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# LED Traffic Signal Replacement Schedules: Facilitating Smooth Freight Flows 

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## List of Abbreviations

Analysis of Variance (ANOVA)<br>Approved Products List (APL)<br>Federal Highway Administration (FHWA)<br>Institute of Transportation Engineers (ITE)<br>Life Cycle Cost Analysis (LCCA)<br>Light Emitting Diode (LED)<br>Local Technical Assistance Program (LTAP)<br>Luminous Intensity (LI)<br>Manual on Uniform Traffic Control Devices (MUTCD)<br>Mid-America Transportation Center (MATC)<br>Missouri Department of Transportation (MoDOT)<br>Nebraska Transportation Center (NTC)<br>New York State Department of Transportation (NYSDOT)<br>New York State Energy Research and Development Authority (NYSERDA)<br>Transportation Management System (TMS)<br>Vehicle Traffic Control Signal Heads - Light Emitting Diode Circular Signal Supplement (VTCSH-LED)

## Disclaimer

The opinions, findings, and conclusions expressed in this publication are those of the principal investigators. They are not necessarily those of the University of Nebraska Lincoln Mid-America Transportation Center, the Missouri Department of Transportation, the U.S. Department of Transportation or the Federal Highway Administration. This report does not constitute a standard or regulation.


#### Abstract

This research details a field study of LED traffic signals in Missouri and develops a replacement schedule based on key findings. Rates of degradation were statistically analyzed using Analysis of Variance (ANOVA). Results of this research will provide a methodology for engineering managers in state departments of transportation and local communities in identifying best practices and replacement standards for LED traffic signal technology. These findings will facilitate smooth freight flows through the use of more efficient technologies.


## Executive Summary

The goals of this study are 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 LEDs based on the realities of traffic flow, intersection geometrics in Missouri, and the basic science of LED components, and to provide guidelines for cost-effective replacement plans based on these findings. This study uses a combination of field testing and statistical analysis. Specifically, the project includes an evaluation of the impact of manufacturer, indicator type, color, and directional view variables on the degradation of LED traffic signals. A comprehensive LED replacement plan is developed based on the collected data.

Previous studies have measured intensity readings for individual signal heads only by color, rather than by 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 also failed to determine detailed replacement guidelines that include recommendations based on signal head intensity and ITE threshold compliance from the driver's perspective; differences by color, indicator type, and manufacturer; and economic cost-benefit analysis of replacement of individual signal sections versus entire heads. Typically these studies recommended generic replacement schedules based largely on manufacturer warranty, typically five years plus one.

Our findings support the economic value of LED traffic signals over traditional incandescent bulbs and suggest that LED lighting should be evaluated for other applications, including roadway luminaires, parking area lighting, and facilities lighting.

Our findings do not recommend any one manufacturer over another. Cross-sectional results suggest that useful life of LED traffic signals meets or exceeds useful life warranty expectations for most indicator types and manufacturers. Pending longitudinal evaluation, we
recommend an implementation strategy that replaces circular green and green arrow indicators at approximately eight years of age. Preliminary results suggest that circular red indicators hover below the Institute of Transportation Engineers (ITE) threshold for a lengthy period following a rapid drop-off after installation. Based on limitedly observed degradation patterns, we suggest 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 the ITE threshold, we suggest replacement at the ten year mark. If the intensity reading is significantly below the ITE threshold, circular red signal indicators should be replaced at the same time as circular green and green arrow signal indicators. Our concerns over the intensity of circular yellow indicators prevent us from making any recommendation; however, our findings support a replacement plan of six years for yellow arrow indicators.

Two separate clusters emergent from the collected data (see figures 5.4 and 5.5, main report) raise questions as to why a second group of older LED signals has unusually high luminous intensity values. A shift in manufacturing design may be one possible explanation. Our results suggest that the older design degrades more slowly. This should be confirmed through additional longitudinal laboratory and field analyses.

Additionally, our study results strongly indicate 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 our study in either the laboratory or in the field. See Appendix B. 1 for more detail.

Lastly, there is evidence that circular red Dialights degrade to the ITE minimum thresholds rather rapidly. As seen from table B.1, main report, a new circular red Dialight
provided for laboratory study was only slightly above the ITE threshold. Furthermore, figure 5.20, main report shows that the average light intensity value for all age groups of circular red Dialights 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. We strongly recommend the creation of a comprehensive intersection database to promote greater ease of tracking and replacement of LED traffic signals.

## Chapter 1 Introduction

Over the last two decades light-emitting diodes (LEDs) have replaced incandescent bulbs in traffic signals because of their energy savings and much longer service life (Urbanik 2008). Departments of transportation (DOTs) have gained sufficient experience with converting traffic signal indication, however, much of the initial phasing out of incandescent bulbs is complete and many of the first installments of LEDs now need replacement. The standard practices of maintaining and replacing incandescent lamps cannot be simply transferred and applied to LED signals. Engineering managers have to deal with the differences in long term performance between the two technologies and develop new practices that reflect these differences. There is still much uncertainty related to the monitoring, maintenance and replacement of LEDs over the course of their useful life (Urbanik 2008). DOTs have a need for sustainable replacement strategies, but lack a comprehensive understanding of LEDs from an economic, performance and safety perspective.

The problem is severe enough that in 2006 the Institute of Transportation Engineers (ITE) International Board of Direction decided that the lack of knowledge revolving around maintenance and replacement of LEDs warranted the creation of a special task force to address the issue (Behura 2007). To ensure that LEDs aren't left in the field with light output below the recommended values, DOTs are still searching for a reliable method to monitor the light output of LEDs which degrade over time. Determining when an LED signal has reached the end of its useful life is not as clear-cut as it was in the past with incandescent bulbs and new evaluation methods must be created. Whereas incandescent bulbs simply burned out instantly upon failure, LED light output slowly degrades over their five to ten year life cycle. By definition, they reach their end of life when they output an insufficient amount of light as detected by a driver. The

ITE provides standards on minimum light output and light distribution and measures this minimum threshold in candelas (cd). Agencies use the ITE specifications as standards; however they still experience difficulty effectively monitoring the vast amount of LED signals under their control.

With the absence of national standards regarding maintenance for LEDs, transportation agencies are on their own in evaluating the useful life of the LEDs in their traffic signals and determining when they need replacement. This is a costly process that can have large effects on their budgets (Bullough 2009). Many agencies already have scarce funding for citywide replacement or maintenance programs (Behura 2007) and the recent economic downturn only worsens the budget situation.

The large differences between the two signal light technologies, the money concerns and the safety risk clearly show a need for a sustainable, systematic replacement schedule. With current practices, LEDs are often left in use beyond their end of life. When this happens they are functioning, but emit light output levels lower than established standards. Engineering managers need a reliable method of monitoring light output levels to better predict failed light output levels.

In the 1990's LEDs showed the ability to provide huge energy savings for agencies because they consumed a lot less power (watts). As a result, agencies began replacing indicators containing older bulb technology (Urbanik 2008). Early LEDs cost several hundred dollars versus only a few dollars for an incandescent bulb, but their longer expected life and proven energy saving capabilities suggested that they could still yield lower total life cycle costs. Agencies began evaluation programs where intersections were outfitted with LEDs and studied. Early life cycle analyses showed that, despite the huge upfront equipment costs of LEDs, their
benefits still led to lower life cycle costs. MoDOT conducted their own Life Cycle Cost Analysis (LCCA) when they first experimented with installing LED signals at a state intersection and had similar findings. They experienced a $75 \%$ energy reduction and $90 \%$ maintenance cost reduction which led to a lower total life cycle cost, despite the high costs of LEDs in 1999. MoDOT noted that the life cycle costs of LEDs would continue to decrease as LED prices are reduced (Careaga and Allen 2000). Over the last decade, prices have indeed decreased significantly making LEDs an even clearer choice.

Further speeding the transition was the Energy Policy Act of 2005. Title I, Subtitle C, Section 135 mandates that any traffic signal module or pedestrian module manufactured after January 1, 2006 meet the ENERGY STAR energy-efficiency specifications (U.S. Congress, 2005). The U.S. Environmental Protection Agency's ENERGY STAR program sets caps on the maximum amount of wattage a module can consume (ENERGY STAR 2003). This combination of legislation effectively mandated the use of LEDs in all new installations.

### 1.1 Sustainable Advantages of LEDs

Today, LEDs are clearly the superior choice. They use less energy, have longer life expectancies, require less maintenance and have an overall cheaper life-cycle cost. From an energy conservation perspective, LEDs consume far less power. The national average for energy savings is about $85 \%$. Life expectancies are a little less clear because there is a difference between rated life and actual life. Manufacturers rate the average life of LED at 100,000 hours, however this is for a single LED under laboratory conditions, whereas traffic signals contain several hundred LEDs in a system and operate outdoors in harsher environments (Hong and Narendran 2004). These two differences are why the actual life of a LED is actually lower than its rated life. Despite this reduction when compared to the mere 8,000 hours that incandescent
bulbs are rated at (Urbanik 2008), the advantage in useful life is still clear. In practice, LEDs last anywhere from five to 10 years, however in the past, MoDOT replaced incandescent bulbs typically every 1 to 1.5 years (Careaga and Allen 2000). The benefit of such a longer life expectancy is that maintenance crews have to visit intersections less frequently to replace the indicators. Each time a bulb has to be replaced, a two-man maintenance crew must travel to the intersection, set up temporary traffic control and get on a lift to physically change the bulb. The labor cost from frequent visits notably increases the overall lifecycle costs while simultaneously endangering workers, wasting time and fuel for both maintenance workers and the traveling public (additional discussion of operations and maintenance cost-benefit analysis can be found in appendix E).


Figure 1.1 Sustainable benefit of LEDs

### 1.2 ITE Standards

The ITE sets minimum standards for LED modules manufacturers (Behura 2005). These standards were updated for circular LEDs when the Vehicle Traffic Control Signal Heads - Light Emitting Diode Circular Signal Supplement (VTCSH-LED) was published by the ITE in 2005 (Institute of Transportation Engineers 2005). This supplement has been adopted into the Federal Highway Administration's (FHWA) Manual on Uniform Traffic Control Devices (MUTCD). In 2007, the ITE published an additional supplement for arrow indicators (Institute of

Transportation Engineers 2007), and a third supplement in 2009 for pedestrian countdown signals.

