C
50 X Independence	6/14/2013	17^{o} C
47 X 50 E	6/30/2013	18^{o} C
47 X 50 W	6/20/2013	21^{o} C
Columbia		
763 X University	6/8/2013	12^{o} C
763 X Paris	6/8/2013	12^{o} C
763 X Big Bear	6/8/2013	12^{o} C
Jefferson City		
63 X MO	6/3/2013	12^{o} C
Cape Girardeau		
74 *Silver Springs	6/21/2013	22^{o} C
74 *Fountain	6/21/2013	22^{o} C
Jackson		
Hwy D X Farmington	7/16 /2013	22^{o} C
34 X Main	7/25/2013	13^{o} C
St. Louis		
Keller X61	6/16/2013	21^{o} C
Forder X 61	8/13/2013	16^{o} C
Mehl X 61	8/1/2013	18^{o} C

For the analysis, graphs have been plotted per group through MATLAB software and the effect of temperature is noticed across the age differences. The ages with larger data is considered for the analysis. These graphs are interpreted based on the slopes which represent degradation of lights with respect to temperature. The graphs related to the temprature analysis for red, green, yellow, green arrow, and yellow arrow can be found in the Appendix. In Tables 5.3 – 5.7 the slope differences are calculated among the Set1, Set2 with respect to same age grouping. This slope difference shows less deviation with respect to temperature.

Table 5.3 - Temperature Analysis: Slope Difference for Red Light

Age (years)	Temperature Difference (Absolute value)	Slope: Set 1	Slope: Set 2	Slope Difference (Absolute value)	Manufacturer
2	14^o C	$-1.1 * 10^6$	$-1.6 * 10^6$	$0.5 * 10^6$	GE
4	26^o C	$-1.8 * 10^6$	$-1.5 * 10^6$	$0.3 * 10^6$	Dialight
9	28^o C	$-1.4 * 10^6$	$-2.4 * 10^6$	$1 * 10^6$	GE

The above table interprets the temperature difference between two sets recorded and the significant slope difference obtained because of temperature change. In this case, the behavior of Dialights are more reliable than GE, since, the slope difference which symbolizes the degradation of intensity is less in Dialight as compared to GE at approximately the same temperature difference (26^o C and 28^o C). Similarly the following tables represent the temperature analysis of the green indications belonging to the same intersections.

Table 5.4 - Temperature Analysis: Slope Difference of Green Light

Age	Temperature Difference (Absolute value)	Slope: Set 1	Slope: Set 2	Slope Difference (Absolute value)	Manufacturer
1 year	15^o C	$-1.1 * 10^6$	$-3.6 * 10^6$	$2.5 * 10^6$	GE
4 years	29^o C	$-0.088 * 10^6$	$-0.18 * 10^6$	$0.092 * 10^6$	Dialight

In this case, though the intensity at age 4 years is much less than age 1 year, the slope difference is much less in 4 years as compared to 1 year. Hence, Dialight shows less deviation in intensity over GE with significant temperature differences.

Table 5.5 - Temperature Analysis: Slope Difference for Yellow Light

Age	Temperature Difference (Absolute value)	Slope: Set 1	Slope: Set 2	Slope Difference (Absolute value)	Manufacturer
1 year	15^o C	$-3.3 * 10^6$	$-8.1 * 10^6$	$4.8 * 10^6$	GE
4 years	29^o C	$-1.3 * 10^6$	$-2.6 * 10^6$	$1.3 * 10^6$	Dialight

In the case of yellow indications as well, Dialight has less intensity degradation with respect to temperature as compared to GE. There is significant difference in intensity due to temperature in GE.

Table 5.6 - Temperature Analysis: Slope Difference for Green Arrow

Age	Temperature Difference (Absolute value)	Slope: Set 1	Slope: Set 2	Slope Difference (Absolute value)	Manufacturer
1 year	13^{o} C	$-1.1 * 10^{6}$	$-3.8 * 10^{6}$	$2.7 * 10^{6}$	GE
7 years	25^{o} C	$-1.0 * 10^{6}$	$-0.2 * 10^{6}$	$0.8 * 10^{6}$	Dialight
10 years	24^{o} C	$-0.76 * 10^{6}$	$-0.47 * 10^{6}$	$0.29 * 10^{6}$	Dialight

Here, also, with less slope difference, Dialight is better in handling temperature difference as compared GE for given data.

