Louisiana Transportation Research Center

Final Report 563

LED Traffic Signal Management System

by

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16. Abstract

This research originated from the opportunity to develop a methodology to assess when LED (Light Emitting Diode) traffic signal modules begin to fail to meet the Institute of Transportation Engineers (ITE) performance specification for luminous intensity for motorists. The ultimate goal of this research project is to provide the Louisiana Department of Transportation and Development (DOTD) with a replacement schedule for LED signal modules. To this end, the objective of this research is to develop lifetime curves of these modules and to establish the life-span of signal modules. These curves will depict how these modules' luminous intensity degrades until reaching the end of their useful life. The research methodology and findings will allow other researchers in different climatic regions to test their own modules. In this research, the operating time of LED signal modules is equal to 20,000 hours of operation. The research methodology is comprised of three data sets of measurements of the luminous intensity of the signal modules. The first data set was collected by an independent lab with multiple data points per module. This lab data set was measured sequentially at a fixed 2,000-hour time interval for the first 10,000 hours of operation, and then once again at 20,000 hours. The other two data sets were collected by DOTD employees at the Traffic Services yard using two distinct devices with one data point per module. These in-house data sets will be measured sequentially at a fixed 500-hour time interval for the duration of this research project. The results of this study indicate that a five-year replacement schedule of LED modules appears to be too soon. It is unknown at this point what the exact lifetime curve of these specific LED modules is.

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ABSTRACT

This research originated from the opportunity to develop a methodology to assess when LED (Light Emitting Diode) traffic signal modules begin to fail to meet the Institute of Transportation Engineers (ITE) performance specification for luminous intensity for motorists. The ultimate goal of this research project is to provide the Louisiana Department of Transportation and Development (DOTD) with a replacement schedule for LED signal modules. To this end, the objective of this research is to develop lifetime curves of these modules and to establish the life-span of signal modules. These curves will depict how these modules' luminous intensity degrades until reaching the end of their useful life. The research methodology and findings will allow other researchers in different climatic regions to test their own modules. In this research, the operating time of LED signal modules is equal to 20,000 hours of operation. The research methodology is comprised of three data sets of measurements of the luminous intensity of the signal modules. The first data set was collected by an independent lab with multiple data points per module. This lab data set was measured sequentially at a fixed 2,000-hour time interval for the first 10,000 hours of operation, and then once again at 20,000 hours. The other two data sets were collected by DOTD employees at the Traffic Services yard using two distinct devices with one data point per module. These in-house data sets will be measured sequentially at a fixed 500-hour time interval for the duration of this research project. The results of this study indicate that a five-year replacement schedule of LED modules appears to be too soon. It is unknown at this point what the exact lifetime curve of these specific LED modules is.

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IMPLEMENTATION STATEMENT

The results of this research have two implementation possibilities. First, findings from the lifetime curves developed in this study may be used to develop an optimal replacement schedule for circular LED traffic signal modules. This schedule will be based on lifetime curves that comply with the ITE minimum luminous intensity values in order to reduce the likelihood of hazards at signalized intersections. Second, the lifetime curves may be used in determining if current warranties provided to DOTD by LED signal module vendors are realistic. Current plans for LED replacement are based on warranty claims by vendors. Prior to this research, DOTD did not conduct independent testing to check the validity of their claims. This research would provide an independent basis for future replacement programs. If results indicate that the life cycle of LED modules are significantly shorter than five years, it would require adjusting replacement plans accordingly. Conversely, if they are longer than the warranty period, DOTD will be able to maximize the signal module useful life. A sharp increase of crashes is not anticipated when a signal reaches its useful life. In fact, DOTD has a policy of using a minimum of two signal heads per approach at a signalized intersection as a built in safety redundancy. DOTD needs a replacement schedule for the following reasons: (1) if the LEDs are not replaced when they reach the ITE minimum luminous intensity, they will continue to degrade over time and will eventually become a problem for any driver to see, (2) DOTD needs to protect itself against litigation, (3) to ensure that DOTD is not prematurely replacing LEDs and thus potentially saving the taxpayer.

The primary target audience of this research is the DOTD District Traffic Operations Engineers. The larger municipalities within the state such as Baton Rouge and Lafayette may use this data to implement their own replacement strategies.

The recommended implementation for this research is to develop a maintenance replacement plan for DOTD Districts. Initially, this will be done as a pilot program. The target audience for the test program is the districts while the beneficiaries are the motoring public. During the pilot program, certain factors that may affect a full-scale implementation (e.g., technological requirements and communication strategies) will be assessed. Personnel recommended for the implementation team are: representatives from Traffic Services and District Traffic Operations and possibly an attorney from DOTD. Potential detractors to this implementation include: inconsistent procedures for LED replacements among the districts, and education of the target audience about the lifetime curves.

Practical areas of application include implementing a replacement strategy for the districts. Currently the districts do not have a methodical approach to LED replacement. An example of a methodical approach would be to replace all LEDs on arterial streets the first two years, then collector streets the next two years, and finally local roads the final two years on a hypothetical six-year lifetime replacement plan. It is understood that some districts will have more or less of each type of roadway and should adjust accordingly. The first activity required for implementation is the marketing. For this implementation to be successful, complete buy-in from the Districts is a necessity. It is highly recommended that a District Traffic Operations Engineer be on the implementation team to assist the author with marketing. Once the marketing is complete, a pilot program should be initiated. This is when any additional resources or training may be identified. Once the pilot program is complete and all issues worked out, the full-scale implementation may begin.

The implementation plan has three distinct phases. Phase 1 is marketing. At the conclusion of this research, a champion of this project should meet with the districts to show them the methodology of this research and obtain buy-in from all district personnel. It is recommended that Phase 1 take no less than six months. Phase 2 is the pilot program. It is recommended that the pilot program take at least two replacement cycles or two years to be complete. This will ensure that any outstanding issues would be addressed. Phase 3 is full implementation. This phase will go on indefinitely.

The only quantifiable method to evaluate the implementation is to obtain the purchase history of LEDs by the districts both before and after implementation and compare them. The purchase history of LEDs after implementation should go on until at least one full lifetime of the LEDs.

This research is a potential cost savings if the LED modules last beyond their warranty period, which is currently five years. According to the Traffic Services section of DOTD, the replacement cost per LED module (including materials and labor) in 2010 and 2015 was approximately $45.40 and $32.47 respectively. Table 1, based upon the aforementioned costs, depicts the following information.

1. Replacement intervals based on possibilities of lifetime curves resulting from this research.

2. Number of LED modules replaced annually based on the replacement intervals.

3. Cost estimates to replace all of LED modules per replacement intervals in 2010 and 2015.

4. Percentage of cost savings estimates to replace LED modules beyond the 5-year warranty period in accordance with replacement intervals.

Table 1
Cost savings based on the possibilities of lifetime curves

Replacement interval (year)	**LED modules changed out per replacement interval**	**Annual cost to replace the number of LED modules per replacement interval ($)**		**Percentage of cost savings to replace the number of LED modules per replacement interval (%)**
		2010	2015	
5	20,100	912,560	652,727	N/A
5.5	18,273	829,600	593,389	9
6	16,750	760,467	543,940	17
6.5	15,462	701,969	502,098	23
7	14,357	651,829	466,234	29

This research is also beneficial if the LEDs fail before their warranty dates, because perhaps DOTD can exclude the vendor from future bids. Another equally important potential impact is the compliance with the ITE minimum luminous intensity values. This is especially important in litigation against DOTD. Without lifetime curves, it will be difficult to prove whether or not a signal was in compliance with the minimum standards or not at a given intersection, in the event of a lawsuit against the DOTD.

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INTRODUCTION

In the past, an incandescent bulb burned out with a catastrophic failure resulting in no light whatsoever. LEDs have basically two failure modes: catastrophic and degradation over time. Degradation failures are also known as maintenance failures. LEDs typically fade out slowly and very rarely fail catastrophically *[1]*. The light source of a signal module is comprised of an array of multiple individual LEDs. The probability of all of the LEDs failing catastrophically at the same time is low. It is anticipated that there will be no catastrophic failures for the duration of this research. In reference to degradation failures, the fading of the entire array of LEDs of traffic signal modules throughout their operational lives is a serious concern of Traffic Engineers throughout the nation. The Institute of Transportation Engineers (ITE) developed minimum luminous intensity standards for LED signal modules *[2]*. These standards vary depending on angle of view. It is feasible for the typical younger driver to still be able to see an LED signal module that has already reached the ITE minimum luminous intensity standards.

There are approximately 3,350 intersections throughout the State of Louisiana, which require the operation of more than 100,000 LED traffic signal modules. In order to manage the operation of such a large number of units, DOTD has specified that signal module replacement be made at the time of the manufacturer's warranty. As a result, DOTD's general rule is to schedule module replacement every five years from date of installation. A management practice of this kind may generate hazards at the intersections because one cannot assume that the warranty period is also the life-span. DOTD is currently seeking a management strategy for replacing circular traffic signal modules, so this strategy must conform to ITE's specification for minimum luminous intensity. Therefore, DOTD is considering a replacement schedule based on signal module lifetime curves.

The intent of this research study is to provide DOTD with LED traffic signal lifetime curves. Lifetime of an LED is the duration from its initial light output to its minimum allowable light output *[3]*. Figure 1 exemplifies a lifetime curve of individual LEDs produced by their manufacturer *[4]*. In order to produce this curve, LEDs were operated continuously at specified temperature (+55º C) with a drive current of 20 mA DC for the duration of the test (16,000 hours). This curve was created with data measured at pre-determined intervals of time up to 16,000 hours and projected data beyond 16,000 hours up to 100,000 hours. Because this curve is based upon projection, the manufacturer warranty is 50,000 hours. Therefore, the LED signal module lifetime curves obtained through this research will further investigate this issue by collecting data at 20,000 hours of continuous operation.

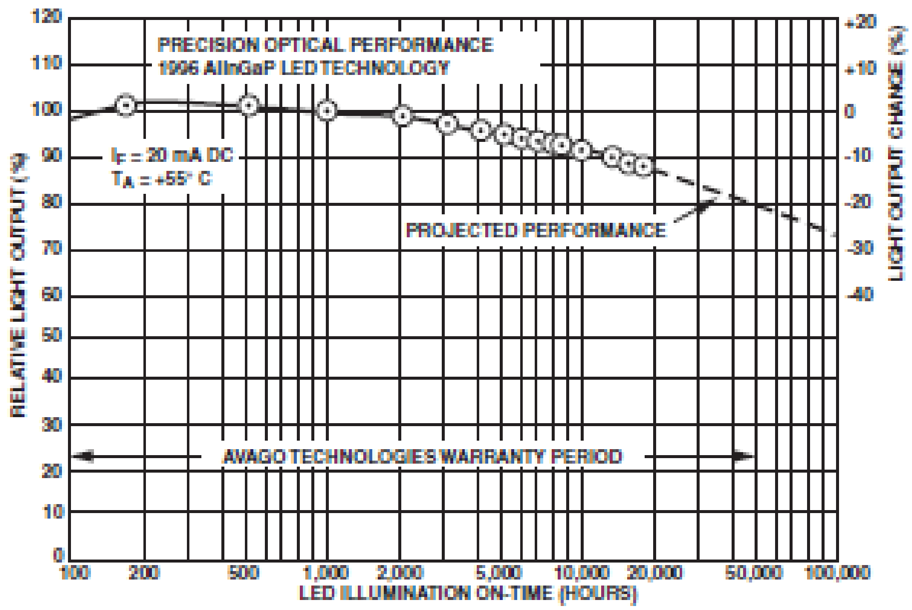


Figure 1
Projected lifetime curve of individual LEDs (source: Avago Technologies)

The curves obtained through this research will also show the time duration it takes for the luminous intensity of the observed data to reduce from the initial value to the ITE minimum luminous intensity. Below this minimum, the graph will show when it will be necessary to replace the traffic signal modules. Therefore, these curves will establish the safe signal module operation area between the observed data and ITE minimum luminous intensity. Knowing this information, DOTD may be able to schedule traffic signal replacement independent of the manufacturer's warranty, if the warranty is in no way a function of the ITE minimum luminous intensity.