The VTCSH-LED sets standards in several areas. The subjects of light intensity and warranty are of particular interest for the present research. The VTCSH-LED supplement rewrote the rules on luminous intensity that formerly applied to incandescent bulbs dating back to 1933 (Behura 2005). The supplement reinforces the need for new LED monitoring and replacement practices. It requires that $8 "(200 \mathrm{~mm})$ and $12 "(300 \mathrm{~mm})$ modules meet the minimum luminous intensities shown in figure 1.2 (Institute of Transportation Engineers 2005). These minimum values uphold a new ratio of red, yellow and green ( $\mathrm{R}: \mathrm{Y}: \mathrm{G}$ ) to $1: 2.5: 1.3$. The values most commonly seen in the literature and on LED signal manufacturers' websites are those for a vertical angle of -2.5 degrees and a horizontal angle of zero degrees. This is likely due to most measurements being taken in a lab, directly in front of the LED. All LEDs included in our study were 12 " modules, and measurements were taken in the field from a driver's perspective; therefore, the most commonly used minimum thresholds were not utilized. The average angle for all readings taken during this study was 10 degrees below the vertical; thus, the values shown in figure 1.2 were chosen for analysis.

| Vertical Angle: <br> Horizontal <br> Angle: | -2.5 degrees <br> 0 degrees |  | -10 <br> degrees <br> 0 degrees |
| :--- | :---: | :---: | :---: |
| Signal Size: | $8 \prime$ <br> $(200 \mathrm{~mm})$ | $12^{\prime \prime}$ <br> $(300 \mathrm{~mm})$ | $12^{\prime \prime}$ <br> $(300 \mathrm{~mm})$ |
| Circular Red | 165 | 365 | $\mathbf{1 9 7}$ |
| Circular Yellow | 410 | 910 | $\mathbf{4 9 1}$ |
| Circular Green | 215 | 475 | $\mathbf{2 5 7}$ |
| Yellow Arrow | - | 146 | $\mathbf{7 9}$ |
| Green Arrow | - | 76 | $\mathbf{4 1}$ |

Figure 1.2 ITE Minimum luminous intensities (cd)

The new ITE supplement sets standards requiring manufacturers to warrant their modules for at least five years, meaning manufacturers must repair or replace any indicators for which minimum luminous output levels fall below the ITE threshold (Institute of Transportation Engineers 2005).

### 1.3 Problems Associated with LEDs: 2007 ITE Survey

After the ITE International Board of Direction created a task force to address the issue of LED maintenance and replacement, the ITE developed a (2007) survey directed toward groups involved with the manufacture, sales, use, and maintenance of LEDs (Behura 2007). In total, 76 traffic agencies and six traffic signal vendors/manufacturers responded to the survey, revealing the following:

- $60 \%$ have no monitoring/replacement procedure
- Half use the ITE specification and half use no specification for minimum light output.
- Replacement approach
- $35 \%$ : no replacement approach
- $35 \%$ : complaint drive
- 24 \%: routine, scheduled replacement
- $3 \%$ : replace on vendor product life cycle
- $3 \%$ : based on in-service test results
- Of those that use a scheduled replacement approach:
- $38 \%$ - five years
- $10 \%$ - six years
- $52 \%$ - Greater than six years
- $73 \%$ use a five-year warranty period (Behura 2007)

As Behura (2007) points out, the ITE survey illustrates several key problems, which motivate the current research. As a whole, current practices of LED monitoring and replacement are inadequate. Figure 1.3 shows that $70 \%$ of those surveyed either have no replacement plan or wait until they receive a complaint before replacing an LED indicator. Guidelines for monitoring and replacement would be beneficial; however, agencies lack the funding and/or resources to address these issues in order to ensure high levels of visibility. Although $82 \%$ of agencies indicated that they use ITE LED specifications, it is obvious that these standards serve no purpose if $60 \%$ lack a monitoring program to check light output levels.

Replacement Approach


Figure 1.3 Current replacement approaches

### 1.4 Current Replacement and Monitoring Practices

An agency currently has two options for choosing a replacement strategy: either replace individual LEDs as they fall below the minimum threshold one at a time, or, segment the signals into groups, either by intersection or signal indication, and replace entire groups at a time. These basic strategies imply that an agency either executes the replacement at a pre-defined interval (usually based on vendor warranty), or only after they receive a complaint. Without guidelines based on the realities of long-term LED performance, agencies that practice scheduled replacement often use the manufacturer's warranty as the interval rate. Doing so keeps liability in the hands of the manufacturer, but is not cost-efficient. Behura (2007) points out that, while warranties range from four to seven years with an average of five, LEDs may last two years or more beyond this estimate, as manufacturers err on the side of caution to avoid costly replacements and potential risk.

Replacement periods based on a manufacturer's warranty are a safe bet, but a truly sustainable solution for DOTs would be to seek to extend the use of an LED past the warranty period whenever possible. The only way to safely accomplish this objective is through statistical understanding of LED life based on actual degradation rates and performance.

To date, several studies and analyses have attempted to determine best practices for replacing LEDs. Bullough (2009) compared the life cycle costs of spot replacement versus group replacement plans, finding in most scenarios that group replacement has a greater cost benefit; however, these results relied heavily on an estimation of useful life and expected failure rates. Although LEDs degrade gradually over time, a limited amount of spot replacements will inevitably be needed even when a group replacement plan has been adopted. Bullough (2009) recommends testing LEDs in the laboratory after the decision has been made to replace them,
then setting aside a small percentage of the LEDs that have the greatest remaining useful life. These partially used but not dead LEDs could be used as a stockpile for spot replacing other LEDs that fail before the scheduled replacement period. This simple addition to any replacement strategy would help reduce LED signal purchases.

In brief, the basis of any monitoring program involves inspecting LED modules either in the field, or in the lab. While Behura (2007) notes that laboratory measurement can provide the most accurate readings, common sense dictates that large quantities of LEDs cannot be actively monitored using this method. A lab measurement requires removal of the LED module from the road, whereas field testing inspects active LEDs on the road. Maintaining a database that contains all relevant information on each module, such as intersection, pole location, head number, color, type, manufacturer, date of installation, and warranty, is recommended for agencies due to the fact that they monitor large quantities of LEDs (Behura 2007).

The New York State Department of Transportation (NYSDOT) performed field measurements with a portable luminance meter on an intersection recently converted to LEDs, finding this method to be a successful means of spot checking signal performance for ITE compliance (New York State Energy Research and Development Authority [NYSERDA] 2001). These field readings were taken at different angles from the vertical angle. And since, for safety reasons, they were taken from sidewalks and traffic islands, they do not portray an accurate estimation from the driver's point of view, because they are not at a horizontal angle or zero degrees. Additionally, no known attempts have been made to use field testing as a means of interpolating the rate of LED degradation.

Although monitoring and replacement strategies currently do exist, there is still no widespread method that incorporates actual degradation rates. A monitoring program that seeks
to understand this degradation rate could provide accurate estimations of useful life that would aid in developing sustainable LED replacement strategies.

## Chapter 2 Objectives

This study provides a repeatable methodology for use by the Missouri Department of Transportation (MoDOT) and other DOTs for the evaluation of LED life expectancy based on the realities of traffic flow, intersection geometrics in Missouri, and the basic science of LED components. We further provide guidelines for cost-effective replacement plans based on our findings. The study utilizes a combination of field testing and statistical analysis.

Specifically, the project includes an evaluation of the impact of manufacturer, indicator type, color, and directional view variables on the degradation of LED traffic signals. Subsequently, we develop a comprehensive LED replacement plan based on our collected data. The final report provides a comprehensive literature review, and is organized around the following tasks: 1) collecting and analyzing data for measuring the light emission capability of circular and arrow indicators, 2) development of models for measuring the useful life of LED lights, 3) development of an LED replacement plan, 4) plans for dissemination through the Local Technical Assistance Program (LTAP).

## Chapter 3 Project Management Approach

Our study included a detailed work schedule, complete with external review processes, and includes the following deliverables: 1) a review of the literature; in particular, we provide details of the models required for data collection and analysis, along with references to literature containing additional information that MoDOT may need in the future, 2) a detailed documentation of the field data. Specifically, we provide the collected raw and processed data, along with a description of the software used for analysis, 3) an evaluation of the output degradation. We provide a detailed report that quantifies the output degradation, its rate, and the useful life of the LEDs by all the factors specified above (e.g., make, model, color, etc.). We describe the statistical analysis performed in determining which factors are responsible for degradation and which factors are not. In addition, we will provide manufacturers' information based on model, circular/arrow indication, warrantee date, and compliance with the current ITE standard. 4) We provide a replacement plan, or schedule, developed from robust statistical analysis. 5) Information developed and implemented through this research project will be shared with local agencies via the LTAP program. We also plan to disseminate the results regionally through the Mid-America Transportation Center (MATC), extending the value of the research beyond Missouri to other Midwestern states.


Figure 3.1 An overview of the task performed in the project

## Chapter 4 Data Collection and Analysis

### 4.1 Field Testing

To date, most LED monitoring programs have involved either removing the indicator and testing it in a laboratory, or using an expensive luminance meter to take readings of the LED from the side of the road. These methods have their benefits, but they also have problems that prevent them from being a comprehensive solution. Though an accurate method of testing, laboratory testing requires too much effort; with state budgets already strained, large-scale use of this method is not feasible. On the other hand, field testing is a cheaper, less intrusive method, but current practices utilize expensive equipment, do not take measurements from the driver's perspective, and do nothing to measure degradation rate. The ability to take a sample of readings from a vehicle, but without disturbing the traffic flow or putting workers in danger, is essential. Another critical issue is calculating the rate of degradation and performing a robust statistical analyses to make predictions about entire cities' or states' LED signals.

Safety is a very important factor in the LED monitoring data collection period. In addition to staying inside of a vehicle, our data collectors recorded readings at night, when traffic was minimal. Data collectors were also required to participate in the Missouri Local Technical Assistance Program (LTAP) Work Zone training program prior to data collection. Readings of the light emission capability of circular and arrow indicators were collected from selected intersections over an 11-week period.

An original field testing instrument was developed by our research team for collecting illuminance readings from intersections across the state of Missouri. Illuminance has a unit of lux, and is a measurement of the density of light falling into an area (lumens $/ \mathrm{m}^{2}$ ). In this case the area is a vehicle, in which a driver would be looking at the traffic signal. The basic components of the instrument comprised a commercial light meter, a range finder, a laser pen, and a custom-
manufactured Fresnel lens. Pictures of the instrument can be found in Appendix D. The Fresnel lens was mounted inside a cylindrical casing that blocked out any ambient light. The instrument worked by filtering in light output emitted from the LED where it was then focused by the Fresnel lens into a concentrated beam. The light meter was placed behind the Fresnel lens at its focal length so that it effectively captured all the light emitted into the opening of the cylindrical casing. Alone, the light meter would be incapable of measuring the illuminance of an LED from long distances, since the ambient light would drown out the light output from the LED; therefore, the Fresnel lens was essential to the design. The range finder was mounted on top of the casing, and measured the distance from the instrument to the LED in feet, which was later converted into meters. The light meter was connected to a laptop via a USB cable. The range finder was connected via a serial port. Both measuring devices fed information into an interface application created to collect and download the field data into a database program. The application could be run for a set period of time to capture the entire cycle of the signal. The laser pen was also mounted on top of the casing to help aim the instrument at the center of the LED light. By combining these components, our research team was able to effectively design an affordable measuring device that was also portable and capable of collecting readings from inside a vehicle at distances that simulated a driver's perspective. Our field testing approach is illustrated in figure 4.1.