Table 5.7 - Temperature Analysis: Slope Difference for Yellow Arrow

Age	Temperature Difference (Absolute value)	Slope: Set 1	Slope: Set 2	Slope Difference (Absolute value)	Manufacturer
7 years	25^{o} C	$-0.88 * 10^{6}$	$-2.2 * 10^{6}$	$1.32 * 10^{6}$	Dialight

The effect of temperature can be observed on the intensity of yellow arrow indications for given data in two sets. Thus, it can be noticed that with the increase in temperature, the intensity value of LED traffic indications is also increasing. This means at higher temperatures the LED traffic indications have higher intensity values. Also, less deviation between maximum intensity value and minimum intensity value is desired for less life degradation. This factor is calculated by measuring the slope value of the fit. It has been observed that Dialight shows less slope deviation with significant temperature differences.

As can be seen from the above temperature analysis, as the temperature is increasing, the intensity of LED traffic indication output is also increasing. With respect to the manufacturer analysis using the slope difference as a critical parameter, the results show that Dialight manufactured red, green, yellow, and green arrow indications perform better than that of GE manufactured indications with respect to temperature. The slope differences for red, green, yellow, and green arrow lights shows that Dialight has less light intensity variation over the GE.

To conclude, the temperature analysis shows the effect of temperature on intensity degradation of available traffic indications. The data used in the analysis is collected over two periods in extremely different seasons. With a considerable temperature change in the two sets of data, it is observed that as temperatures are increasing the value of intensity is also increasing for a given distance. Increases in temperature show better intensity. Slope difference is a parameter used to quantify the degradation of intensity. This study provides flexibility to MoDOT to choose between higher life and higher intensity with faster degradation.

5.1 Laboratory Validation of Instrument Performance:

Laboratory analysis was performed using red, green, and yellow LED traffic indications provided by MoDOT for validation of the intensity measuring instrument and light meter. The readings are recorded in intervals of 10 ft., using a range between 10-120 ft. and 5-6 samples are taken at the rate of one sample per second.

Figure 5.3 and 5.4 presents the overview of the intensity readings obtained for red, green, and yellow LED traffic indicators. Performance in comparison with manufacturer provided data shows that the readings collected with the study device is at a statistically significant confidence level.

Figure 5.3- Average Intensity in Lux versus Distance in ft. for Lab Analysis

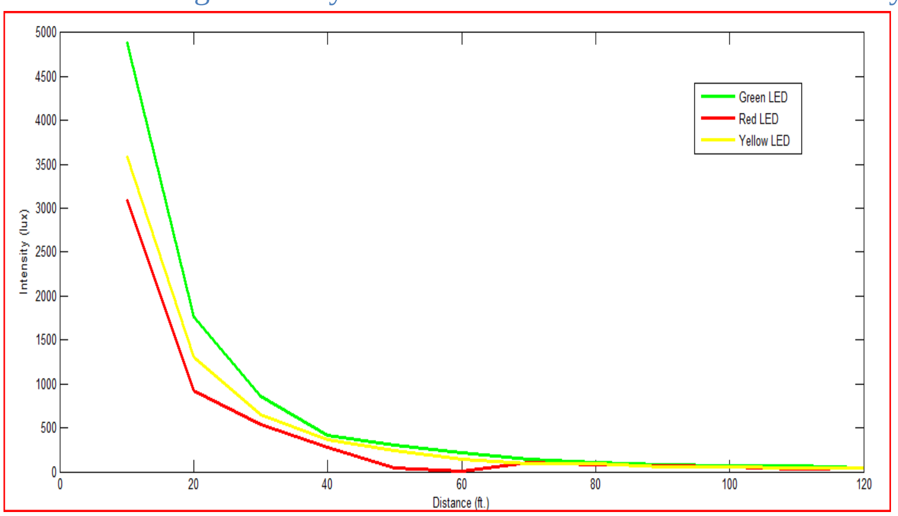
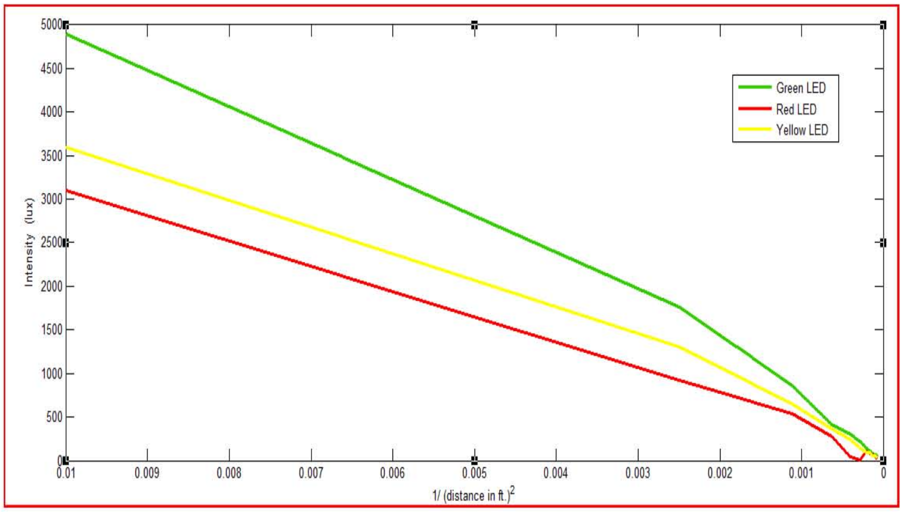