As part of this research effort, LTRC also conducted a survey in the United States and Canada to see what their maintenance procedures were. The appendix shows the results of this survey. The purpose of this survey was to see if any best practices could be adopted. Results of the survey are as follows:

- The survey's response rate is 36%.
- A majority of respondents manages the transportation agency's inventory of LED traffic signals without monitoring the luminous intensity degradation.
- The current approach to replace LED traffic signals is based solely on some type of failure as discovered by the field crew.
- A majority of respondents expressed an interest in utilizing specific lifetime curves as part of the transportation agency's strategy for LED traffic signal replacement.

Literature Review

Institute of Transportation Engineers Standards

The ITE standards are complex and vary depending on a driver's position in relation to the signal. Table 2 lists the horizontal and vertical angles for multiple drivers' positions and their respective ITE requirement for LED signal modules' minimum luminous intensity. Luminous intensities are the same for identical left/right angles *[2]*. According to P. Giacomo, "The candela (cd) is the luminous intensity, in a given direction, of a source which emits monochromatic radiation of frequency 540 x 10^{12} Hertz and whose radiant intensity in that direction is 1/683 Watt per steradian." *[5]*. Figure 2 illustrates the driver's view of the coordinates (vertical angle, horizontal angle) in Table 2. Figures 3-5 shows the bird's eye view of ITE luminous intensities for red, yellow, and green and their respective coordinates.

Table 2
ITE minimum acceptable luminous intensity values for 12-inch LED signal modules

Vertical angle	**Left/right angle**	**Luminous intensity (candela)** Red	Yellow	Green
12.5 up	2.5	37	91	48
	7.5	29	73	38
7.5 up	2.5	69	173	90
	7.5	55	137	71
	12.5	40	100	52
2.5 up	2.5	150	373	195
	7.5	124	309	162
	12.5	84	209	109
	17.5	47	118	62
	22.5	26	64	33
2.5 down	2.5	358	892	466
	7.5	292	728	380
	12.5	201	501	261
	17.5	117	291	152
	22.5	62	155	81
	27.5	33	82	43
7.5 down	2.5	281	701	366
	7.5	234	582	304
	12.5	157	391	204
	17.5	91	228	119
	22.5	47	118	62
	27.5	26	64	33
12.5 down	2.5	110	273	143
	7.5	88	218	114
	12.5	62	155	81
	17.5	37	91	48
	22.5	18	46	24
	27.5	11	27	14
17.5 down	2.5	51	127	67
	7.5	40	100	52
	12.5	29	73	38
	17.5	15	36	19
	22.5	7	18	10
22.5 down	2.5	37	91	48
	7.5	29	73	38
	12.5	22	55	29
	17.5	11	27	14
27.5 down	2.5	26	64	33
	7.5	18	46	24

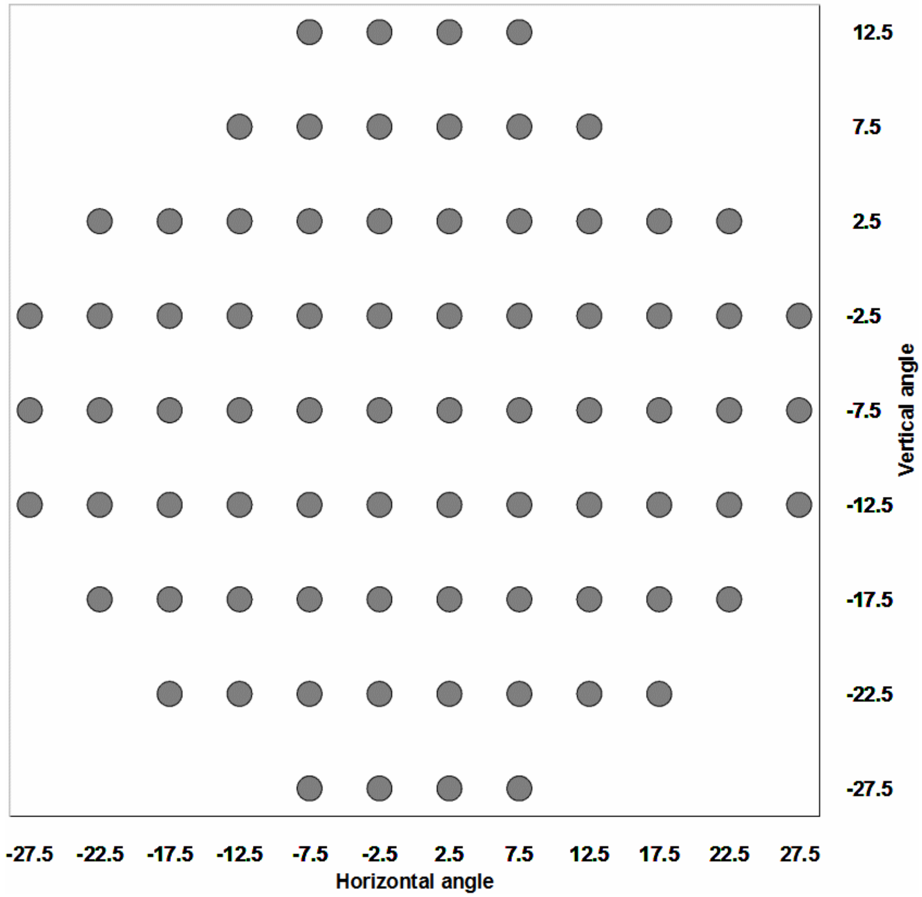


Figure 2
Drivers' view of ITE coordinates (vertical angle, horizontal angle) (top) when they approach an intersection (bottom)

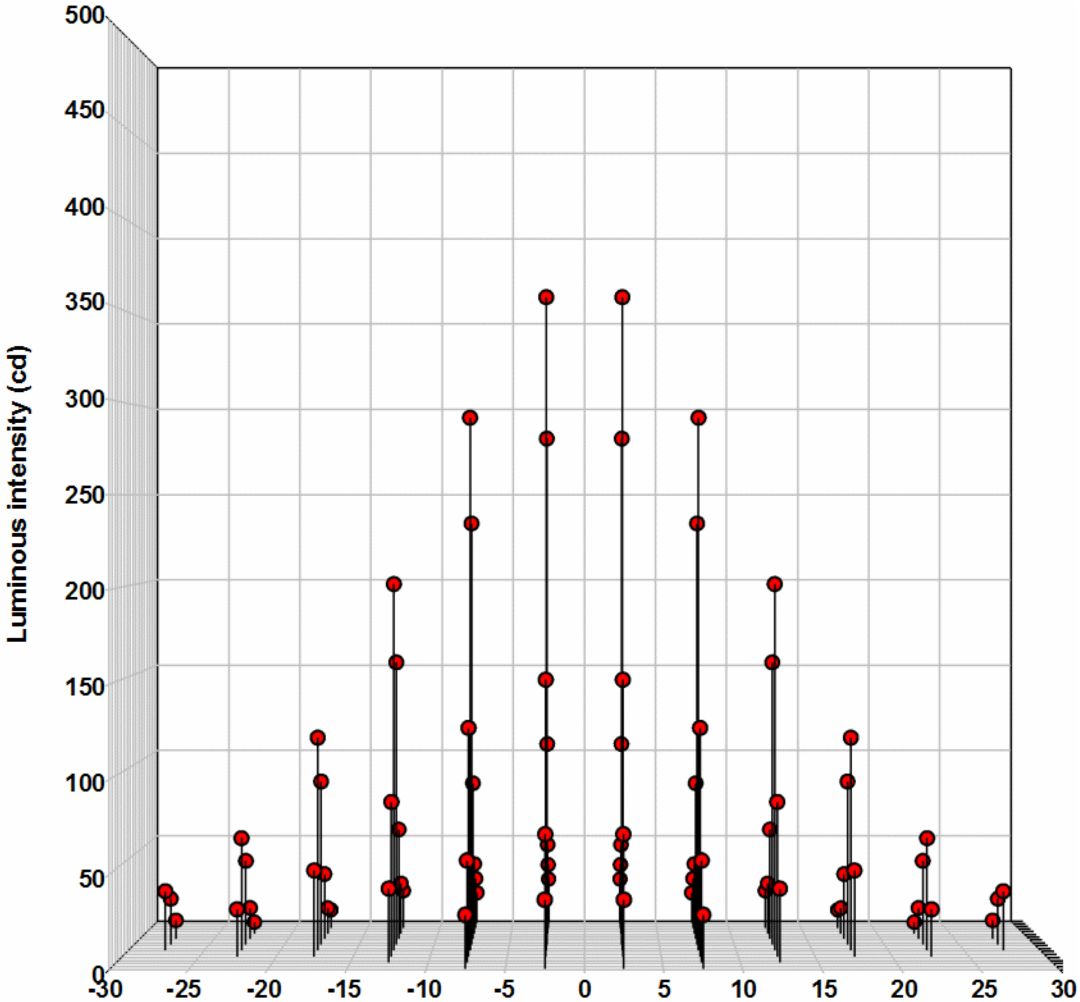


Figure 3
Bird's eye view of ITE luminous intensities for red and its respective coordinates in Table 2

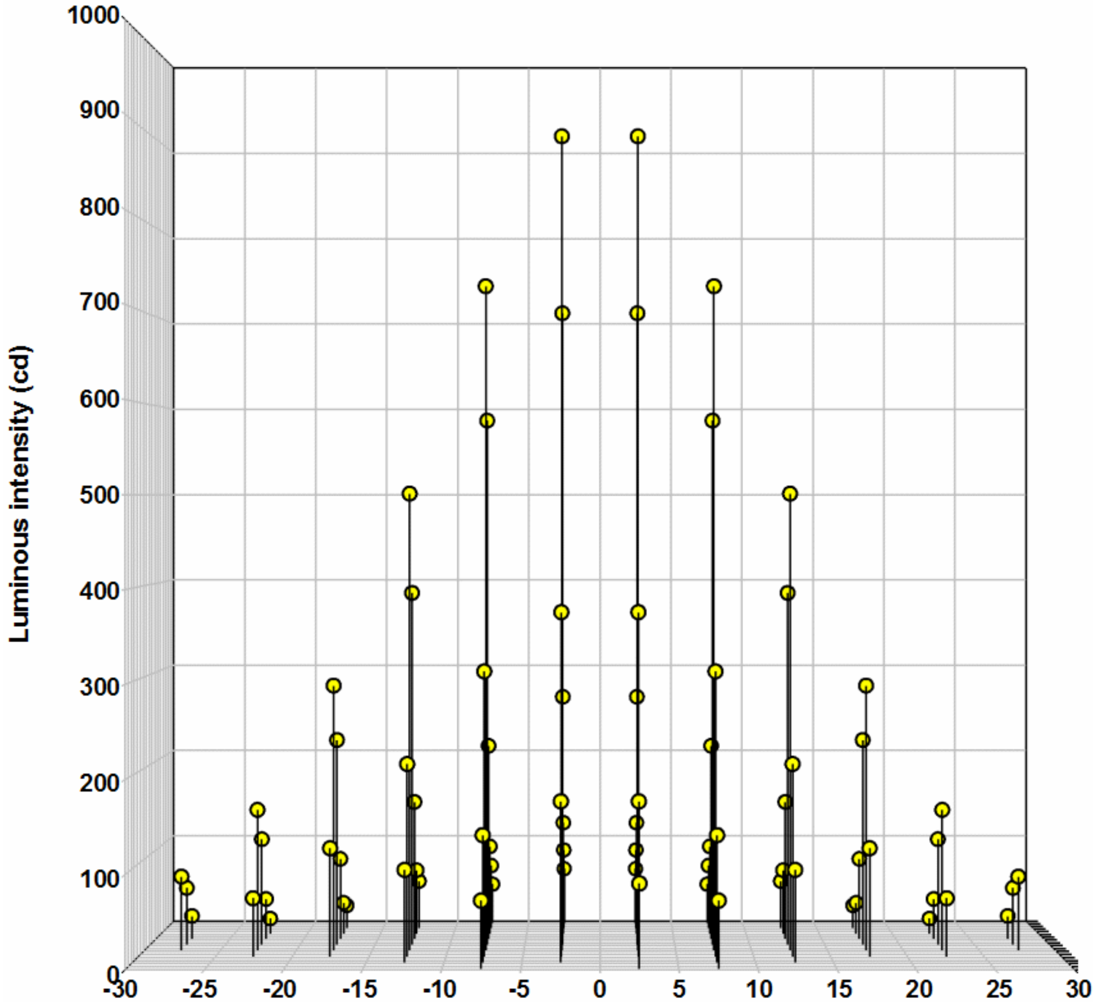


Figure 4
Bird's eye view of ITE luminous intensities for yellow and its respective coordinates in Table 2