Figure 4.1 Field data collection process

Data was collected over a period of 11 weeks. Readings were recorded in a computerized database program. The following information, contained in table 4.1, was recorded for each reading: street intersection, direction of travel (northbound, southbound, eastbound, or westbound), signal head number (1-5), indicator type (red, yellow, green \& circular or arrow), manufacturer, installation date, date measured, illuminance (lux), and distance measured from signal. An exact installation date was not available for some of the LED signals provided by MoDT. In these cases LED manufacture date, or the date the LED was purchased by MoDOT, was used. This finding reinforces the need for a computerized database to track this information.

Table 4.1 A sample data collection table for luminous intensity of a given type of LED

| Intersection | Direction | Signal <br> Head | Indicator | Manufacturer | Date of <br> Installation | Date <br> Measured | Age | Lux | Distance |
| :--- | :--- | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |

From the collected raw data, we determined the rate of decrease in luminous intensity (i.e., degradation, over time). We assumed that the age of an LED was the number of hours of non-stop operation since installation. The Luminous Intensity (LI) is a measure of the power emitted by a light source in a particular direction per unit solid angle (based on the luminosity function, which is a model of the sensitivity of the human eye). The SI unit of luminous intensity is the candela (cd). Luminance is a measure of the luminous intensity per unit area of light travelling in a given direction. Hence, the unit of luminance is $\mathrm{cd} / \mathrm{m}^{2}$. All of our readings measured illuminance (lux) and thus were converted by inputting the distance at which they were recorded into the inverse square law. The inverse square law is illustrated figure 4.2.

$$
\text { Luminous Intensity }(\mathrm{cd})=\text { Illuminance }(\text { lux }) \times \text { Distance }^{2}(\mathrm{~m})
$$

Figure 4.2 Inverse square law for converting readings from illuminance (lux) to luminance (cd)

The rate of degradation was then determined by letting $L I(t)$ denote the luminous intensity in cd from a given LED when the age of the LED is $t$ hours, as seen in figure 4.3. The numerator measures the difference in luminous intensity at time $t$ and at the time of installation. The denominator measures the number of hours of operation. The equation below captures the overall rate of degradation over time:

$$
\text { Rate of degradation }=\frac{L I(t)-L I(0)}{t}(c d \text { per hour })
$$

Figure 4.3 Equation for calculating the rate of degradation

The overall rate of degradation, while useful, does not tell a complete story. For the analysis to be useful, the distribution for the lifetime of the LED had to be determined. The distribution fit directly addresses MoDOT's needs for an LED replacement schedule, providing information related to the probability of failure of an LED at a given point in its lifetime (Lewis 1994). These probabilities were critical for developing a cost-effective replacement plan for LEDs that ensures traffic safety.

It is important to note that the LED becomes less visible to drivers once its luminous intensity falls below a pre-specified threshold. We will refer to this threshold as M. Data for M was gathered from the ITE supplements.

### 4.2 Data Collection Constraints

No comprehensive database of LED indicators currently exists at MoDOT. This is not atypical, and is consistent with standard practices followed by most state DOTs. Individual districts do maintain data sheets that contain some information regarding the traffic signal and the individual signal heads, but this typically does not include full details on manufacturer, age, and model. Obtaining this information was a time- and labor-intensive process for MoDOT employees, and had to be completed on top of regular duties. Inclement weather at the beginning of the study period understandably delayed the compilation of signal head information. In addition, signal heads were installed to meet traffic control needs-not as part of a controlled performance study-so signal placement by manufacturer and age was somewhat random. These complexities created challenges for creating an optimal sampling strategy. The study duration allowed for only a three-month data collection phase, and prevented repeat sampling of studied intersections beyond the initial collection efforts. Recommendations for the construction of a comprehensive database appear as part of overall study recommendation

Chapter 5 Development of Models for Measuring Useful Life of LED Lights The methodology used to evaluate and sort the collected data is described as the equivalent of a process map. This process allowed the research team to determine which data records could be grouped to improve the statistical significance of results and contribute to useful life models and degradation studies that are used to determine replacement schedules. Note that the ability to form groups does not mean that statistically significant results are possible, only that sufficient data is present to perform analysis.

### 5.1 Descriptive Statistics

We collected luminous intensity data from 372 unique LED indications in Missouri, which serve as data points. These data points cover five manufacturers (ACT, Dialight, GE, LTEK and PHILIPS) and five indicator types (Circular Green, Circular Red, Circular Yellow, Green Arrow, Yellow Arrow). The distribution of the 372 data points are summarized in tables 5.1 and 5.2, and are displayed in figures 5.1, 5.2, and 5.3. Table 5.1 shows that $51.3 \%$ of the measured LED traffic indicators were Dialight products, $38.7 \%$ were GE, $9.4 \%$ LTEK, and less than $1 \%$ were ACT and PHILIPS. Therefore, only products from three manufacturers were studied: Dialight, GE, and LTEK.

Table 5.1 Distribution of LED traffic signals over manufacturers and indicators

| Manufacturer | Circular <br> Green | Circular <br> Red | Circular <br> Yellow | Green <br> Arrow | Yellow <br> Arrow | Subtotal |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| ACT | 1 |  |  |  |  | $\mathbf{1}$ | $\mathbf{0 . 3 \%}$ |
| DIALIGHT | 10 | 67 | 30 | 56 | 28 | $\mathbf{1 9 1}$ | $\mathbf{5 1 . 3 \%}$ |
| GE | 68 | 34 | 5 | 25 | 12 | $\mathbf{1 4 4}$ | $\mathbf{3 8 . 7 \%}$ |
| LTEK |  |  | 34 |  | 1 | $\mathbf{3 5}$ | $\mathbf{9 . 4 \%}$ |
| PHILIPS |  | 1 |  |  |  | $\mathbf{1}$ | $\mathbf{0 . 3 \%}$ |
| subtotal | $\mathbf{7 9}$ | $\mathbf{1 0 2}$ | $\mathbf{6 9}$ | $\mathbf{8 1}$ | $\mathbf{4 1}$ | $\mathbf{3 7 2}$ |  |
|  | $\mathbf{2 1 . 2 \%}$ | $\mathbf{2 7 . 4 \%}$ | $\mathbf{1 8 . 5 \%}$ | $\mathbf{2 1 . 8 \%}$ | $\mathbf{1 1 . 0 \%}$ |  | $\mathbf{1 0 0 \%}$ |

ACT (Act One Communications [http://actoneled.com/ledtraffic/signals.htm](http://actoneled.com/ledtraffic/signals.htm)); Dialight (Dialight < http://www.dialight.com/ >);GE (General Electric http://www.lumination.com/category_products.php?cat_id=21\&id=42 >); LTEK (Leotek <http://www.leotek.com/products/traffic-and-transit.asp >);
PHILIPS (Lumileds [http://www.philipslumileds.com/](http://www.philipslumileds.com/))

The manufacturer-indicator combination divides the 372 data points into 25 groups (see table 5.1). Figure 5.1 indicates the 10 groups that can be studied:

- Dialight (Circular Green, Circular Red, Circular Yellow, Green Arrow, Yellow Arrow)
- GE (Circular Green, Circular Red, Green Arrow, Yellow Arrow)
- LTEK (Circular Yellow)


Figure 5.1 Distribution of LED traffic signals by manufacturers (further split by indicator type)

Figure 5.2 (next page) suggests that five manufacturer comparisons should be performed:

- Circular Green (Dialight vs. GE)
- Circular Red ( Dialight vs. GE)
- Circular Yellow (Dialight vs. LTEK)
- Green Arrow (Dialight vs. GE)
- Yellow Arrow (Dialight vs. GE)


Figure 5.2 Distribution of LED traffic signals by indicator type (further split by manufacturers)

Figure 5.3 (next page) displays the distribution of the 372 data points over their ages. These indicators are not evenly distributed over ages, and occur mainly in the following age segments:

- $51.9 \%$ - within two to five years of age
- $22 \%$ - within 5.9-8.0 years of age
- $9.4 \%$ - nine years of age
- $10.5 \%-12$ years of age or older

The uneven distribution of data over ages might impede the recognition of degradation patterns.


Figure 5.3 Distribution of LED traffic signals over ages

Table 5.2 further provides the distribution of the 372 data points over ages, grouped by manufacturer and indicator. The 10 groups with at least 10 records are highlighted by color. Each group contains LED indicators at multiple ages; therefore, a degradation pattern might be found for each of the 10 groups.

Table 5.2 Distribution of LED indicators over manufacturers, indicators, and ages