Figure 5.4 - Inverse Square Law Curve for Lab Analysis



6.0 Conclusions

LED traffic signal indications have been shown to economically outperform incandescent bulbs through longer lifetimes, reduced electricity consumption, and reduced maintenance activity. However, the uncertainty of when to replace LED traffic signal indications has concerned many DOTs. Previous traffic signal replacement methods, such as spot replacement, do not work well with LED traffic indications due to different degradation patterns and increased O&M costs. Results from this research shows that generic replacement schedules provide insufficient detail to make the best decisions based on operations and maintenance replacement costs, color, and indicator type. Using results from the data analysis, the research team developed detailed replacement guidelines for some Dialight and GE products. Due to insufficient data and age variance, statistically robust decisions for circular yellow LEDs were not possible.

The previous MoDOT Traffic Signal study (TRyy1001) recommended a comprehensive tracking and replacement system based on lifetime estimates of each traffic signal indication. The research team continues the recommendation of such a system, but the replacement rates for LED traffic signal indications now have new values, which are based on the results of this study.

Table 6.1 – Applicable Estimated Lifetimes

Manufacturer	Indication Type	Estimated Lifetime (years)
DIAL	Green Arrow	14.2
DIAL	Red Circular	17.6
DIAL	Yellow Arrow	12.8
GE	Green Circular	6.6
GE	Green Arrow	9.8
GE	Yellow Arrow	7.5

Based on findings in this study and the previous study, the following replacement schedule is recommended for MoDOT LED Traffic Signal Indications by indication shape (arrow, circular) and manufacturer (GE, Dialight). These findings are provided in Table 6.2.

Table 6.2 – Recommended Replacement Schedule by Signal Shape and Manufacturer

Replacement Schedule Cycle		
	Dialight	**GE**
Arrow	13 years	9 years
Circular	9 years	7 years

The replacement cycle values in Table 6.2 were based on results from MoDOT TRyy1001 and this study. The previous MoDOT study recommended a replacement cycle time of 7-9 years for all circular indications. Due to updated results, the maximum of this range was selected for the circular Dialight indications because the Dialight circular red achieved an estimated lifetime of approximately 17 years. The previous study concluded the Dialight circular green indication should have a replacement cycle of approximately 8.45 years, which has been rounded up to 9 years. Unfortunately, due to the shortened output cycle for circular yellow indications, data analysis did not yield strong enough results to draw any conclusions on the lifetime of Dialight circular yellow indications. Based on previous recommendations and updated results within this study, the replacement cycle time for GE circular indications was determined to be 7 years.

Due to the significantly different lifetimes between manufacturers, the traffic signal indications were separated by manufacturer. By separating traffic signal replacement by manufacturer, MoDOT can realize the economic benefits of extended signal indication lifetimes. Group replacement of signal indications is recommended in order to reduce overall labor costs.