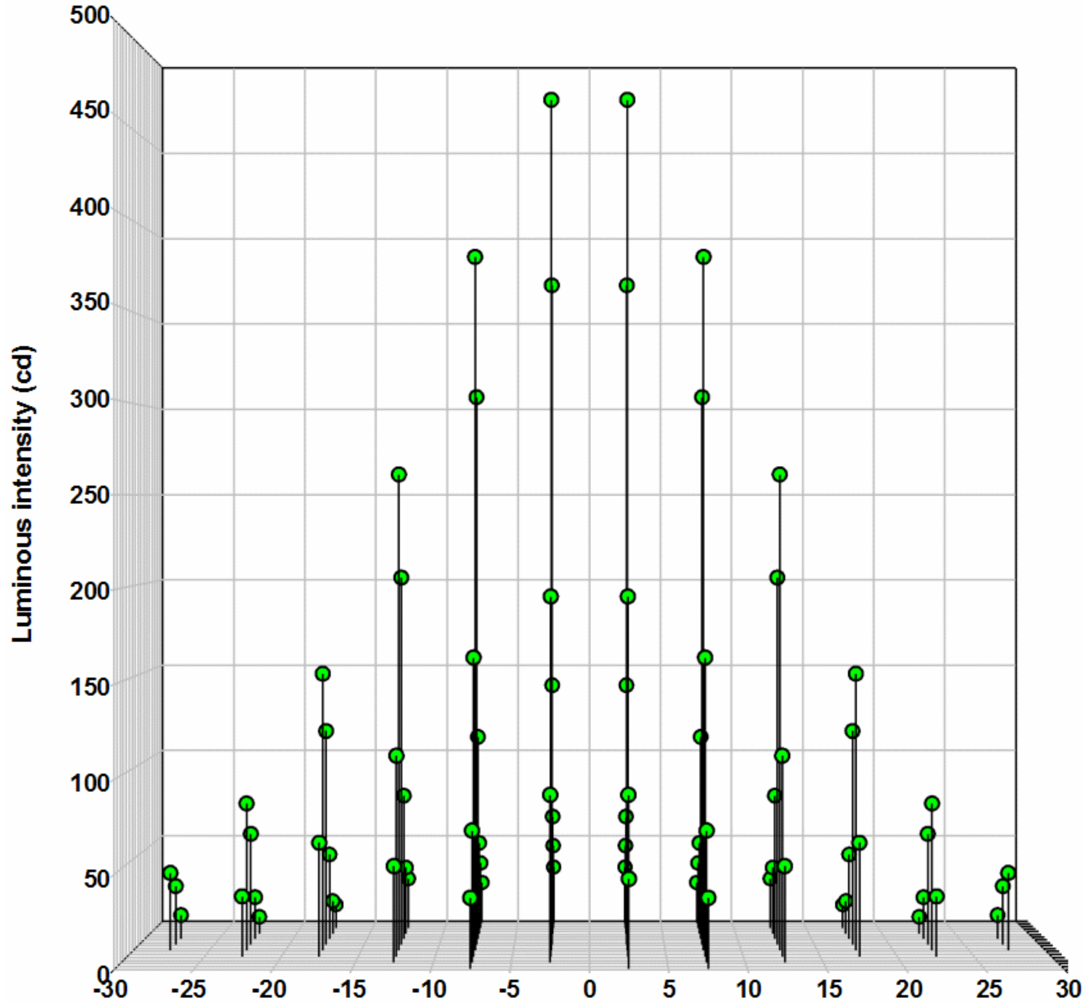


Figure 5
Bird's eye view of ITE luminous intensities for green and its respective coordinates in Table 2

Previous Research

A research effort was conducted in Missouri to develop a replacement strategy for LED signal modules *[6-7]*. The Missouri researchers used existing samples already installed at field locations. Missouri's measurements were taken in the field using a luminous intensity meter made in-house. Missouri Department of Transportation (MoDOT), at the time of their study, did not have an accurate inventory database of their signalized intersections *[6]*. Therefore, they could not have known with certainty the age of the signal modules. The Missouri research had a data collection period of three months. Because of this, this research had a one-time data collection sampling for each intersection *[6]*. The University of Missouri research failed to capture all failure modes of signal modules in accordance with the ITE coordinates in Table 2. There are 78 vertical and horizontal angle combinations in Table 2 in which a module could fail. The Missouri report used a single failure angle combination:

-10 degrees vertical and 0 degrees horizontal. This is an unrealistic assumption that all traffic signals will be aligned perfectly in the field and that the driver's perspective will be from a static fixed point. It does not account for angles of view of approaching vehicles beyond the fixed point, which is exactly why ITE standards have so many failure modes of different angle combinations. The University of Missouri research evaluated different manufacturers.

An additional research effort was sponsored by the District Department of Transportation (DDOT), in Washington, D.C., to develop a replacement schedule of LED traffic signal modules *[8]*. The entire focus of this research was to measure luminous intensity using a single handheld device to capture just one angle combination in accordance with ITE standards. The DDOT study collected measurements of the LED modules already operating at field locations. The DDOT study did not evaluate the handheld device for accuracy. The DDOT report presents two scenarios of data collection. The first scenario is data collection conducted in field locations using the handheld device. The second scenario is data collection conducted in a shop using the same handheld device that was used in the field locations.

Reliability Engineering

It is widely known in reliability engineering circles that operation of electronic devices and components follow a bathtub failure distribution curve as in Figure 6 *[9-13]*. The hazard rate at early life failures of Figure 6 decreases rapidly. The hazard rate at the useful life failures of Figure 6 is approximately constant. The hazard rate at the end of life failures of Figure 6 increases rapidly. It is expected that some of these LED modules will fail at this first stage of the curve in Figure 6. These failures are also expected to be degradation failures and not catastrophic failures. By proper design, catastrophic failures can be considered negligible *[14]*. In the case of LEDs, it is assumed that their end of useful life will be reached before a catastrophic failure.

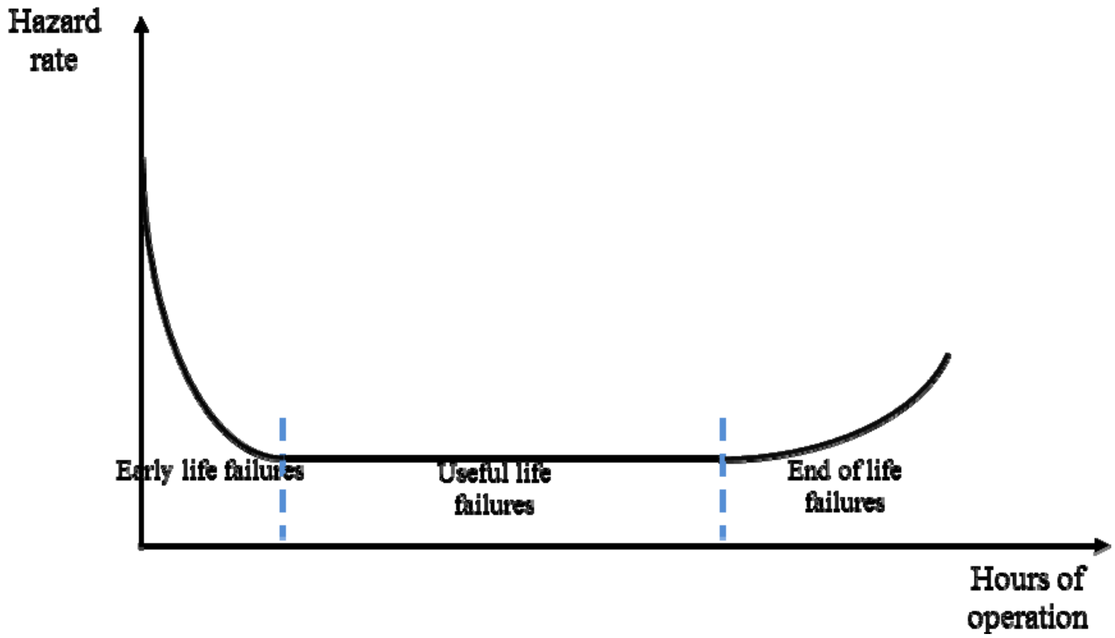


Figure 6
Bathtub curve

OBJECTIVE

The objectives of this research are to develop lifetime curves of LED traffic signal modules of the type currently used by DOTD, and to evaluate the effectiveness of the two handheld devices used to measure luminous intensity as compared to measurements from an independent lab. In order to assess the effectiveness of each handheld device, it is necessary to determine if that device produces repeatable measurements (precision). It is also necessary for the device to produce measurements that corroborate the lab measurements (accuracy).

SCOPE

This research project represents the measurements of the luminous intensity of traffic signal modules that were installed outside at the Traffic Services yard in accordance with the PRC's input. Firstly, Leotek models were chosen for this research, TSL-12R-LX-IL3-A1-CLR - red, TSL-12Y-LX-IL3-A1-C-CLR - yellow, and TSL-12G-LX-IL3-A1-CLR - green. Secondly, the research begins at time zero (t_o) and will continue for 20,000 hours. Assuming a fixed time signal with a 120-second-cycle length (55 seconds of green, 4 seconds of yellow, and 61 seconds of red) and no turning movements (this research does not include arrow signal modules), 20,000 hours equates to five years of green, 68 years of yellow, and four and one half years of red under normal traffic operating conditions (see Figure 7). These signal modules are burning continuously, which does not represent field conditions. Each module cycles on and off once for every 120-second-signal cycle in the field. It was impractical to replicate this with the experimental samples. Therefore, the degradation effects of this "On/Off" cycling are unknown and will not be investigated in this study. Thirdly, three distinct modules of red, yellow, and green each will be sent to an independent lab for testing beginning at initial time (t_o) up to 10,000 hours on a 2,000-hour-basis, and finally at 20,000 hours, totaling 63 modules (nine modules per lab test times seven lab tests). Any module that fails as a result of electronic components prior to reaching the minimum luminous intensity will be considered in determining a hazard rate for early life failures. Unless modules fail before lab tests, no modules will be sent twice for the lab for testing. Upon returning from lab tests, the modules will be put back into operation until completing 20,000 hours. Traffic Services Signal Foremen followed-up with in-house tests carried out every 500 hours in all the modules.