| Count Records |  | Age (years) |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | Grand Total |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Manufacturer | Indicator | 0.95 | 1.03 | 2.28 | 2.36 | 3.00 | 4.00 | 4.36 | 5.00 | 5.12 | 5.28 | 5.36 | 5.47 | 5.53 | 5.70 | 5.90 | 5.95 | 6.00 | 6.03 | 6.12 | 6.28 | 6.53 | 7.00 | 8.00 | 8.20 | 8.23 | 8.36 | 9.00 | 9.18 | 9.43 | 9.51 | 11.0 | 12 |  |
| ACT | Circular Green |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 |  |  |  |  |  |  |  |  |  |  |  |  | 1 |
| ACT Total |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 |  |  |  |  |  |  |  |  |  |  |  |  | 1 |
| Dialight | Circular Green | 1 | 2 |  |  |  |  |  |  |  |  |  |  | 1 |  |  |  |  |  |  |  | 4 |  |  |  |  |  |  |  | 1 |  |  | 1 | 10 |
|  | Circular Red |  |  |  |  | 12 | 12 |  | 6 |  |  |  | 1 | 3 | 1 | 9 |  |  | 2 |  |  | 2 | 3 |  |  |  | 1 | 4 | 1 |  |  |  | 10 | 67 |
|  | Circular Yellow |  |  |  |  | 6 | 12 |  | 6 | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 4 |  |  |  |  | 1 | 30 |
|  | Green Arrow |  |  |  |  | 12 | 12 |  | 12 |  |  |  |  |  |  |  |  | 1 |  |  |  |  | 6 |  |  |  |  | 2 |  |  | 1 |  | 10 | 56 |
|  | Yellow Arrow |  |  |  |  | 4 | 4 |  | 4 |  |  |  |  |  |  |  |  |  |  |  |  |  | 2 |  |  |  |  | 4 |  |  | 1 |  | 9 | 28 |
| Dialight Total |  | 1 | 2 |  |  | 34 | 40 |  | 28 | 1 |  |  | 1 | 4 | 1 | 9 |  | 1 | 2 |  |  | 6 | 11 |  |  |  | 1 | 14 | 1 | 1 | 2 |  | 31 | 191 |
| GE | Circular Green |  |  |  | 1 |  |  | 40 |  |  | 2 | 1 |  |  |  |  |  | 1 |  |  |  |  |  | 7 | 3 |  |  | 13 |  |  |  |  |  | 68 |
|  | Circular Red |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 5 | 9 |  |  |  |  |  | 4 |  |  |  | 8 |  |  |  | 8 |  | 34 |
|  | Circular Yellow |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 5 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 5 |
|  | Green Arrow |  |  |  |  |  | 12 |  |  |  | 1 |  |  |  |  |  | 1 | 4 |  | 7 |  |  |  |  |  |  |  |  |  |  |  |  |  | 25 |
|  | Yellow Arrow |  |  |  |  |  | 3 |  |  |  |  |  |  |  |  |  | 5 | 4 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 12 |
| GE Total |  |  |  |  | 1 |  | 15 | 40 |  |  | 3 | 1 |  |  |  |  | 11 | 23 |  | 7 |  |  |  | 11 | 3 |  |  | 21 |  |  |  | 8 |  | 144 |
| LTEK | Circular Yellow |  |  | 26 |  | 8 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 34 |
|  | Yellow Arrow |  |  |  | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 |
| LTEK Total |  |  |  | 26 | 1 | 8 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 35 |
| PHILIPS | Circular Red |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 |  |  |  |  |  |  |  | 1 |
| PHILIPS Total |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 |  |  |  |  |  |  |  | 1 |
| Grand Total |  | 1 | 2 | 26 | 2 | 42 | 55 | 40 | 28 | 1 | 3 | 1 | 1 | 4 | 1 | 9 | 11 | 24 | 2 | 7 | 1 | 6 | 11 | 11 | 3 | 1 | 1 | 35 | 1 | 1 | 2 | 8 | 31 | 372 |

### 5.2 Identification of Factors that Impact Degradation Patterns

The 372 data points were placed on the space of Luminous Intensity against Age, as shown in figure 5.4. They data tended to form two clusters: cluster one contained all data points between zero and seven years of age, while cluster two contained all data points eight years of age and older. This second cluster seemed to exceed performance expectations.


Figure 5.4 Luminous intensity vs. age for all LEDs

Further, we plotted the average luminous intensity at each year of age, as shown in figure 5.5. Two clusters of average value are clearly separated, confirming the observation from figure 5.4. The cluster circled by the dashed curve includes 50 LED indicators: 15 are Dialight products and 35 are GE products. They are located at the following intersections: $47 \& \mathrm{~V}, 50 \&$ Prairie Dell, 61 \& Forder, 61 \& Keller, 61 \& Mehl, 63 \& MO, 763 \& BigBear, 763 \& Paris, 763 \& University, and Rte63 \& Lowes. There are many possible explanations, which may be worth
further investigation, why we observed the two separate clusters. For example, this cluster of 50 LEDs all happened to be eight years old or older. It is possible that manufacturers changed designs during this time period, and therefore there exists a second group of older LEDs that all have unusually high luminous intensity values. Our current understanding is that manufacturers are moving away from the older LED design, where the signal can clearly be identified as using LED technology as opposed to an incandescent bulb. In this style of manufacture, all of the individual LEDs are positioned on a circuit board in a circular or arrow shape and are clearly visible. MoDOT provided us with newer Dialight LEDs and we observed that the design is now drastically different: only six LEDs are present in the signal and are behind a tinted diffuser and a plastic Fresnel lens. This new manufacturing style is also evident on GE's and other manufacturers' websites, where they list their latest models as an "incandescent look." See Appendix A for pictures depicting the two different manufacturing styles and additional discussion.


Figure 5.5 Average luminous intensity vs. age

To determine whether each indicator had a unique degradation pattern, we plotted the average luminous intensity for every indicator at each year of age, as seen in figure 5.6. Figure 5.6 indicates between-indicator differences. For example, arrow indicators may have different degradation patterns than circular indicators. Therefore, for each indicator type we studied the plots of luminous intensity over Age, comprising figures 5.7-5.11. A degradation pattern is not observed for circular green, circular red, and yellow arrow. Circular yellow shows a clear pattern, and green arrow has a weak pattern. Removal of the older clusters does allow observance of degradation patterns; however, these may not be statistically significant due to limited available data.


Figure 5.6 Average luminous intensity vs. age (split by indicator)


Figure 5.7 Luminous intensity vs. age (circular green)


Figure 5.8 Luminous intensity vs. age (circular red)


Figure 5.9 Luminous intensity vs. age (circular yellow)


Figure 5.10 Luminous intensity vs. age (green arrow)


Figure 5.11 Luminous intensity vs. age (yellow arrow)

We further investigated the average luminous intensity at each year of age for selected manufacturers, shown in figure 5.12. Between-manufacturer differences are indicated by figure 5.12. Figures 5.13-5.15 are the plots of luminous intensity over ages for each of the three manufacturers. Note that none of these three plots show a degradation pattern.


Figure 5.12 Average luminous intensity vs. age (split by indictor)


Figure 5.13 Luminous intensity vs. age (Dialight)


Figure 5.14 Luminous intensity vs. age (GE)


Figure 5.15 Luminous intensity vs. age (LTEK)

### 5.3 Potential Degradation Patterns

Figures 5.7-5.11 and 5.13-5.15 suggest that the degradation pattern of LED indicators may be affected by two factors (i.e., manufacturer and indicator), as well as their interaction (manufacturer x indicator). Therefore, for the 10 identified manufacturer-indicator combination groups, we plotted the average luminous intensity over ages, as shown in figures 5.16-5.23. For figures 5.16-5.23, a line is included illustrating the corresponding ITE minimum threshold. For most groups, a degradation pattern was observed and fitted.


Figure 5.16 Average luminous intensity vs. age for Dialight (split by indicator)


Figure 5.17 Average luminous intensity vs. age for GE (split by indicator)


Figure 5.18 Average luminous intensity vs. Age for LTEK (split by indicator)


Figure 5.19 Average luminous intensity vs. age for circular green (split by manufacturer)


Figure 5.20 Average luminous intensity vs. age for circular red (split by manufacturer)


Figure 5.21 Average luminous intensity vs. age for circular yellow (split by manufacturer)


Figure 5.22 Average luminous intensity vs. age for green arrow (split by manufacturer)


Figure 5.23 Average luminous intensity vs. age for yellow arrow (split by manufacturer)

## Chapter 6 Development of a Replacement Plan for LEDs

### 6.1 Overview of the Analysis

The goal of the replacement plan statistical analysis is to predict the ages at which the LED indicators need to be replaced. We collected data for light intensity from a large number of signalized intersections. Statistical models were used to predict how quickly light intensity decayed (diminished) with age. These models were used to determine the age at which LEDs require replacement. Our models take into account the ITE standards as well as randomness in light generation from LEDs. We present a detailed account of our statistical analysis below.

### 6.2 Data Screening Constraints

The first step in the process was to collect data for light intensity for LEDs at different signalized intersections identified by MoDOT. Color, age, make (company of manufacture) and type (arrow or circular) were also recorded during data collection. This helped us to separate data based on color, make, and type. Light intensity was then plotted against age. Outliers from the data were removed.

LED technology has a great deal of variability in light illuminance. In particular, LED indicators of a given color manufactured by the same company are expected to emit the same light intensity when purchased, but the rate at which light intensity declines with age may exhibit a large amount of variability per signal head. Our analysis indicates that there is a significant amount of variability in the degradation process, which we refer to as randomness. Our analysis was directed toward finding a trend in the rate of decline, and using this trend in formulating recommendations for a replacement schedule. In the analysis performed, we discarded data outliers that could potentially skew results and provided misleading conclusions. Ideally, it is best to collect data from the same LED indicators at different ages over the lifetime of an
individual signal head. However, this was impractical due to study constraints. As a result, we developed a technique that provides comparable results for different LED indicators so long as there is an appropriate age span for the studied signal heads. Data from LEDs that have the same age, color, make, and type are averaged to obtain an estimate of the light intensity at a given age for the color-make-type combination.

### 6.3 Methodology

We plotted light intensity based on a given color-make-type combination against age. Intensities from LEDs of the same age for a given color-make-type combination are averaged to obtain an estimate of the light intensity at the given age. For example, if the three values for circular green LEDs from GE at the age of two years were 310, 290, and 300, we averaged them to obtain the value $(290+300+310) / 3=300$ in order to obtain an estimate of light intensity at the age of two years. In this way, we constructed estimates for the complete age range. A curve was fitted through the data to predict the rate of degradation. A linear curve (i.e., a straight line) was a good fit for most of the cases examined. To illustrate, consider the graph below (fig. 6.1). It shows age on the $x$-axis and light intensity on the $y$-axis for circular green LEDs manufactured by GE.

The linear fit obtained was as follows: $Y=386.6-28.139 X$, where $Y=$ light intensity and $X=$ age. The value of $Y$ was set to the ITE threshold to determine the age at which LED should be replaced. For instance, in this case, the ITE threshold was 257 . Setting $\mathrm{Y}=257$ in the equation above yielded: $257=386.6-28.139 X$, i.e., $X=4.65$ years. This implied that on average the threshold will be reached in 4.65 years. We used five years as an optimistic estimate for the optimal age of replacing the LED and four years as the pessimistic estimate.

We noticed that in many cases, data showed that after some degradation light intensity actually increased. This is because different LEDs of the same color-make-type actually degraded at different rates. An outlier approach was used in addressing such data. The outlier approach smoothes the data and predicts the most conservative estimate for the age replacement schedule. Figure 6.1 presents an example of degradation patterns. Full degradation analysis is available on CD through MoDOT.


Figure 6.1 Degradation of the average light intensity vs. age for GE circular green

We used a deterministic regression model with which only the average value of the LED's average intensity can be predicted. It is not possible to predict the variability in the intensity based on the regression analysis performed above (see fig. 6.1). Regression equations used for our analysis are presented below.