Appendix A – Temperature Analysis

Figure A.1 - Temperature Analysis for Red Indication: Age 2 years

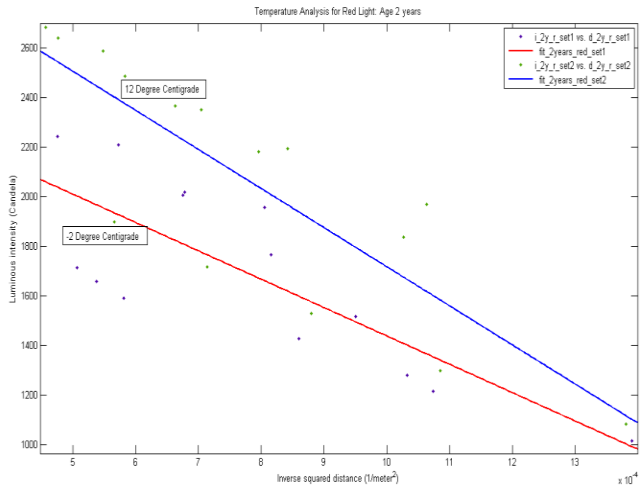


Figure A.2 Temperature Analysis for Red Indication: Age 4 years

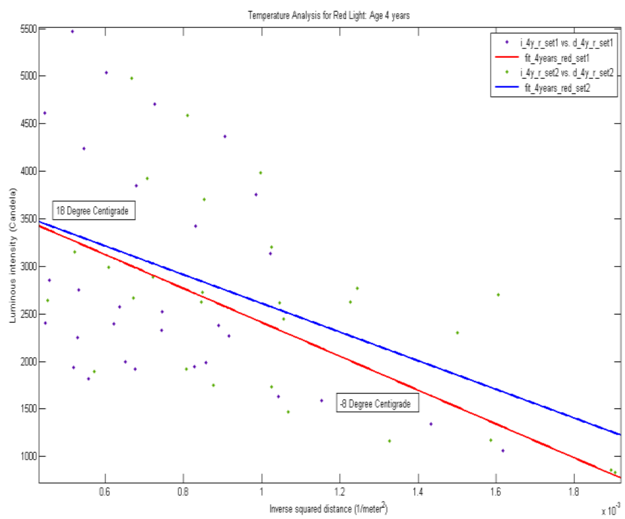


Figure A.3 Temperature Analysis for Red Indication: Age 9 years

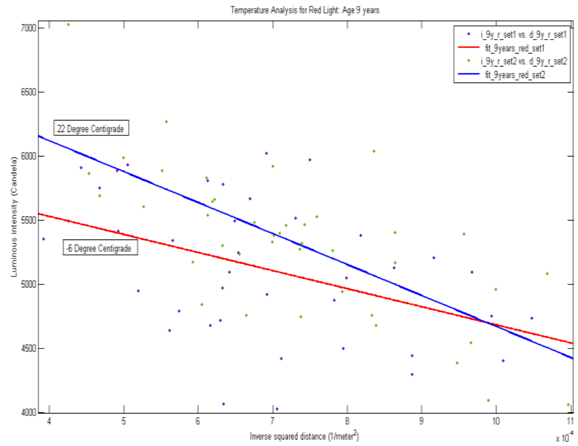


Figure A.4 - Temperature Analysis for Green Indication: Age 1 year

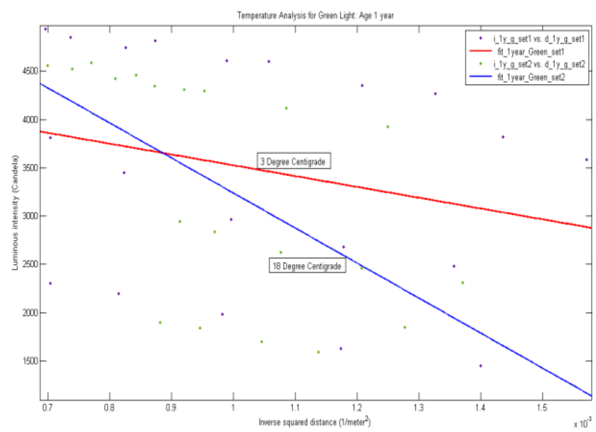


Figure A.5 Temperature Analysis for Green Indication: Age 4 years

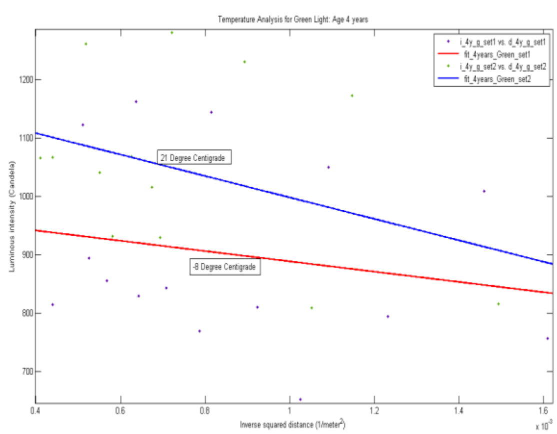


Figure A.6 - Temperature Analysis for Yellow Indication: Age 1 year

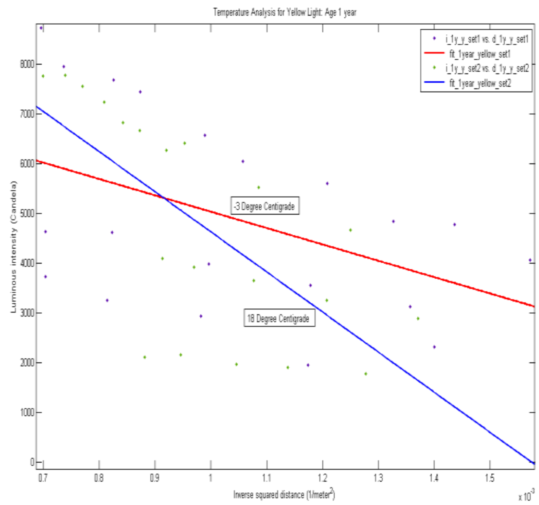


Figure A.7 Temperature Analysis for Yellow Indication: Age 4 years

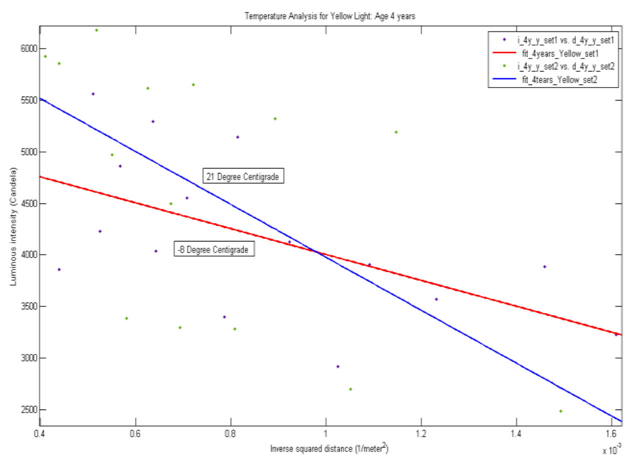


Figure A.8 Temperature Analysis for Green Arrow: Age 1 year

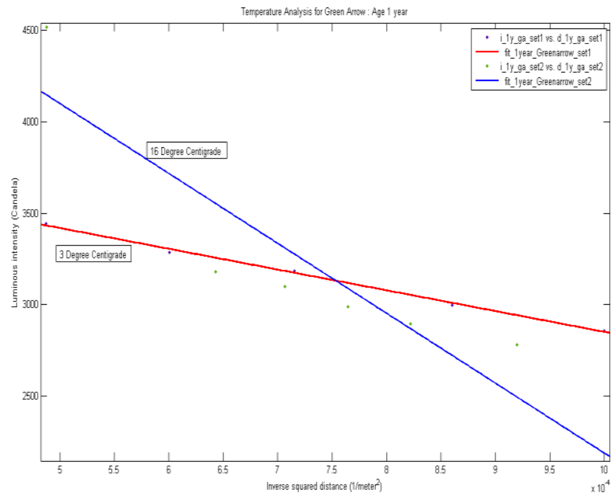


Figure A.9 Temperature Analysis for Green Arrow: Age 7 years

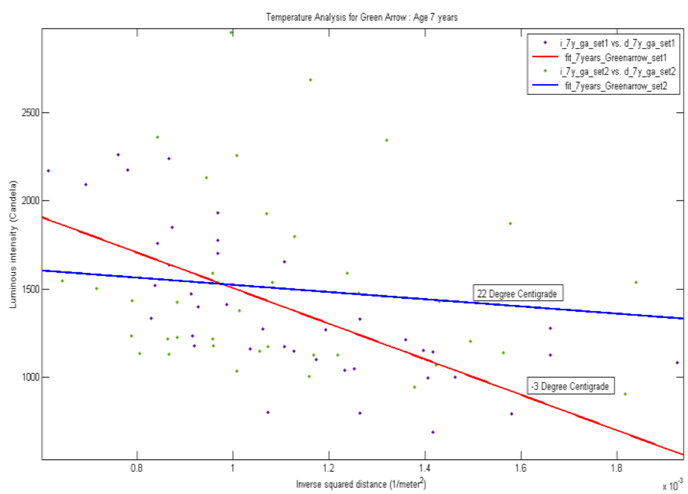