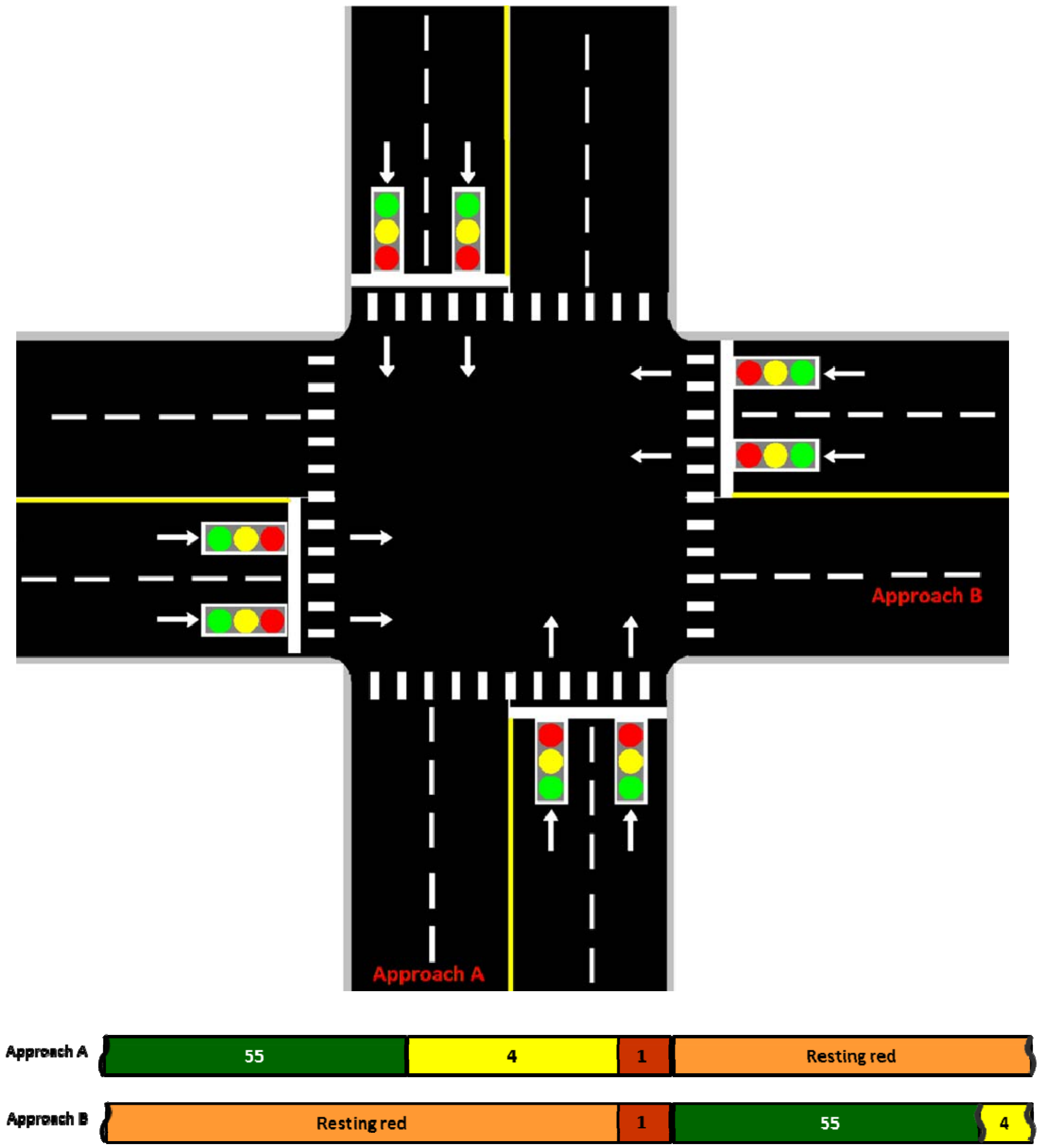


Figure 7
Time intervals for circular modules

METHODOLOGY

Description of LED Traffic Signal Samples

In this study, the 63 traffic signal modules, typically each one with an array of multiple LEDs, are divided evenly according to the color of the light emitted. Hence, this research has 21 identical modules of red, yellow, or green each. Figure 8 depicts how these modules are arrayed in seven columns (1 through 7) that were installed at the yard of Traffic Services. The research team selected the modules randomly from the stock room when working on the columns' set up. Column 1 is the nearest one to the building that houses the modules' power supply system (see Figure 9). Columns 2 and 3 are at the right and left sides of column 1. The remaining columns are placed in ascending order in accordance with their proximity of this building. Table 3 shows serial number and lot number of traffic signal modules in Figure 8.