Table 6.1 Regression equations

| Type | Regression Equation | Solution (yrs) |
| :---: | :---: | :---: |
| Circular, Green, GE | $\mathrm{Y}=-28.139 \mathrm{X}+386.6$ | 4.61 |
| Circular, Green, Dialight | $\mathrm{Y}=-32.415 \mathrm{X}+531.07$ | 8.45 |
| Arrow, Green, Dialight | $\mathrm{Y}=-12.681 \mathrm{X}+154.61$ | 8.95 |
| Arrow, Green, GE | $\mathrm{Y}=-9.8846 \mathrm{X}+116.46$ | 7.63 |
| Circular, Red, GE | $\mathrm{Y}=-6.8846 \mathrm{X}+507.27$ | $* * *$ |
| Circular, Red, Dialight | $\mathrm{Y}=-10.932 \mathrm{X}+190.99$ | $* * *$ |
| Circular, Yellow, Dialight | $\mathrm{Y}=-22.332 \mathrm{X}+298.37$ | $* * *$ |
| Arrow, Yellow, GE | $\mathrm{Y}=-33.366 \mathrm{X}+274.37$ | 5.85 |
| Arrow, Yellow, Dialight | $\mathrm{Y}=-5.9974 \mathrm{X}+115.56$ | 6.09 |

***insufficient data for feasible statistical analysis

### 6.4 Findings

Table 6.2 provides the age of replacement for LEDs for which we were able to obtain sufficient data. Recommended replacement ages for each type of indicator are presented in the "Age for Replacement" column, with both pessimistic (l) and optimistic (m) estimates. Note that even for the color-make-type combinations for which data was gathered, in some cases there was insufficient data (the case of Red-Dialight-Circular, Yellow-LTEK-Circular, Yellow-PhilipsCircular, and Yellow-Dialight-Circular) and in one case, the data was not sufficient to develop an acceptable regression fit (Red-GE-Circular). Tables 6.3 and 6.4 show our findings by manufacturer where table 6.3 is for GE and table 6.4 is for Dialight:

Table 6.2 Age of recommended replacement for all LED signal head types

| Type | Age For Replacement (yrs) <br> $(l, m)$ | ITE Threshold (cd) |
| :---: | :---: | :---: |
| Circular, Green, GE | (4 years, 5 years) | 257 |
| Circular, Green, Dialight | (8 years, 9 years) | 257 |
| Circular, Red, Dialight | $*++($ see Table 6) | 197 |
| Circular, Red, GE | $* *$ | 197 |
| Circular, Yellow, LTEK | $*$ | 491 |
| Circular, Yellow, Philips | $*$ | 491 |
| Circular, Yellow, Dialight | $*$ | 491 |
| Arrow, Green, Dial | (8 years, 9 years) | 41 |
| Arrow, Green, GE | (7 years, 8 years) | 41 |
| Arrow, Yellow, GE | (5 years, 6 years) | 79 |
| Arrow, Yellow, Dialight | (5 years, 6 years) | 79 |

*Insufficient intersections available for study
**Regression fit may not be very reliable due to insufficient age variability

Table 6.3 Replacement schedule for GE

| Type | Age for replacement (yrs) | ITE Threshold (cd) |
| :---: | :---: | :---: |
| Circular, Green | (4 years, 5 years) | 257 |
| Arrow, Green | (7 years, 8 years) | 41 |
| Arrow Yellow | (5 years, 6 years) | 79 |

Table 6.4 Replacement schedule for Dialight

| Type | Age for Replacement (yrs) | ITE Threshold (cd) |
| :---: | :---: | :---: |
| Circular, Green | (8 years, 9 years) | 257 |
| Arrow, Green | (8 years, 9 years) | 41 |
| Arrow, Yellow | ( 5 years, 6 years) | 79 |

++ 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 for Dialight red. Study of additional intersections with sufficient age variability may alleviate this issue.

### 6.5 Summary of Replacement Schedule Constraints

## Dialight Products:

1. Circular Green: Excellent data fit to regression line; however, limited data records, or signal heads, reduce statistical significance of results.
2. Green Arrow: Excellent data fit to regression line; adequate data records to improve statistical significance.
3. Circular Yellow: Degradation present, but issues observed with ITE recommended ratios. Further study warranted.
4. Yellow Arrow: Degradation present, but insufficient data for statistical regression.
5. Circular Red: Issues observed with ITE threshold compliance. Further study warranted.

GE Products:

1. Circular Green: Adequate data records but the majority are four years of age; four year LEDs studied display high levels of variability/signal head. Inadequate indicators of age one to two years to anchor regression line.
2. Green Arrow: Adequate data records but the majority are four years of age; four year LEDs studied display high levels of variability/signal head. Inadequate indicators of age one to two years to anchor regression line.
3. Circular Yellow: Degradation present, but issues observed with ITE recommended ratios. Further study warranted.
4. Yellow Arrow: Degradation present, but insufficient data for statistical regression.
5. Circular Red: Issues observed with ITE threshold compliance. Further study warranted.

## Chapter 7 Conclusions

Based on our findings, LEDs are a superior economic choice. They offer significant benefits in terms of operation and maintenance costs, as well as useful life, with respect to traditional incandescent bulbs. Our useful life results suggest that the replacement plan for LED signal indicators must take into account the cost of replacing an LED signal head and the cost of failure of an LED when it is in use. A failure of an LED indicator, defined as luminous intensity below the ITE threshold, could negatively impact the traffic it controls.

Previous studies have measured intensity readings for individual signal heads only by color, rather than by 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 including recommendations based on: signal head intensity and ITE threshold compliance from the driver's perspective; differences by color, indicator type, and manufacturer; economic cost-benefit analysis of replacement of individual signal heads versus entire traffic signals. Instead, these studies recommended generic replacement schedules based largely on manufacturer warranty, typically five years plus one.

Our results show that generic replacement schedules are not comprehensive enough to inform optimal replacement decisions based on operations and maintenance replacement costs, color, and indicator type. We were able to develop detailed replacement guidelines for the majority of Dialight and GE products. Due to insufficient data and age variance, we are not able to make statistically robust decisions for red and circular yellow LEDs. Because payback period for maintenance costs (see Appendix E) is estimated at two to three years, and green LEDs have a useful life expectancy for two to three additional years over yellow LEDs, we do not recommend common replacement of green and yellow indicators.

The two separate clusters evident in figures 5.4 and 5.5 raise questions as to why a second group of older LEDs had unusually high luminous intensity values. A shift in manufacturing design is one possible explanation. After detailed laboratory analysis of the LED indicators provided by MoDOT, a clear difference in the design of the LEDs was noted. The yellow and green Leoteks, seen on the left in Appendix A, figure A.1, consisted of 200 individual LEDs in a circular shape covered by a tinted plastic cover. To a driver they, can be clearly distinguished as LEDs, versus traditional incandescent lights. We call this the "LEDlook." The Dialights (circular red, green) revealed a different design. As seen on the right in Appendix A, figure A.1, the Dialights contained only six LEDs each and incorporated a prism, a Fresnel lens, and a plastic diffuser. Unlike the Leoteks, the physical LEDs in these Dialights were not visible from the outside of the light, and look very similar to incandescent indicators. The strong resemblance to incandescent indicators was confirmed during our data collection phase. We could not visually confirm whether an indicator was an LED.

Additionally, our study results strongly indicated the need for additional laboratory and field study of circular yellow LEDs. ITE guidelines specify that circular yellow maintain the highest luminous intensity at a red to yellow to green ratio of (1:2.5: 1.3). This implies that the candela values for circular yellow LEDs should have been 2.5 times greater than those of circular red, on average. This was not observed during our study in either the laboratory or in the field. See Appendix B for more detail.

Finally, there is evidence that circular red Dialights degrade to the ITE minimum thresholds rather rapidly. As seen in B. 3 in Appendix B, a new circular red Dialight provided for laboratory study was only slightly above the ITE threshold. Furthermore, figure 5.20 shows that
the average light intensity values for all age groups of circular red Dialights were also below the ITE minimum. This product should also be subjected to further laboratory and field analyses.

### 7.1 Replacement

Circular Green. Although limited statistical inferences can be drawn based on manufacturer, differences were indeed present. Based on our results, Dialight circular green products outperform GE circular green signal heads and have several additional years of expected life, though these conclusions are based on limited data. Results fall within confidence limits. However, high levels of variability per signal head suggest that these differences may not be present when comparable numbers of data records are studied for both manufacturers.

Green Arrow. Dialight and GE green arrow products displayed a comparable useful life and similar degradation patterns.

Yellow Arrow. Comparable useful life degradation patterns were calculated for yellow arrow signal indicators irrespective of manufacturer. ITE ratio discrepancies were observed and further study is needed.

Circular Red. Conclusions regarding circular red indicators cannot be made at this time due to insufficient intersection identification by manufacturer and age variance. Red signal indicators quickly fall below ITE threshold, but do not degrade at a significant rate after the initial reduction in intensity, suggesting that their useful life may approach two to three times manufacturer's warranty. This finding should be confirmed with a longitudinal study.

Circular Yellow. Conclusions regarding circular yellow indicators cannot be made at this time due to issues with illuminance ratios suggested by ITE. Intensity readings were below the recommended brightness ratio from the literature. Further discussions with manufacturers and ITE may provide guidance on updates to the standard, and allow detailed analysis.

### 7.2 General

Obtaining detailed information of each traffic indicator for a given traffic intersection, such as age and manufacturer, proved to be a difficult task. MoDOT currently maintains an intersection inventory which identifies the quantity and color of LEDs in intersections, but it is limited to that information. Determining dates of manufacture, purchase, and installation, all of which are important pieces of information, was often difficult (see Appendix C for further documentation of this observation). We strongly recommend the creation of a comprehensive intersection database that could store information on all 2,500 signalized intersections statewide. Such a database would allow MoDOT to pull every piece of information for any intersection simply by running a query. It would include all available information on traffic intersections maintained by MoDOT, and the following specifics to LEDs: intersection, direction (NB, SB, EB, WB), signal head ( $1,2,3,4,5$ ), indicator type (circular red, circular green, circular yellow, green arrow, yellow arrow), manufacturer, date manufactured, date purchased, date installed, age, recorded light and intensity values over time (cd).

## Chapter 8 Recommendations and Implementation Plan

Our findings support the economic value of LED traffic signals (over traditional incandescent bulbs). Current data does not support any one manufacturer over another. Crosssectional results suggest that the useful life of LED traffic signals meets or exceeds useful life warranty expectations for most indicator types and manufacturers. Pending longitudinal evaluation, we recommend an implementation strategy that replaces circular green and green arrow indicators at approximately eight years of age. Preliminary results suggest that circular red indicators hover below the ITE threshold for a lengthy period following a rapid drop-off after installation. Based on limitedly observed degradation patterns, we suggest that circular red indicators should be evaluated when circular green and green arrow indicators are replaced. If the luminous intensity continues to hover near threshold, we suggest replacement at the ten-year mark. If the intensity reading is significantly below ITE threshold, the LED should be replaced with circular green and green arrow signal heads. Our concerns over the intensity of circular yellow indicators preclude us from making any recommendations; however, our findings support a replacement plan of six years for yellow arrow indicators.