Figure A.10 Temperature Analysis for Green Arrow: Age 10 years

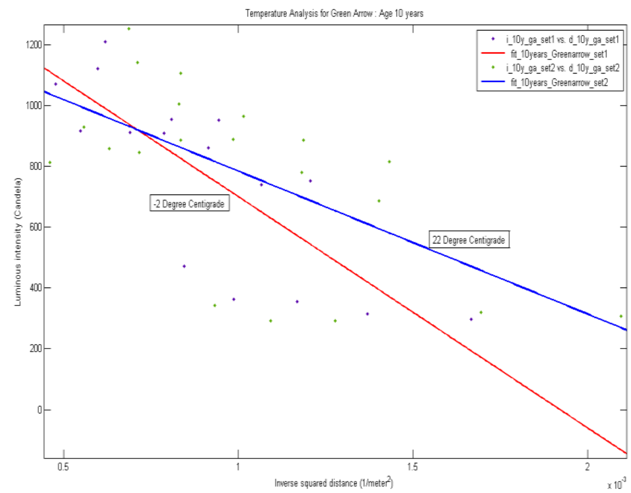
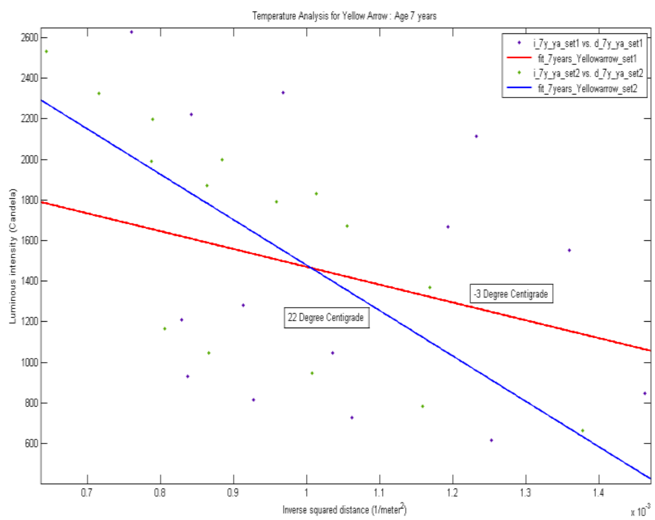


Figure A.11 Temperature Analysis for Yellow Arrow: Age 7 years



References:

1. Lewin, L., Corbin, M., Janoff., (1995). "The application of Light Emitting Diodes to Traffic Signals", IESNA Annual Conference.

2. Vines, J., "Aging of LED Traffic Signal Lights", website http://www.imsasafety.org/journal/mj10/22.pdf, Accessed, 20 January 2014.

3. Replacement Processes for Light Emitting Diode (LED) Traffic Signals. NCHRP Web-only Document 146, Aug 2009.

4. Behura, N., (2007 April). A Survey of Maintenance Practices of Light-Emitting Diode Traffic Signals and Some Recommended Guidelines. ITE Journal.

5. Institute of Transportation Engineers (2005, June 27). Vehicle Traffic Control Signal Heads—Light Emitting Diode Circular Signal Supplement. Washington, D.C.

6. Institute of Transportation Engineers (2007, July 1). Vehicle Traffic Control Signal Heads—Light Emitting Diode Circular Signal Supplement. Washington, D.C.

7. Bullogh, J.D. (2009). Replacement Process for Light Emitting Diodes for Traffic Signals. Contactor's Final report, NCHRP Web Only Document 146, Transportation Research Board. pp 26-30.

8. Urbanik,T., (2008). LED Traffic Signal Monitoring, Maintenance and Replacement Issues. A Synthesis of Highway Practice. NCHRP (Synthesis 387). Washington, D.C.

9. Evaluation of life expectancy of LED traffic signals and development of a replacement schedule in the District of Columbia. Available from Internet: *app.ocp.**dc**.gov/pdf/DCKA-2012-B-0112_Amd4att2.pdf*. (Accessed January 2014).

10. Long, S. et al, Life Expectancy Evaluation and Replacement Schedule Development for LED Traffic Signals. Rolla, USA: Missouri University of Science and Technology, 2010.

11.Long, S. et al, Evaluating Useful Life and Developing Replacement Schedules for LED Traffic Signals: Statistical Methodology and Field study, Engineering Management Journal, 2012.

7.0 Acknowledgements

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