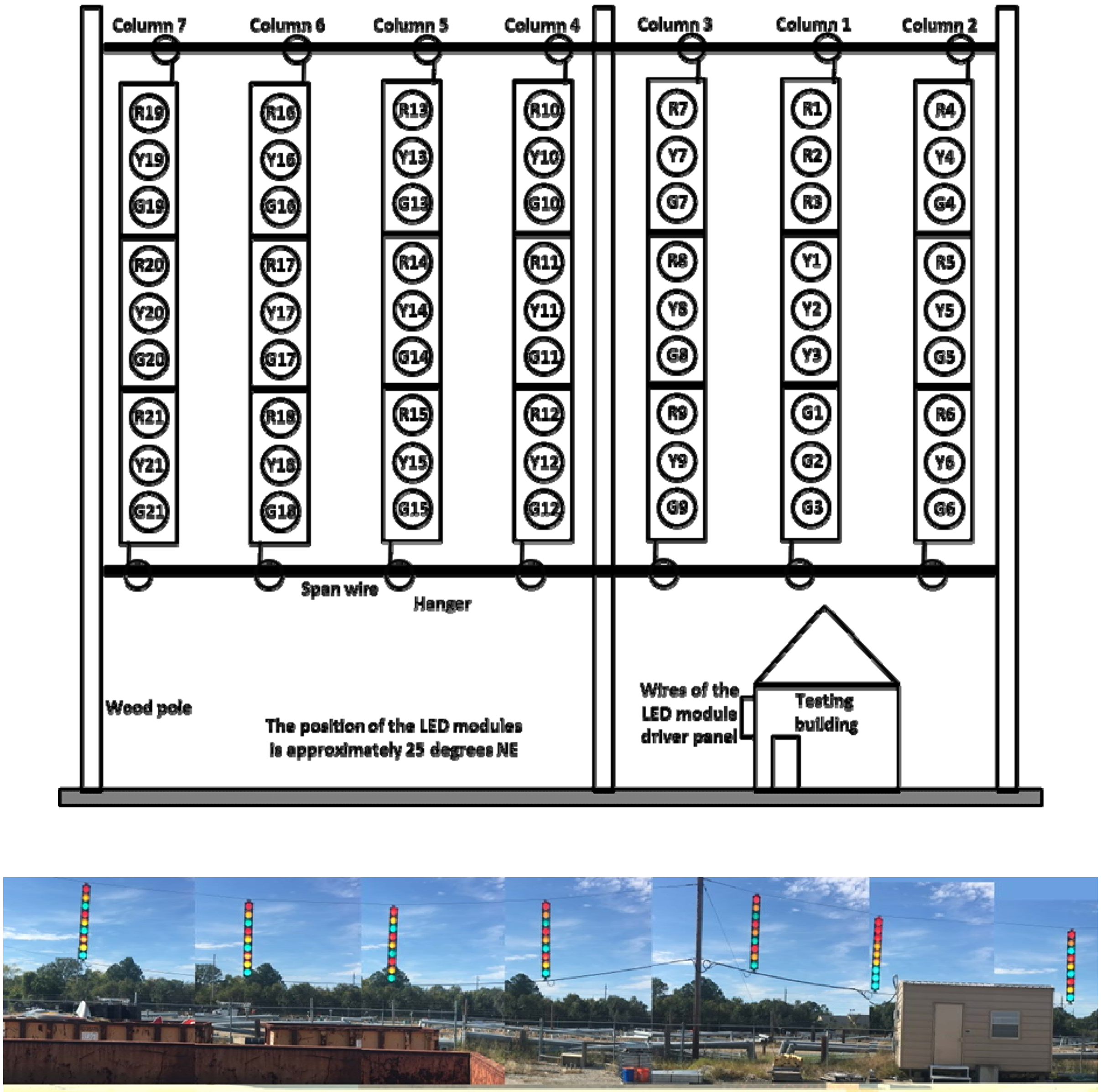


Figure 8
Traffic signal module layout

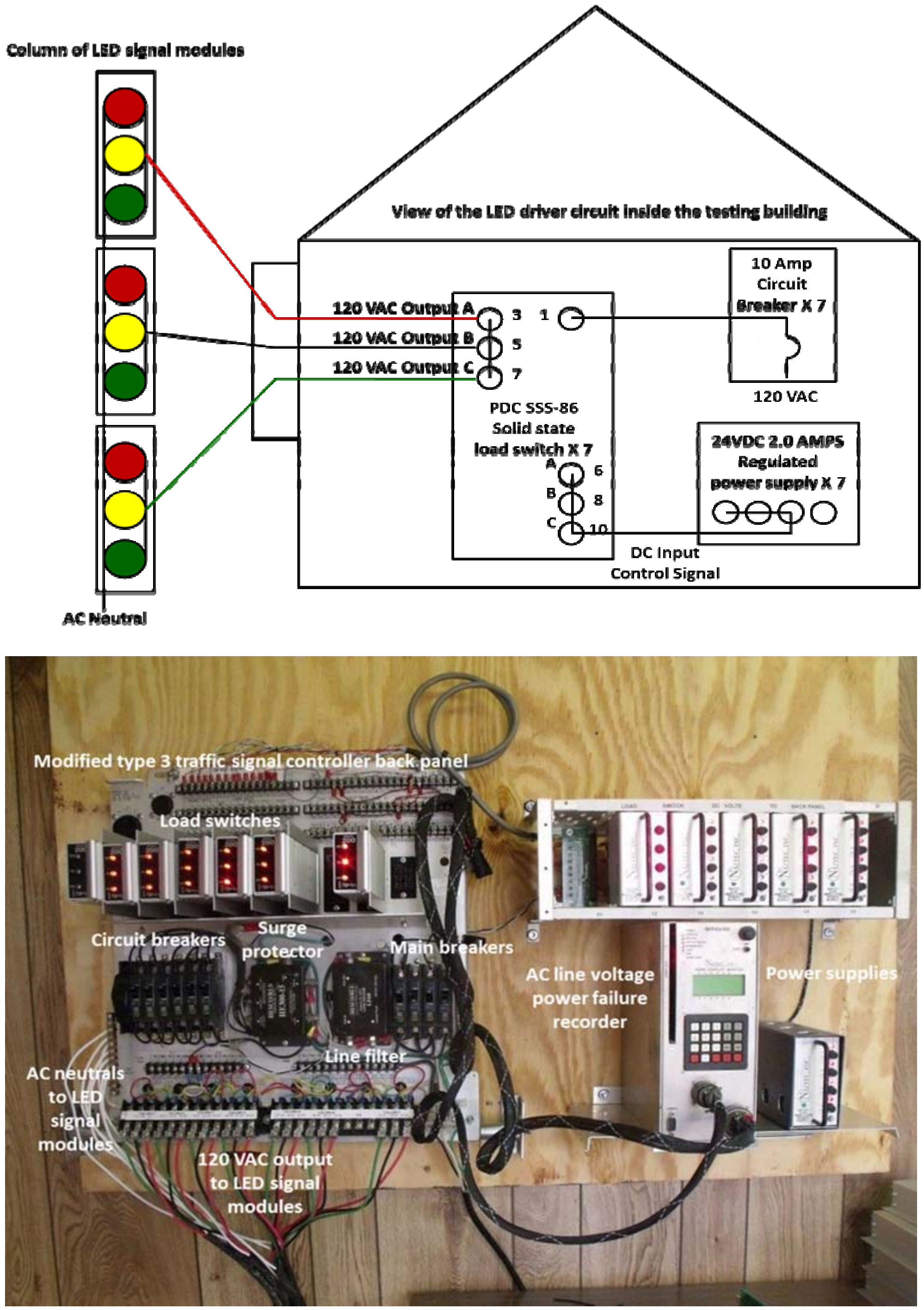


Figure 9
Power supply for LED luminous intensity testing

Table 3
Serial number and lot number of the traffic signal modules in Figure 8

	Red			**Yellow**			**Green**	
Sample ID	Serial no.	Lot no.	Sample ID	Serial no.	Lot no.	Sample ID	Serial no.	Lot no.
R16	10212800	WO02-99020052	**Y21**	10213585	WO02-99020053	**G16**	10214534	WO02-99020054
R17	10212801	WO02-99020052	**Y16**	10213586	WO02-99020053	**G17**	10214547	WO02-99020054
R12	10A04454	WO12-99100012	**Y20**	10213587	WO02-99020053	**G18**	10215323	WO02-99020054
R11	10A04455	WO12-99100012	**Y15**	10512865	WO12-99050008	**G02**	10B26065	WO02-99110072
R10	10A04456	WO12-99100012	**Y13**	10512866	WO12-99050008	**G09**	10B26066	WO02-99110072
R13	10A04457	WO12-99100012	**Y14**	10512867	WO12-99050008	**G07**	10B26067	WO02-99110072
R14	10A04458	WO12-99100012	**Y19**	10512868	WO12-99050008	**G08**	10B26068	WO02-99110072
R18	10A04459	WO12-99100012	**Y10**	10935091	WO02-99090139	**G14**	11128078	WO12-100010014
R20	10A04460	WO12-99100012	**Y11**	10935092	WO02-99090139	**G13**	11128079	WO12-100010014
R15	10A04461	WO12-99100012	**Y06**	10935093	WO02-99090139	**G12**	11128080	WO12-100010014
R21	10A04462	WO12-99100012	**Y12**	10935094	WO02-99090139	**G11**	11128081	WO12-100010014
R19	10A04463	WO12-99100012	**Y05**	10935095	WO02-99090139	**G10**	11128082	WO12-100010014
R07	10A04465	WO12-99100012	**Y07**	10935096	WO02-99090139	**G21**	11128084	WO12-100010014
R08	10A04466	WO12-99100012	**Y08**	10935097	WO02-99090139	**G19**	11128085	WO12-100010014
R09	10A04467	WO12-99100012	**Y09**	10935098	WO02-99090139	**G15**	11128086	WO12-100010014
R02	10A04468	WO12-99100012	**Y01**	10935099	WO02-99090139	**G20**	11128087	WO12-100010014
R05	10A04469	WO12-99100012	**Y02**	10935100	WO02-99090139	**G06**	11128088	WO12-100010014
R06	10A04470	WO12-99100012	**Y18**	10935151	WO02-99090139	**G05**	11128089	WO12-100010014
R04	10A04471	WO12-99100012	**Y17**	10935152	WO02-99090139	**G04**	11128090	WO12-100010014
R03	10A04472	WO12-99100012	**Y03**	10935153	WO02-99090139	**G03**	11128091	WO12-100010014
R01	10A04473	WO12-99100012	**Y04**	10935154	WO02-99090139	**G01**	11128092	WO12-100010014

Measurement Techniques

In this study, the signal modules were tested using three different techniques, two handheld devices, and measurements made by an independent lab.

Lab Measurement of Luminous Intensity

An independent lab measured the luminous intensity of these modules by using a goniophotometer system to collect multiple data points per module. A goniophotometer system is comprised of a goniometer (see Figure 10) that is an insturment that measures angles and a photometer that is an instrument that measures light *[15]*.

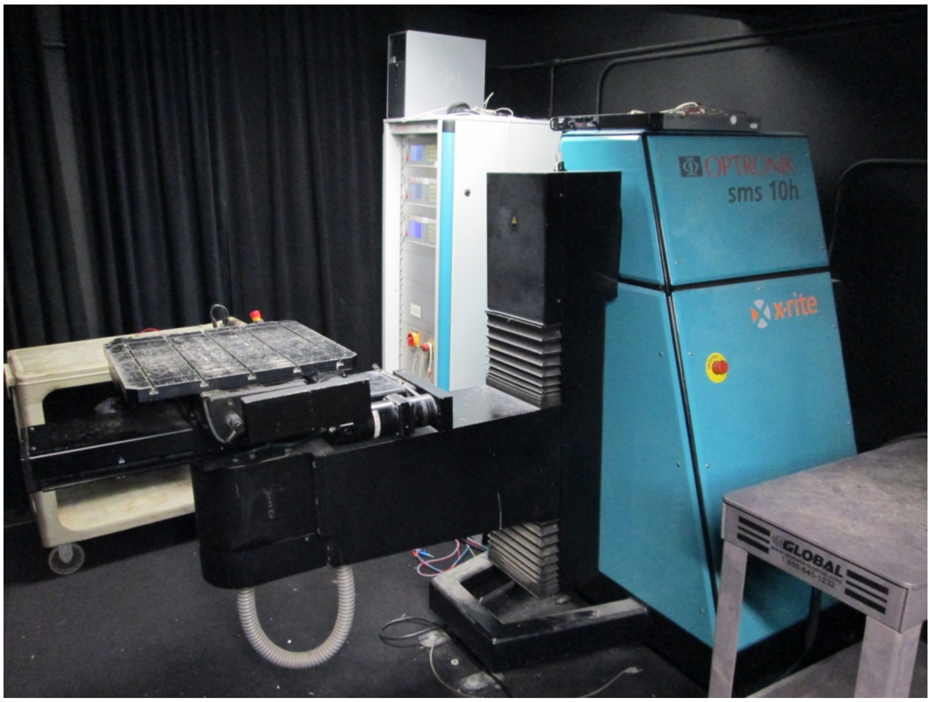


Figure 10
Goniometer to position the LED signal module according to each one of the angle coordinates from ITE (source: Intertek)

Each one of the data points obtained from the lab represents a distinct angle coordinate in relation to the driver's view as shown in both Table 2 and Figure 2. The lab only measured the modules in one column in Figure 8 at a time. The lab measurements began at t_o by sending out the modules from column 1. Once these modules returned from the lab, they were put back into operation and they will burn until they reach 20,000 hours. At 2,000 hours, the modules in column 2 were disconnected from the circuit and sent to lab testing. Column 2's modules were put back into operation for an additional 18,000 hours upon arriving from lab tests. At 4,000, 6,000, 8,000, and 10,000 hours the modules from columns 3, 4, 5, and 6, respectively, were taken out from their column and shipped for lab testing. After lab measurements, modules in columns 3, 4, 5, and 6 were put back into operation for an additional 16,000, 14,000, 12,000, and 10,000 hours, respectively. The lab will also take a final measurement at 20,000 hours for modules from column 7.

In-House Measurement of Luminous Intensity

The research team of this project also conducted in-house tests on all of the modules in Figure 8 using two distinct handheld devices, Spectra Candela III Traffic Signal Light Tester Model 2,000 Basic Kit and Traffic Light Intensity Meter (TIM).

Spectra Candela measures luminous intensity of LED signal modules using a Light Integrator connected to a photometer. The Light Integrator is attached to the lens of the traffic light module to be measured. The user adjusts the photometer for each LED color – red, yellow, and green. Light Integrator estimates the average of all the LED's luminous intensity values *[16]*.

A handheld device to measure traffic signal's luminous intensity is described on United States Patent Number 5,185, 637 *[17]*. Based upon the apparent similarity of the Light Integrator of Spectra Candela to the housing of this handheld device, it may be concluded that the principle of operation of both devices appears to be the same. World Intellectual Property Organization (WIPO) Patent Application Number WO/2005/026672 A1, however, recognizes that there are multiple problems in the reflector unit in the aforementioned design *[18]*.

The principle of operation of TIM appears to be similar to that of the handheld device described in the WIPO Patent Application Number WO/2005/026672 A1. TIM collects the luminous intensity from a signal module's lens, independently of the LED color, and directs it to a focal point using internal lenses. Then, a sensor estimates the luminous intensity at the focal point.

The team collected one data point per module by putting each device, Spectra Candela and TIM, perpendicular to the module lens (at 0° vertical and 0° horizontal) to measure its luminous intensity. The first in-house measurement was taken at time zero (t_o), and subsequently every 500 hours up to 20,000 hours. The field measurements were taken in ambient weather conditions (see Figure 11). ITE has also established the minimum luminous intensity values at 0° vertical and 0° horizontal for signal modules. The values at this coordinate for red, yellow, and green are 234, 582, and 304 cd respectively. These values correspond with the ITE minimum luminous intensity for 7.5 degrees down and 7.5 degrees either right or left in accordance with Table 2.

Figure 11
Traffic Services Signal Foremen take in-house measurements every 500 hours in all the modules in a bucket truck (top) using Spectra Candela (center) and TIM (bottom)

Data Correlation Between In-House and Lab Measurements

It is unknown at this point in the research project if the LED modules will trend toward failure at the 0, 0 [0 degrees up or down and 0 degrees left or right] coordinate first or at some angle other than 0, 0. The handheld devices can only measure luminous intensity at 0, 0 while the lab can measure luminous intensity at all of the angles as specified by ITE. If the trend is, in fact, that 0, 0 fails first, then the life curves will be based on a model where the useful life of an LED module is basically when the 0, 0 curve goes below the minimum acceptable ITE standards.

If, on the other hand, the trend shows failures at an angle other than 0, 0 then those particular curves must be correlated back to the handheld devices. Figure 12 is a depiction of this scenario. Here there are two charts: Handheld Curve measured at 0, 0 above and Lab Curve measured at 7.5 down and 12.5 left, below. As the reader can see, there are two different minimum acceptable luminous intensities depending on the angle of measurement. In this example, the lab has detected a failure at the 7.5 down and 12.5 left while the luminous intensity is still well above minimum standards at 0, 0. Two things can be done to correlate the data back to the handheld curve. Firstly, if there are many failures at this angle, then it would be prudent to say that this is the time of the end of useful life for these modules. To show this graphically, draw a vertical line at time of failure at 7.5 down and 12.5 left onto the graph of 0, 0 and this becomes the time of failure regardless of what the luminous intensity of the handheld measurements are. Secondly, if there are only a few failures at 7.5 down and 12.5 left with no failures detected by the handheld, such as with early life failures, then it would not be prudent to say this is the end of useful life for this module. In this situation, the vertical line can still be drawn onto the handheld curve from the time of failure on the lab curve. Then a horizontal line can be drawn from the intersection of this vertical line and the handheld curve to the vertical axis in order to obtain the luminous intensity. This could potentially become the correlated minimum acceptable luminous intensity for the handheld device. In Figure 12, it is shown that the lab reading of 7.5 down and 12.5 left has failed at 157 cd which correlates to 364 cd of the handheld device.