Based on our conclusions, we strongly recommend that MoDOT create a database system to manage their LED traffic signal replacement plan. This database would allow for effective identification of traffic signals requiring LED intensity checks for ITE threshold compliance. Based on enhanced degradation information gained through future LED intensity checks, the replacement program interface application could analyze and predict future funding needs, check manufacture warranties for potential replacement, and lead to performance-based specification for LED product inclusion into the current Approved Products List (APL). Specific implementation strategies include incorporation of the new database module with the existing

Transportation Management System (TMS) that currently records other pertinent information about traffic signals, as well as the use of undergraduate or graduate student interns to collect relevant signal head information and conduct data entry

Chapter 9 Principle Investigator and Project Members


## References

Act One Communications. Retrieved October 1, 2010. www.actoneled.com.
Anonymous. 1999. "Newark first city in New Jersey to get new LED traffic lights." Transportation Research Board of the National Academies, September 1, 1999. http://trid.trb.org/.

Anonymous. 2000. "Review of articles and information on LED traffic signals." Lighting Research Center, Rensselar Polytechnic Institute and American Council for an Energy Efficient Economy (July).

Anonymous, 2001. "Energy efficiency success story, LED traffic signals = energy savings, for the city of Portland, Oregon." www.sustainableportland.org.

Anonymous. 2003. "Final report: Conventional vs. LED traffic signals; Operational characteristics and economic feasibility." Arkansas Department of Economic Development, Traffic Engineering Division, Department of Public Works, Little Rock, AK, July 1, 2003. www.cee1.org/gov/led.

Anonymous. 2004. "State energy program case studies: California says 'Go' to energy-saving traffic lights." U.S. Department of Energy, Washington, D.C. www.energy.ca.gov.

Behura, N. 2007. "A survey of maintenance practices of light-emitting diode traffic signals and some recommended guidelines." Institute of Transportation Engineers, 77: 18-22.

Behura, N. 2005. "The new ITE light-emitting diode traffic signal specifications - A guide for purchasers." ITE Journal, 38-40. November, 2005.

Briggs, B., 2000. "City lights get brighter: New LED bulbs figure to save Denver millions." February 8, 2000.

Bullough, J. D., J. D. Snyder, A. M. Smith, and T. R. Klein. 2009. "Replacment processes for Light Emitting Diode (LED) traffic signals." Contractor's final report. NCHRP WebOnly Document 146, Transportation Research Board. https://www.transportationresearch.gov/dotrc/hfct/Shared\ Research/Replacement\  Processes\%20for\%20Light\%20Emitting\%20Diode\%20Traffic\%20Signals.pdf

Careaga, A., and T. Allen, T. 2000. "Light Emitting Diode (LED) signal installation." Final Report, Missouri Department of Transportation, Jefferson City, MO.

Crawford, G. L. 1999. "Roadway safety improvements: Using liability to evaluate." Enhancing transportation safety in the 21 st century ITE International Conference, Kissimmee, FL

Das, S., 1999. "High-technology traffic signals given green light." Australasian Business Intelligence, July, 1999.

ENERGY STAR. 2003. "ENERGY STAR program requirements for traffic signals: Eligibility criteria." Accessed May, 2010. http://www.energystar.gov

Hong, E., \& N. Narendran. 2004. "A method for projecting useful life of LED lighting systems." Third International Conference on Solid State Lighting, Proceedings of SPIE, 5187: 9399.

Institute of Transportation Engineers. 2005. "Vehicle traffic control signal heads: Light Emitting Diode (LED) circular signal supplement." Washington, D.C.: author.

Institute of Transportation Engineers. 2007. "Vehicle traffic control signal heads: Light Emitting Diode (LED) vehicle arrow traffic signal supplement." Washington, D.C.: author.

Lewis, E.E. 1994. Introduction to reliability engineering, second edition. NY: John Wiley.
Leotek. 2010. Accessed October 1, 2010. www.leotek.com.
Long, M., 1999. "Anaheim Public Utilities receives coveted recognition for new traffic signal lights that save ratepayers $\$ 214,000$ annually." Anaheim Public Utilities, Public Press, June, 1999.

Montgomery, D. 2009. Design and Analysis of Experiments, Seventh Edition, New York: Wiley.
New York State Energy Research and Development Authority (NYSERDA). 2001. "Evaluation of NYSDOT LED traffic installation." www.lightingresearch.org/programs/transportation/LED/pdf/NYSDOTEval.pdf

Palmer, T. C. 1999. "A bright idea: Red strobes to save energy, get drivers' attention." Boston Globe, May 10, 1999.

Suozzo, M. 1998. "A market transformation opportunity assessment for LED traffic signals." American Council for an Energy Efficient Economy, Washington, D.C.

Suozzo, M., 1999. "Case studies of successful LED traffic signal installations and documentation of a three-color signal demonstration." Report to Boston Edison Company, Washington, DC, American Council for an Energy-Efficient Economy.

Urbanik, T. 2008. "LED traffic signal monitoring, maintenance, and replacement issues. A synthesis of highway practice." NCHRP Synthesis 387, Transportation Research Board, Washington, D.C.
U.S. Congress. 2005. Energy Policy Act of 2005. Accessed May 2010. http://www.epa.gov.

Winer, Darryl, 1998, Report of U.S. communities acting to protect the climate, by the International Council for Local Environmental Initiatives (ICLEI).

Wu, M. S., H. H. Huang, B. J. Huang, C. W. Tang, and C. W. Cheng. 2008. "Economic feasibility of solar-powered LED roadway lighting." ISESCO Journal of Science and Technology Vision, 4, no. 6: 43-47.

## Appendix A

## A. 1 LED Indicators Provided by MoDOT

MoDOT provided six LEDs. Three of the LEDs functioned and were considered to be new. The other three were either failed completely or strings of LEDs were out. The new LEDs were used for all of the experiments and served as a baseline for how a new LED would perform, to facilitate comparison of LEDs in the field to this ceiling value. The description and notes of the new LEDs are as follows:

- Green: Dialight
- Yellow: Leotek
- Red: Dialight


Figure A. 1 Differences in manufacturing style: "LED-look" vs. "incandescent-look"

The three bad LEDs were also investigated. Descriptions and notes are as follows:

- Green: Leotek - clear lens, 85 LEDs, five LEDs out (string of two and string of three)
- Green: Leotek - tinted green lens, 85 LEDs, seven LEDs out, eight flickering
- Red: Dialight - wouldn't turn on at all $\rightarrow$ bad power source


## Appendix B

## B. 1 Instrument Verification

To establish a baseline on how luminous intensity decreased as the distance from the light source (LED traffic signal) increased, a long hallway in the Electrical Engineering building served as a laboratory environment. Several experiments were performed in this hallway to compare the field results with laboratory results and also to verify the instrument design.

Setup for verifying instrument and determining magnification factor. An LED indicator was placed at one end of a 150-foot-long hallway at a fixed height. Starting at the light, distances of $5 \mathrm{ft}, 10 \mathrm{ft}, 15 \mathrm{ft}, 20 \mathrm{ft}$ and every 10 ft after that up to 150 ft were measured and marked off to the end of the hallway. Before turning the LED on, the instrument was placed on a chair at the same fixed height as the traffic signal and used to take luminous intensity (lux) recordings at each of the marked distances. These values determined the amount of ambient light present in the hallway at each distance, or "noise". The recorded noise values were all the same for the experiment when the Fresnel lens was used but changed during the experiment when no Fresnel lens was used. This was due to the sun setting and less light entering a window in the hallway. The noise values can be seen below in table B.1.

Table B. 1 Ambient light values subtracted from measured illuminance

| "Noise" Ambient Light Subtracted <br> Fresnel Lens |  |  | No Fresnel Lens |  |
| :---: | :---: | :---: | :---: | :---: |

This same process was then repeated while each of the three different colored circular traffic indicators was turned on. The illuminance (lux) values were again recorded and the "noise" was then subtracted from these values to determine the true lux value, labeled "adjusted reading (lux)." These measurements and calculations are detailed below in tables B.2-B.4.

Table B. 2 Measured illuminance and luminance values with and without Fresnel lens and corresponding magnification factor for 12 " green circular Dialight

| Distance <br> (ft) | Distance (m) | 12" Green Dialight |  |  |  |  |  | Mag (X) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | Fresnel Lens |  |  | No Fresnel Lens |  |  |  |
|  |  | Recorded Reading (lux) | Adjusted <br> Reading <br> (lux) | Adjusted Reading (cd) | Recorded Reading (lux) | Adjusted Reading (lux) | Adjusted Reading (cd) |  |
| 5 | 1.5 | 8670 | 8667 | 20130 | 203 | 192 | 447 | 45 |
| 10 | 3.0 | 5190 | 5186 | 48175 | 71 | 54 | 500 | 96 |
| 15 | 4.6 | 2870 | 2865 | 59881 | 48 | 24.0 | 502 | 119 |
| 20 | 6.1 | 1652 | 1645 | 61145 | 41 | 15.2 | 565 | 108 |
| 30 | 9.1 | 776 | 769 | 64281 | 32 | 7.2 | 602 | 107 |
| 40 | 12.2 | 450 | 442 | 65716 | 27 | 4.3 | 639 | 103 |
| 50 | 15.2 | 288 | 280 | 65009 | 28 | 2.6 | 604 | 108 |
| 60 | 18.3 | 200 | 192 | 64081 | 24 | 2.0 | 669 | 96 |
| 70 | 21.3 | 147 | 138 | 62821 | 26 | 1.8 | 819 | 77 |
| 80 | 24.4 | 127 | 118 | 69923 | 25 | 1.2 | 713 | 98 |
| 90 | 27.4 | 103 | 94 | 70360 | 20 | 0.8 | 602 | 117 |
| 100 | 30.5 | 86 | 76 | 70885 | 20 | 0.8 | 743 | 95 |
| 110 | 33.5 | 74 | 64 | 72057 | 21 | 0.6 | 674 | 107 |
| 120 | 36.6 | 64 | 54 | 71706 | 23 | 0.5 | 669 | 107 |
| 130 | 39.6 | 58 | 47 | 73950 | 27 | 0.8 | 1256 | 59 |
| 140 | 42.7 | 52 | 41 | 74839 | 24 | 0.5 | 910 | 82 |
| 150 | 45.7 | 48 | 37 | 76506 | 24 | 1.5 | 3135 | 24 |
| Averages: |  | 64,204 |  |  |  |  | 551 | 98 |

Table B. 3 Measured illuminance and luminance values with and without Fresnel lens and corresponding magnification factor for 12 " red circular Dialight


Table B. 4 Measured illuminance and luminance values with and without Fresnel lens and corresponding magnification factor for 12 " yellow circular Leotek


This data was first plotted using the adjusted lux readings as the Y -axis and the distance in feet as the X axis. Based on the graph pictured below in figure B. 1 it is evident that each of the three colored LEDs follow roughly the same curve.