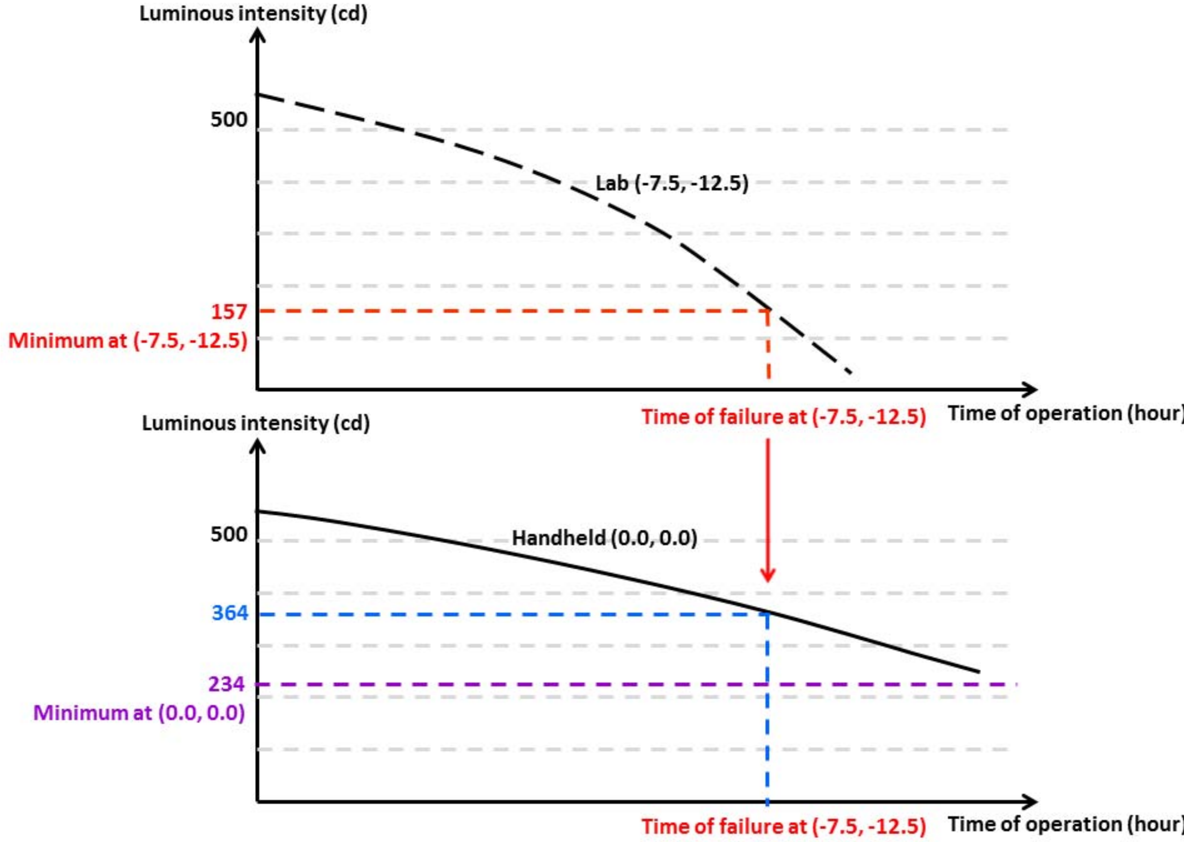


Figure 12
Data correlation between handheld device measurements at (0, 0) and lab measurements at any coordinate

DISCUSSION OF RESULTS

Luminous Intensity Values Collected by the Lab Using Goniophotometer

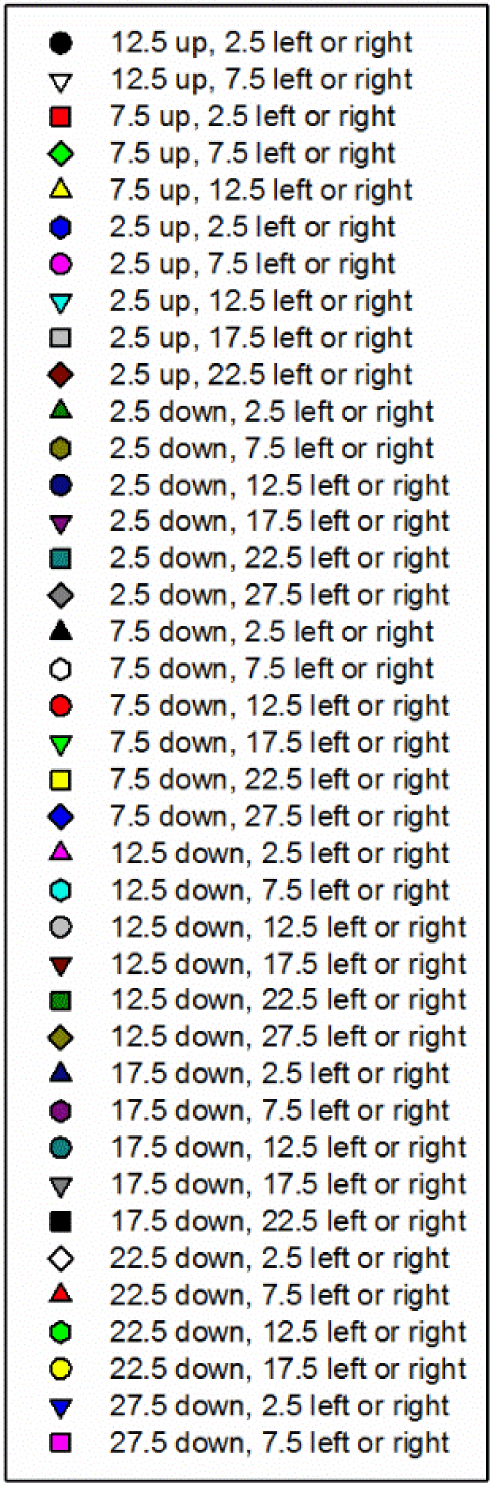
Figure 13 to Figure 19 represent the 95% lower confidence interval of luminous intensity readings taken in laboratory for red (top), yellow (center), and green (bottom) signal modules at t_o, 2,000 hours, 4,000 hours, 6,000 hours, 8,000 hours, 10,000 hours, and 20,000 hours, respectively. Because the size of the sample is smaller than 30, the confidence interval, which can encompass the population mean, was constructed using t *[19]*. In Figure 13 to Figure 19, the X and Y axes represent, respectively, the relative luminous intensity and the vertical angles for each horizontal angle either left or right. The symbols plotted in Figure 13 to Figure 19 represent the ITE specified coordinates (see Table 4). It should also be noted that all points (ITE specified coordinate) in Figure 13 to Figure 19 are independent of each other. Each point represents three lab tests in Figure 13 to Figure 19, except for the top of Figure 18 (see explanation in the next paragraph). The results of these three tests are used to construct the confidence intervals. The relative luminous intensity values result from their original readings as measured divided by the ITE minimum luminous intensity values at each coordinate specified in Table 2. Failure of each red, yellow, and green module occurs when the relative luminous intensity is less than 1 in Figure 13 to Figure 19. The luminous intensity values in Figure 13 to Figure 19 are closer to 1 for the coordinates that have the highest minimum luminous intensity values in Table 2. The purpose of Figure 13 to Figure 19 is to simplify data interpretation. With 78 coordinates for each color, it would quickly become cumbersome to identify when and where the failure occurs if they were plotted separately.

The samples R16 and R17 (see Figure 8) failed earlier in accordance with lab testing, which is based on ITE standards. These samples are considered outliers, because they are extreme values in the set *[19]*. Thus, these samples were removed from data analyses presented in Figure 18. For this reason, the points in Figure 18 represents the lab results for sample R18.

Luminous intensity values in Figure 13 to Figure 19 present oscillations as a function of time for some coordinates. Perhaps, if the interval of measurements were smaller, more oscillations would be detected for the LED modules. It appears that the luminous intensity values of these signal modules oscillate throughout time decreasing toward 1, then increasing before decreasing again.

Table 4

Legend of the symbols in Figure 13 to Figure 19 in accordance with ITE specified coordinates



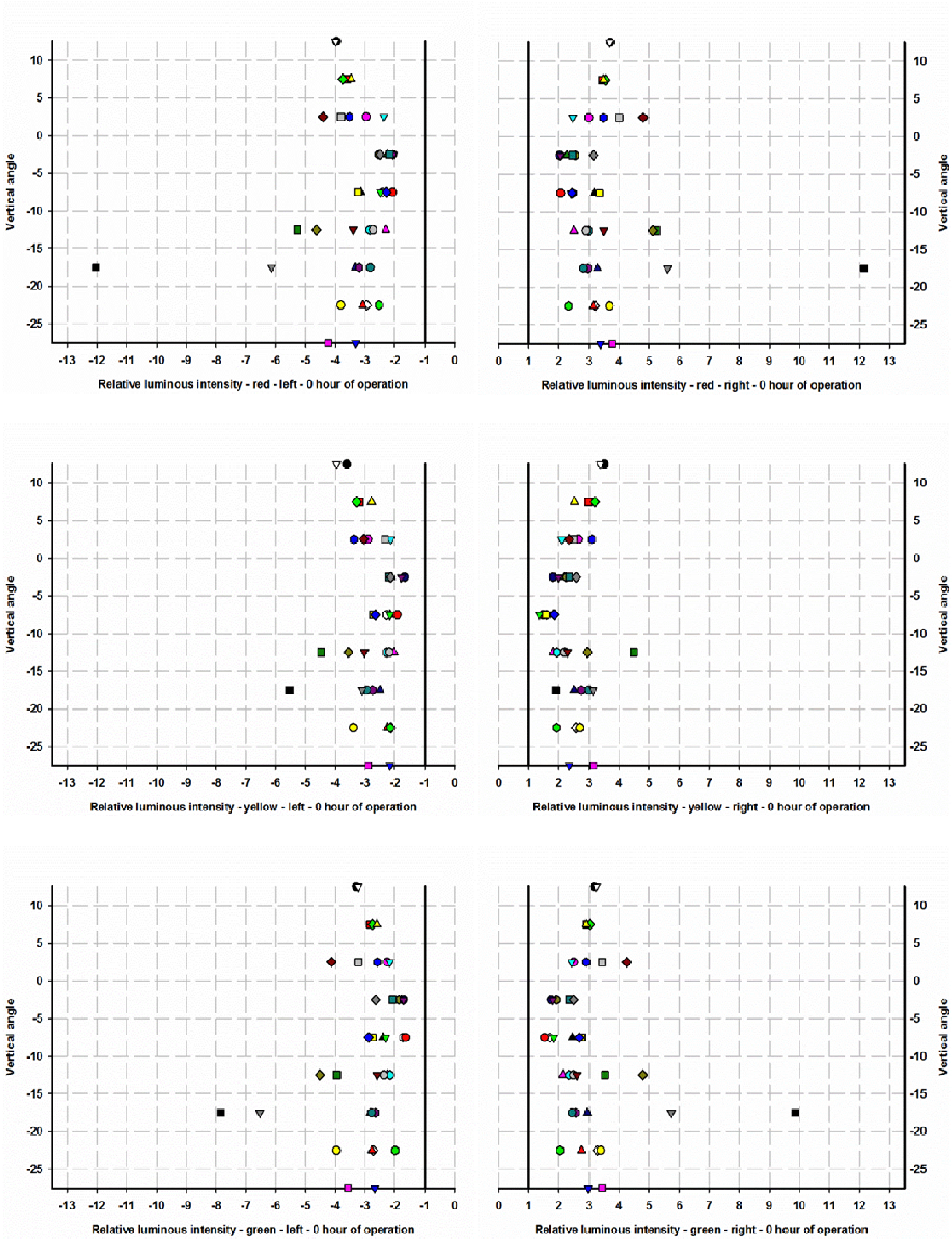


Figure 13
Luminous intensity of red, yellow, and green modules at 0 hour – 95%LCI