Figure B. 1 Illuminance (lux) vs. distance (feet) for circular green, yellow and red LEDs

Several observations were made upon comparing the average luminance (cd) values of the new circular LEDs provided by MoDOT seen in tables 8-10 to the ITE values established for the minimum luminous intensity level that must be met at an angle of -2.5 degrees below the vertical. Note that the ITE values for -2.5 degrees were used this time because the measurements were made in a laboratory environment and not at a - 10 degree angle like they were in the field. These comparisons can be seen in table B.2. The yellow value of 515 cd for what is considered to be a brand new LED is already well below the ITE threshold of 910cd. This gap between the observed values for yellow and the minimum threshold established by the ITE were consistent across most of the collected data as well. This shows that the yellow LEDs are not performing up to the levels expected in the field. Also, the new red Dialight was only slightly above the ITE
minimum threshold, with a value of 376 cd compared to 365 cd minimum. This concurs with figure 5.20 , which shows that the average intensity for all the red Dialights studied in the field was also below the minimum threshold.

Additionally the observed ratio of red to yellow to green for the new LEDs was lower for yellow when compared to the ITE ratio. Again, this is due to the fact that yellow LEDs were observed to not emit the high light intensity expected of them.

*From 2005 ITE Vehicle Traffic Control Signal Heads: Light Emitting Diode (LED) Circular Signal Supplement
Figure B. 2 (cd) Luminance and R:Y:G ratio for new LED lights compared to ITE standards

To linearize the results from figure A.1, the data was again plotted, only this time Log10 was taken for both the X axis (Distance in meters) and Y axis (Luminous intensity in lux) and a trendline was added to the resulting graphs. This trendline shows the slope at which the luminous intensity decreased for each of the three colors of LED circular traffic indicators. For circular green, the slope was -1.90 , for red the slope was -1.85 and for circular yellow the slope was 2.00. These slopes are all geometrically comparable to a theoretical slope of -2 . The advantage of obtaining the actual slopes and not using the theoretical slope of -2 is that the data conversion is unique for each color of LED light based on how the light performed in the laboratory.

The Log-Log based graphs of luminous intensity over distance for each of the three LED circular traffic indicators can also be found in figure B.3:


Figure B. 3 Log-log scaled graphs of lux vs. distance for all three colors of LEDs and the fitted curves

The purpose of this experiment was to establish the slopes at which the luminous intensity decreases over distance was to convert the field readings which were taken at whatever distance the vehicle was form the signal head, into comparable numbers and verify the inverse square law. The distances at which lux readings were recorded ranged from 32 ft to 193 ft ( 10 m to $59 \mathrm{~m})$. The three separate equations obtained from the experiment were applied to the recorded data to convert all the readings from various distances to "peak" values at a distance of zero meters so that they could be compared.

All circular green and green arrow indicators were converted to peak values using the equation obtained for the circular green Dialight LED in the lab:

$$
\begin{equation*}
y=-1.9014 x+5.6852 \tag{B.1}
\end{equation*}
$$

All circular red indicators were converted to peak values using the equation obtained for the circular red Dialight LED in the lab:

$$
\begin{equation*}
y=-1.8455 x+5.4656 \tag{B.2}
\end{equation*}
$$

All circular yellow and yellow arrow signals were converted to peak values using the equation obtained for the circular yellow Leotek LED in the lab:

$$
\begin{equation*}
y=-2.0003 x+5.7719 \tag{B.3}
\end{equation*}
$$

Ideally, separate equations would have been derived for green arrow and yellow arrow LEDs, but because none were available for laboratory testing, the same equations for the circular indicators were used for the respective colored arrows as well.

Once the luminous intensity values were standardized to a common distance of zero meters, they were then converted into candelas (cd), the unit used by the ITE for establishing minimum thresholds. By plotting the cd values we were able to confirm the validity of using the inverse square law, where lux readings were converted into cd simply by inputting the distance into the inverse square law. The scatter plot shown in figure B. 4 (below) confirms the use of the inverse square law.


Figure B.4. Scatter plot comparing two different conversion methodologies

## B. 2 Magnification Factor

The same experiment detailed earlier was repeated, only this time without the use of the Fresnel lens. The data is summarized in tables B.1-B.4. The data immediately verified the use of the Fresnel magnifying lens. Without it, readings became meaningless at a certain distance from the LED light because of the existence of ambient light. The Fresnel lens effectively allowed us to take accurate readings from far-off distances by concentrating the light onto the light meter. However, this benefit had to be reversed in order to compare our values to the ITE standards, which are not taken with a Fresnel lens. By repeating the same experiment without the Fresnel lens it was possible to calculate the average magnification factor at which the Fresnel lens intensified the light intensity readings. These values were averaged for the first 50 feet during the experiment, because any readings without the Fresnel lens past this distance were invalid. After averaging the magnification factor for each of the three LEDs it was clear that the use of the Fresnel lens effectively magnified our readings by a factor of 100 . This factor was applied to all of the 372 data points to reduce the magnification effect of the Fresnel lens and make the data points comparable to ITE standards.

## Appendix C

## C. 1 Date Codes

Determining dates of LED manufacture and installation proved to be a difficult task.
Information was provided on an intersection-by-intersection basis, with diagrams depicting the traffic signal layout of every intersection for each direction of traffic. A sample of sheet depicting typical problems experienced with interpreting the manufacture and installation dates is shown below for the intersection of Route 63 and Pine Street in Rolla, Missouri.



```
In+ersection: Rte 63 & Pine St
```

In+ersection: Rte 63 \& Pine St
County/Ci+y: Phelps/Rolla
County/Ci+y: Phelps/Rolla
Direction: NB \square SB X EB \squareWB

```
Direction: NB \square SB X EB \squareWB 
```

Figure C. 1 Problems encountered with determining the installation date

As seen in the diagram above, the date codes are provided in many different forms. In the best case scenario, the date that the LED was installed was recorded as "month, year," for example "July 2005." This provided the exact date of the LED signal's installation; however, it did not indicate when the signal was manufactured. It had been simply assumed that the manufacture, purchase, and installation date were all fairly close. This best case scenario was not the case, however, even for many of the LEDs as depicted above. Sometimes the date code would be listed as a series of four numbers (e.g., GE 0607). It was discovered that the numbers had a code, which could be interpreted one of three ways depending on the manufacturer:

1. month, year
2. year, month
3. week of the year, year

This made interpreting the date codes very cumbersome, and also very critical, because of the possibility of large age differences based on discrepancies in the manner in which dates were code. Using the example of GE0607, the dates of installation could be three very different dates:

1. June, 2007
2. July, 2006
3. February, 2007

This margin of error could be even greater for codes such as 0107 , which could be interpreted as January 2007 or July 2001—a six year difference. Other date codes were simply never deciphered (e.g., some of the Dialights seen above in fig. C.1). This reduced the total amount of data available for analysis.

## C. 2 Blank Intersection Sheet



Intersection: $\qquad$
County/City: $\qquad$
Direction: NB $\square$ SB $\square$ EB $\square$ WB $\square$

| Manufacturer |
| :--- |
| Act One Communications (ACT) |
| American Signal Corporation (ASC) |
| Dialight (DIAL) |
| Duralight (DURA) |
| Execellence Opto Inc.(EDI) |
| Gelcore (GEL) |
| Ledtronics (LED) |
| Leotek (LTEK) |



Circular Red (R)
Circular Yellow (Y
Yellow Arrow (YA)
Circular Green (G)
Green Arrow (GA)


Figure C. 2 Data intersection sheet

Appendix D

## D. 1 Instrument



Figure D. 1 Data collection instrument with light meter


Figure D. 2 Fresnel lens focusing light from LED into a beam focused on the light meter
*Magnification factor of this concentration was determined to be 100 x


Figure D. 3 Front view of instrument showing mounted laser pen and range finder


Figure D. 4 Top view of instrument showing spring used for calibrating laser pen guidance


Figure D. 5 Illustration of the instrument design

## Appendix E

## E. 1 Operations and Maintenance

Objective. The primary objective of this report is to provide MoDOT with an economic estimation to demonstrate the potential value of replacing traditional incandescent bulbs with LED indicators. The cost and effectiveness of applying LEDs are analyzed in this report. A suggestive summary follows to provide MoDOT with suggestions for the application of this research.

Background. Since late 1990s, LEDs traffic signals have been drawing wide attention from many cities in the US and globally (Anonymous 2000a). Examples of wide replacement centers include Boston, MA (Palmer 1999; Suozzo 1999), Framingham, MA (Suozzo 1999), Newton, MA (Suozzo 1999), Denver, CO (Winer 1998; Briggs 2000), Lee County, FL (Crawford 1999), Portland, Oregon (Anon. 2001), Stockholm, Sweden (Jonsson 1999), and Victoria, Australia (Das 1999). A 2004 California Energy Commission report listed 78 cities that had installed LED traffic signal indicators (Anon. 2004). Two major advantages of using LED traffic lights include remarkable energy savings and substantial maintenance savings. A single major disadvantage is high initial cost. Our analysis shows that LED traffic lights have equal or better functionality than traditional incandescent bulbs (see the effectiveness analysis below), and that LED replacement has a payback period of about two years and will lead to savings of millions of dollars over time.

Effectiveness Analysis. We divided effectiveness of installing LEDs into three categories: functionality, environmental effects, and economic effects. Advantages and disadvantages of LED traffic lights in comparison to traditional incandescent bulbs are summarized as follows: Functionality

- LEDs have a much longer life than incandescent bulbs, referred number include 100,000 hours vs. 5000 hours (Anon. 1999), six years vs. two years (Anon. 2001)
- LED technology eliminates catastrophic failure of signal indicators thanks to the multiple LEDs in one unit.
- LEDs do not change color when dimming, a common problem among incandescent bulbs.
- The visibility of LEDs is usually better than incandescent bulbs.
- At dawn and dusk, when sunlight shines directly into the signal head, uncomfortable glare shines from the reflective material behind incandescent bulbs. LEDs do not require such material and thus eliminate this problem (Anon. 2003).
- LEDs have more directional light beams than incandescent bulbs. This will cause some visibility problem if the signal heads are hanging freely in some intersections. This problem could be solved by securely attaching the signal head (Anon. 2003).
- LEDs are sometimes too bright to view in the dark. This issue could be solved by regulating the power input to the signal heads with some light sensors.
- LEDs do not generate as much heat as incandescent bulbs. Therefore they avoid burning the lens cover. However, in heavy snow, the heat from LEDs is usually not enough to melt the snow and ice accumulated on the visor (Anon. 2003).
- LEDs require adequately low power consumption to operate using battery back-up during power outage.