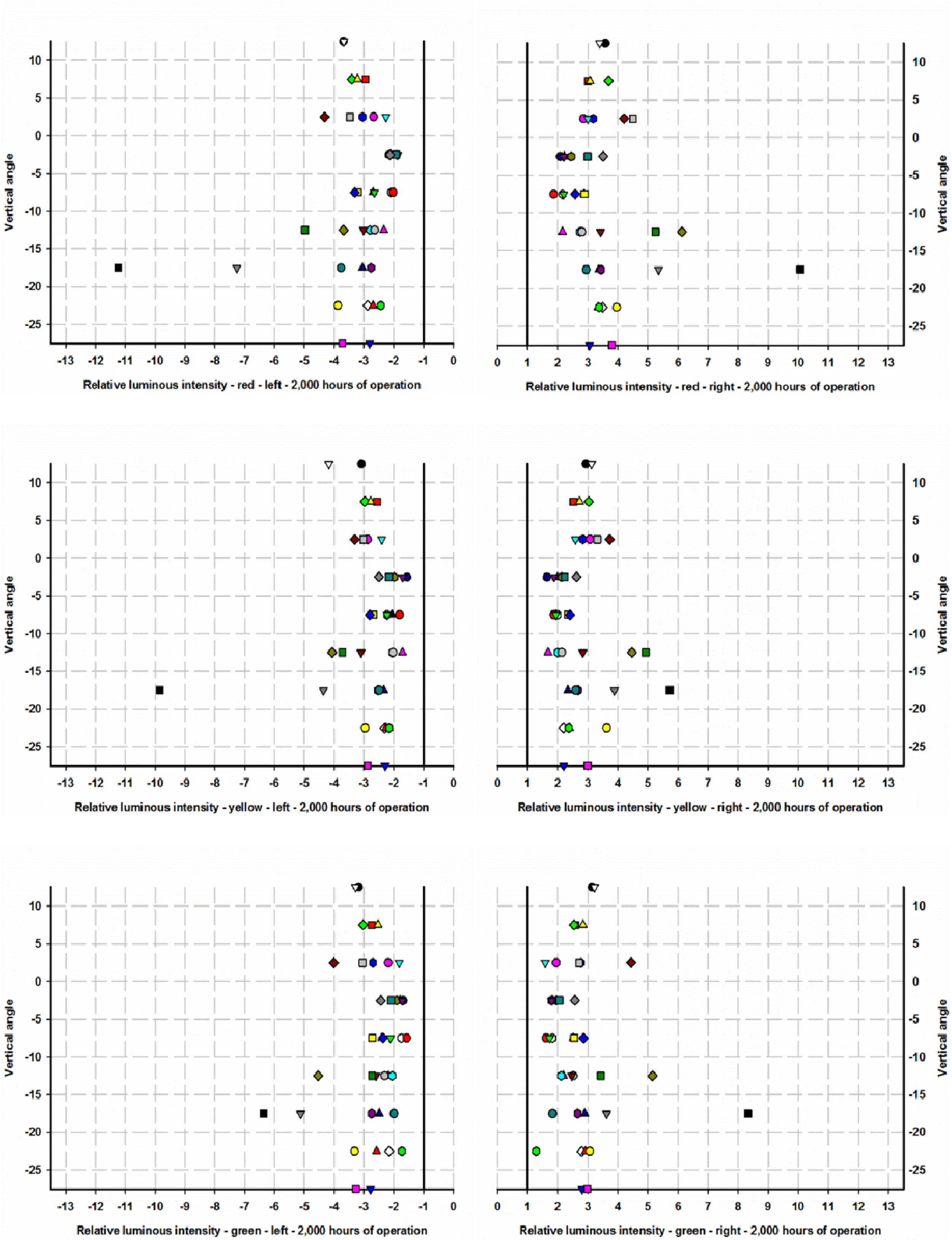


Figure 14
Luminous intensity of red, yellow, and green modules at 2,000 hours – 95%LCI

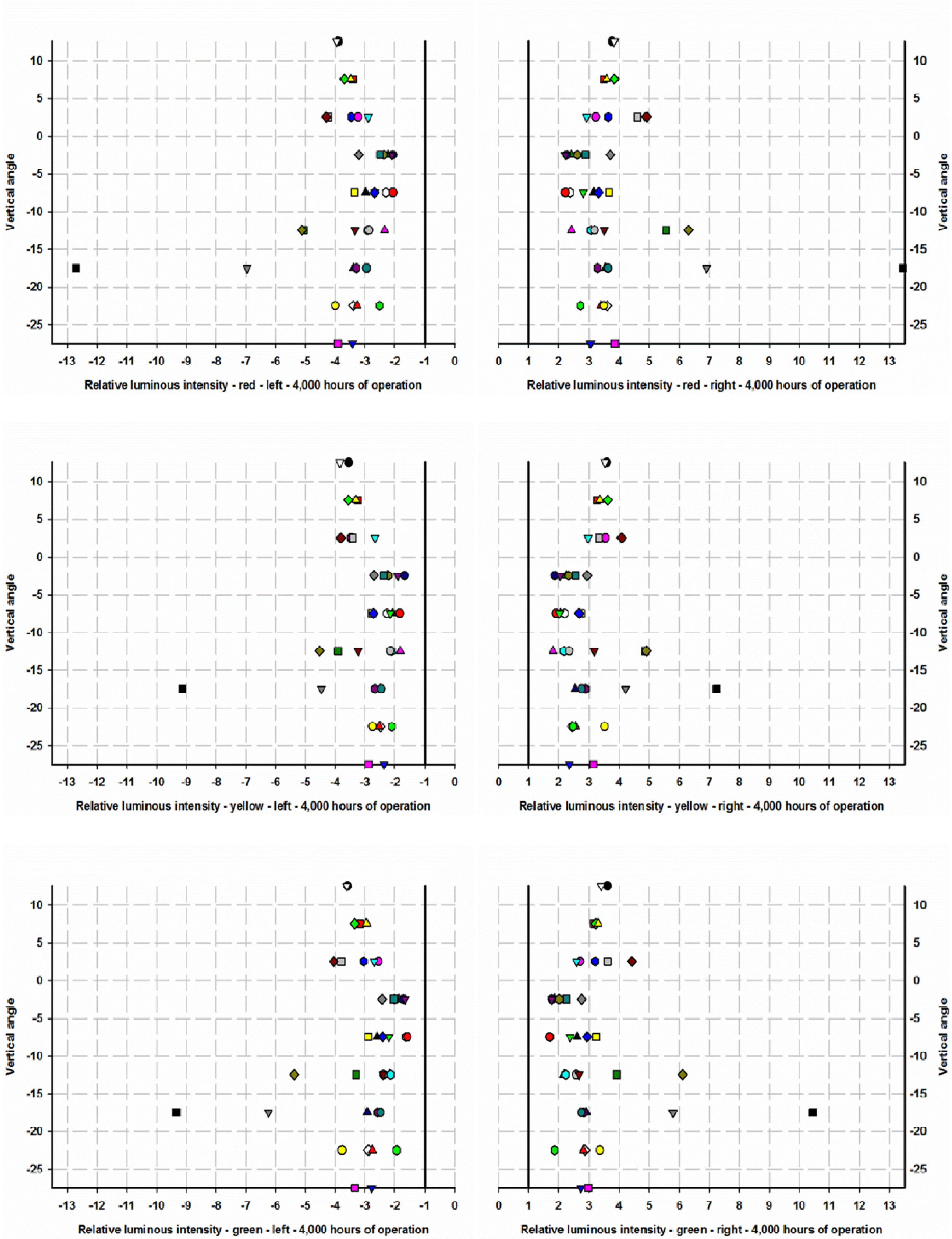


Figure 15
Luminous intensity of red, yellow, and green modules at 4,000 hours – 95%LCI

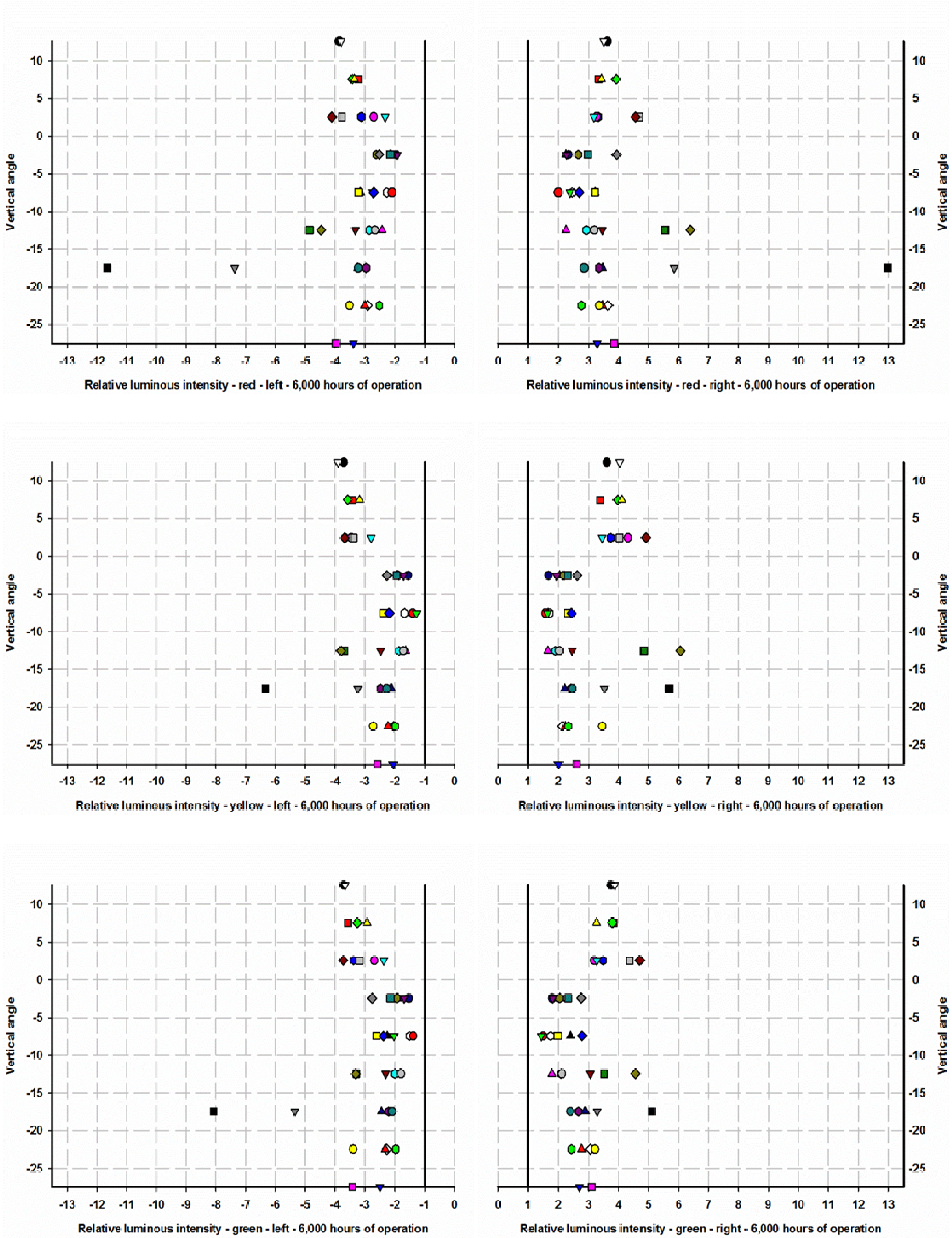


Figure 16
Luminous intensity of red, yellow, and green modules at 6,000 hours – 95%LCI