## Environmental Effects

- LEDs save on a great deal of energy consumption, thus reducing greenhouse gas emissions. The city of Denver, CO reported a reduction of 5,300 metric tons of $\mathrm{CO}_{2}$,
23.3 metric tons of $\mathrm{SO}_{2}$ and 20.8 metric tons of $\mathrm{NO}_{\mathrm{x}}$ emission each year after installing 20,500 LED traffic lights (Winer 1998).


## Economic Effects

- LED indicators have a much higher initial cost compared to incandescent bulbs, typically $\$ 100$ vs. $\$ 3$ per unit (Anon. 2000).
- After years of operation, LEDs save millions of dollars in relamping, emergency repairing, maintenance and energy cost. Denver replaced 20,500 traffic indicators with LEDs and reported an annual savings of \$430,000 (Winer 1998). Stockholm replaced 27,000 traffic indicators with LEDs and reported an annual savings of \$479,000 (Jonsson 1999).

Table E. 1 Effectiveness of replacing traditional incandescent bulbs with LEDs

| Categories | A/D | Description | Reference |
| :--- | :--- | :--- | :--- |
| Functionality | A | Long life time | Suozzo, 1998 |
|  | A | Elimination of catastrophic failure | Anon., 2003 |
|  | A | Brighter | Suozzo, 1998 |
|  | A | Elimination of reflection of sunlight | Avoid burning lens cover |
|  | A | Do not change color when dimming | Anon., 2003 |
|  | A | Use battery backup during power outage | Anon., 2000 |
|  | D | Directional visibility causes | Anon., 2004 |
|  | D | Not enough heat to melt covering snow and ice | Anon., 2003 |
|  | D | Anon., 2003 |  |
|  | Too bright in night if not regulated | Anon., 2000 |  |
| Environmental | A | Lower energy consumption | Wu et al., 2008 |
| Effects | A | Lower GHG emission | Anon., 2003 |
| Economic | A | Lower emergency fix cost | Anon., 2003 |
|  | A | Lower relamping cost | Anon., 2001 |
|  | A | Lower maintenance cost | Wu et al., 2008 |
|  | D | Higher initial cost | Anon., 2000 |

Note: A = Advantage, D = Disadvantage
Most effects are reported from more than one literatures. Referenced literature was selected at the authors' convenience.

Economic Evaluation. The cost analysis was performed using a top-down approach, which requires a host of assumptions. Data were collected from five major LED vendors (General Electric, ActOne, LeoTek, Philips and Dialight), various case studies, and reliable publications. However, in real conditions, reasonable variation of some key factors may significantly affect results. The level of customizing investments is not the focus of this analysis. Thus, this study does not consider the installation size and the specific area installed. The results are scalable when there are more inputs, such as reasonable ratios, and specific model numbers of LED indicators. The energy consumption of LEDs is calculated by multiplying the unit wattage by an average time of an indication is on in every year.

Table E. 2 shows a comparison of estimated price and wattage between three LED indicators and incandescent bulbs. The annual energy saving is the difference in energy consumption between the LED and incandescent. The energy savings by using LED can reach 90\%.

Table E. 2 Comparison between LEDs and incandescent bulbs

| Display Type | Price (Anon., 2003) | Wattage (ActOne, 2010) |
| :--- | :--- | :--- |
| Incandescent | $\$ 3$ | 150 |
| LED red | $\$ 57$ | 10.5 |
| LED yellow | $\$ 66$ | 13.4 |
| LED green | $\$ 119$ | 10.5 |

A summary of results is exhibited in table E.3. Based on a review of previous literature, a 10 -year life span was applied in this analysis. An average electric cost $\$ 0.1 / \mathrm{kWh}$ (MoDOT Electricity Bill, $3^{\text {rd }}$ quarter 2010) was applied in this analysis. Carbon footprint was considered as one of the benefits of using LEDs. The total $\mathrm{CO}_{2}$ reduction was calculated by multiplying the reduced quantity of kWh produced by LEDs by the average $\mathrm{CO}_{2}$ emissions associated with one kWh generated electricity in Missouri ( $0.000685 \mathrm{lbs} / \mathrm{kWh}$, according to MODOT record). The payback period for a module containing red, yellow, and green LED lights is 2.01 year.

Table E. 3 Summary of results

|  | Red | Yellow | Green | Whole <br> Module | Ref |
| :--- | :---: | :---: | :---: | :---: | :---: |
| Unit Wattage Save (kw) | 0.14 | 0.136 | 0.14 |  | ActOne,2010 |
| Device Cycle Time Percentage | $50 \%$ | $6 \%$ | $44 \%$ | $100 \%$ | Assumption |
| Material Cost (\$/unit) | 57 | 66 | 119 | 242 | Anonym, 2003 |
| Installation Labor (\$/unit) | 15 | 15 | 15 | 45 | Leotek, 2010 |
| Total Initial Investment (\$/unit) | 72 | 81 | 134 | 287 |  |
| Annual Maintenance Saving | 11 | 0 | 11 | 22 | Anonym, 2000 |
| (\$/unit) |  |  |  |  |  |
| Annual Energy Saving (\$/unit) | 60.48 | 7.05 | 53.22 | 120.75 | $\$ 0.1 / \mathrm{kwh}$ |
| Total Annual Savings (\$/unit) | 71.48 | 7.05 | 64.22 | 142.75 |  |
| Payback period (year) | 1.01 | 11.49 | 2.09 | 2.01 |  |
| Annual CO ${ }_{2}$ decrease (tons/unit) | 0.41 | 0.05 | 0.36 | 0.83 | $6.85 \times 10^{-4}$ |
|  |  |  |  |  | tons/kwh <br>  |
|  |  |  |  |  | MoDOT 2010 |

In this calculation, we assumed signal cycle time of $50 \%$ for red indicators, $7 \%$ for yellow, and $43 \%$ for green based, on our observations. There exists no reliable reference to verify these numbers. We also assume that all traffic signals are on 24 hours a day. In reality, some traffic signals are turned to flash after midnight, which leads to a longer payback period than calculated (if 50\% traffic signals are turned to flash for 6 hours/day, the total annual savings will be about $1 / 8$ less, and payback period will be about $1 / 8$ longer). It is noteworthy that yellow lights have a much longer payback period due to their lower percentage of working time. This is the very reason why several cities chose to only replace red and green indicators (Suozzo 1999; Long 1999). Some cities only replaced red indicators because of their remarkably shorter payback time (Crawford 1999).

There are approximately 2,425 signalized intersections, and approximately 155,000 signal indications in Missouri. Combining the findings in table E. 3 with relevant data provided by MoDOT, we found that the simple payback period of LED traffic lights in Missouri is about four years. A 10-year study period and $3.92 \%$ discounted rate is assumed in this study. Based
on these assumptions, the net present value is $\$ 2,826,018$, and the total reduced $\mathrm{CO}_{2}$ emissions are 11,393 pounds. Detailed data and calculations are shown in table E.4.

Table E. 4 Simple payback period of LED in Missouri

| MoDOT Traffic Signals |  |  |  |
| :--- | :---: | :---: | :---: |
| Electricity cost (\$/yr) | 0.10 |  |  |
| Hours/yr | 8,640 |  |  |
| Power of conventional <br> lights(kW) | 0.135 |  | Yellow |
| Conventional Traffic Lights | Red | $6 \%$ | $44 \%$ |
| Cycle time | $50 \%$ | 518 | 3,802 |
| Working time/year | 4,320 | 9,700 | 14,550 |
| No. of lights | 14,550 | 678,845 | $7,467,293$ |
| Annual Consumption | $8,485,560$ |  |  |
| Total Annual Consumption | $16,631,698$ |  |  |
| Annual Electricity Cost (\$) | $1,663,170$ |  |  |
| LED Traffic Lights |  |  |  |
| No. of intersection | 2,425 |  |  |
| Heads/approach | 4 |  |  |
| No. of approach | 4 |  |  |
| No. of indications/head | 4 |  |  |
| No. of LED Indicators | 155,200 |  |  |
| Labor \& fringer | $4,947,787$ |  |  |
| Cash (no electricity cost) | $2,982,278$ |  |  |
| Electricity cost (\$) | $1,187,669$ |  |  |
| Inventory | 318,007 |  |  |
| Equipment | $1,435,784$ |  |  |
| Annual O\&M cost (\$) | $9,683,857$ |  |  |
| Total initial Cost (\$) | $2,783,900$ |  |  |
| Annual O\&M savings (\$) | 213,400 |  |  |
| Annual energy savings (\$) | 475,500 |  |  |
| Total annual savings (\$) | 688,900 |  |  |
| Simple payback period (yrs) | 4 |  |  |
| NPV (\$) | $2,826,018$ |  |  |
| CO reduction (lbs) | 11,393 |  |  |

Figures E.1-E. 3 show 15 scenarios of annual operation and maintenance costs for the 155,200 LED indicators in Missouri, including LED products with three different expected lifetimes and five different standard deviations under those three expected lifetimes. Due to safety considerations, we adopted a more stringent definition of lifetime in this report. We defined that before the end of lifetime, lumen output levels meet the requirement of application. Accordingly, "failure" implies that certain LEDs cannot meet the requirement, rather than burnout. Because LED indicators are new to the marketplace, there is little recorded data to analyze this situation. Our own calculation is based on following assumptions: a) the lifetime of the LED follows normal distribution, b) the maintenance cost under the 5-year warranty (LeoTek) would consist of labor only; after the warranty the cost consists of labor and materials, c) emergent repair labor cost $=\$ 90 /$ head; emergent repair average material cost $=\$ 88$ (which is an average of the material costs of green and red LEDs, since yellow are used much less often than the other two) d) analysis period of this study is 10 years. Relamping is not included in this study because LED relamping is usually over 10 years after installation.

As shown in figures E.1-E.3, LED indicators with good quality (longer mean lifetime) ensure a lower total maintenance cost. It is also shown that maintenance costs increases with time.


Figure E. 1 O\&M cost over for different standard deviations (Mean = 11 years)


Figure E. 2 O\&M cost over for different standard deviations (Mean = 12 years)


Figure E. 3 O\&M cost over for different standard deviations (Mean = 13 years)

Summary. It is widely reported that cities all over the world save millions of dollars by replacing traditional incandescent traffic bulbs with LEDs. Our effectiveness analysis shows that LED indicators have many advantages over traditional ones. Although installing LED indicators requires a high initial investment, the payback period is about two to three years. The results by analyzing 15 scenarios shows that LEDs with good quality (which mean longer expected lifetime and lower standard deviation) would dramatically reduce the operation and maintenance cost. However, since the LED is still new to the marketplace, no recorded data show a reliable operation and maintenance cost. Although many manufacturers claim that the operation and maintenance cost is near zero, these claims are also hard to confirm. Meanwhile, there is not an appropriate depreciation method for LEDs. This report established estimations for payback period. We recommend all decision makers to take serious consideration of replacing incandescent bulbs with LED.