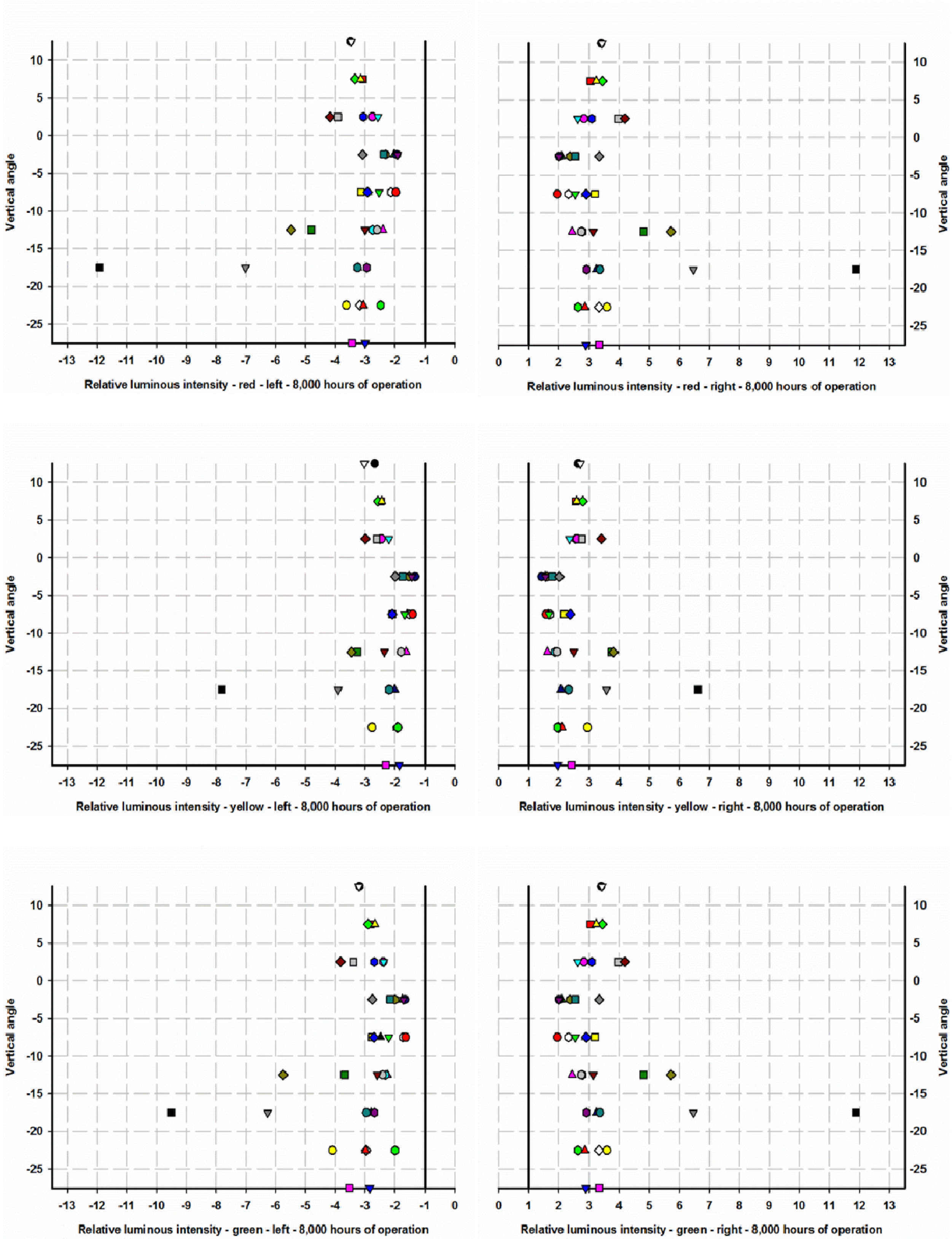


Figure 17
Luminous intensity of red, yellow, and green modules at 8,000 hours – 95%LCI

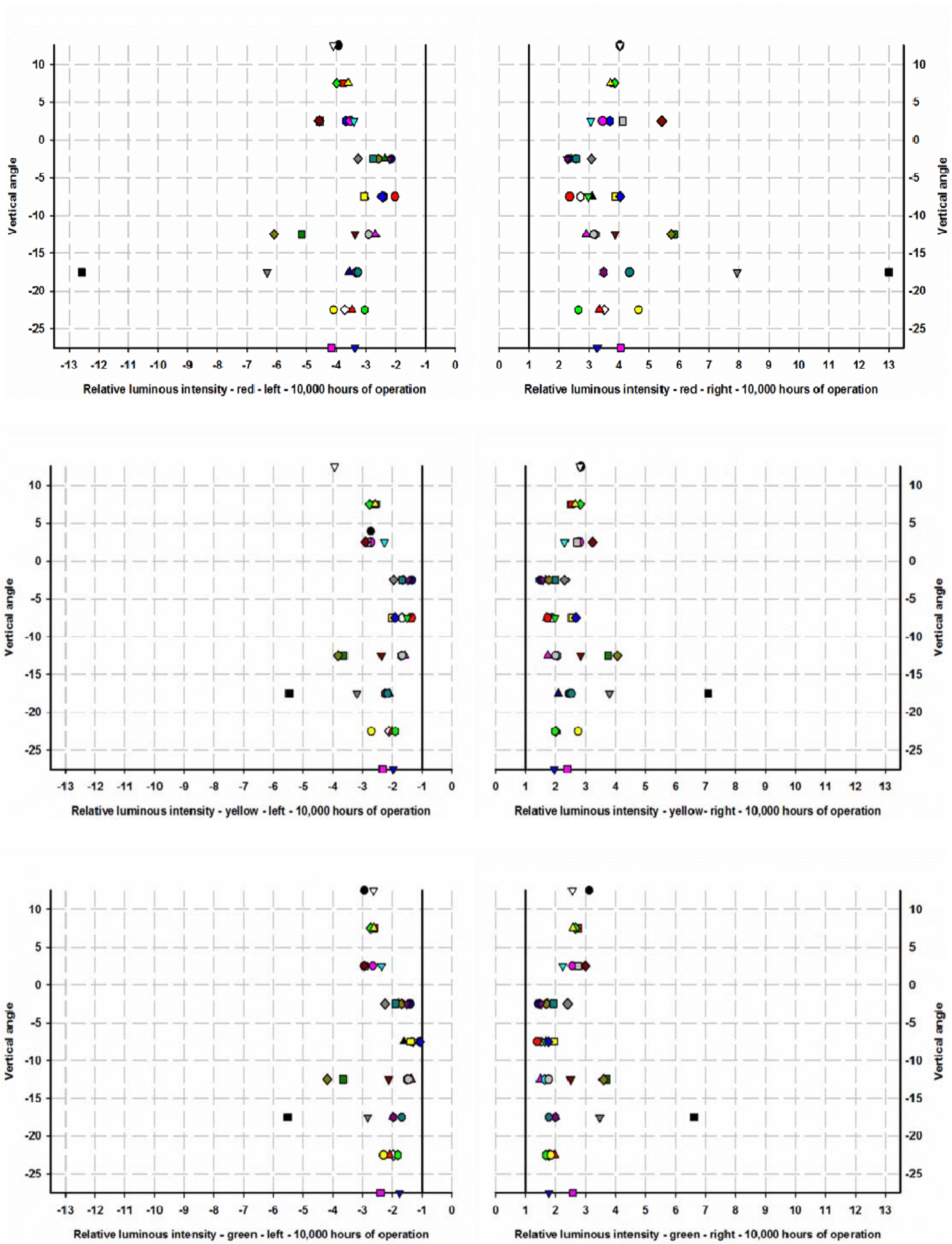


Figure 18
Luminous intensity of red, yellow, and green modules at 10,000 hours – 95%LCI

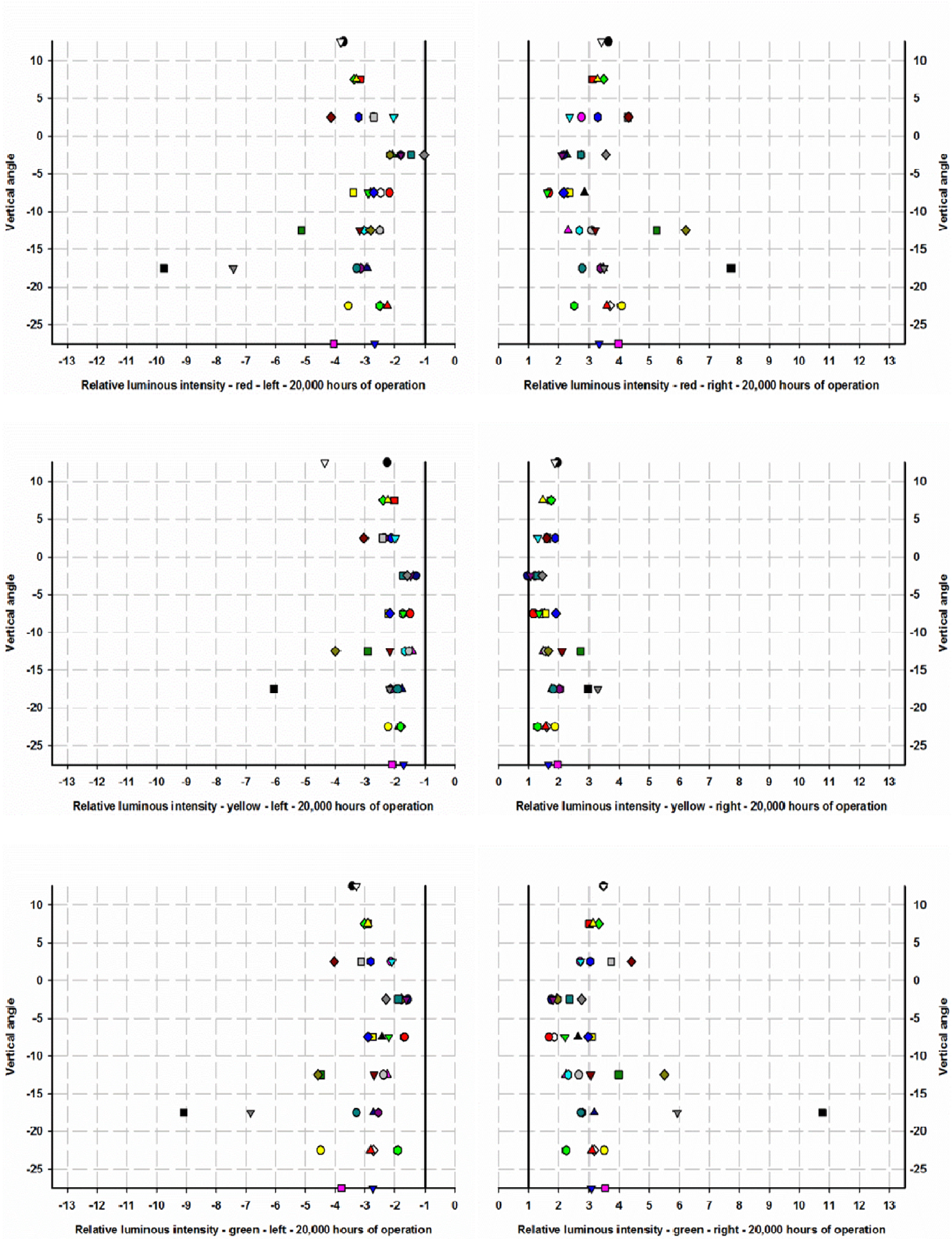


Figure 19
Luminous intensity of red, yellow, and green modules at 20,000 hours – 95%LCI

Luminous Intensity Values Collected Using Spectra Candela and TIM

Figure 20 shows the results of luminous intensity of the LED modules measured using the two handheld light meters, Spectra Candela and TIM. The curves in Figure 20 compare the sample mean and the sample standard deviation of both handheld data sets. The curves in Figure 20 result from the raw data as measured divided by the ITE minimum luminous intensity values at (0, 0), at (-7.5, -7.5), or at (-7.5, 7.5), because the ITE minimum luminous intensity values at these coordinates are the same. Data analyses in Figure 20 (top) do not include samples R16 and R17. Figure 21 specifically illustrates early life failures for samples R16 and R17 (see Figure 6). Each point in Figure 20 (top, center, and bottom) represents 19, 21, and 21 measurements for red, yellow, and green LED modules respectively. Figure 20 depict that the Spectra Candela device has high sample standard deviations for most measurements. This indicates that Spectra Candela is likely imprecise, i.e., it may have reproducibility errors. Conversely, TIM has low standard deviations in Figure 20. This suggests that TIM is a high precision device.

Figure 22 presents the 95% upper and lower confidence intervals of both handheld data sets. These confidence intervals were constructed using the results in Figure 20. The left side of Figure 23 depicts the 95% upper and lower confidence intervals of lab measurements at (-7.5, -7,5) and at (0, 0). The right side of Figure 23 depicts the 95% upper and lower confidence intervals of lab measurements at (-7.5, 7.5) and at (0, 0). Each curve in Figure 22 and Figure 23 will have to drop below 1 for the modules to be considered failed. The comparison between the upper and lower confidence intervals of each handheld device and the lower confidence intervals of lab measurements at (-7.5, -7.5) and at (-7.5, 7.5) indicates that both devices may be inaccurate, i.e., they may have systematic errors compared to the lab measurements.

The cause of the oscillations in the luminous intensity as a function of time in Figure 22 is currently undetermined. These oscillations may be due to ambient temperature, because LEDs are permanently degraded as a result of operating in high ambient temperature. Although the individual LEDs are assembled on heat sinks inside the traffic signal modules, this assembly may not be sufficient to avoid such damage. This would explain why the luminous intensity of both lab and handheld devices has oscillations. If so, the parameters of the lifetime curves will be more complex to determine.

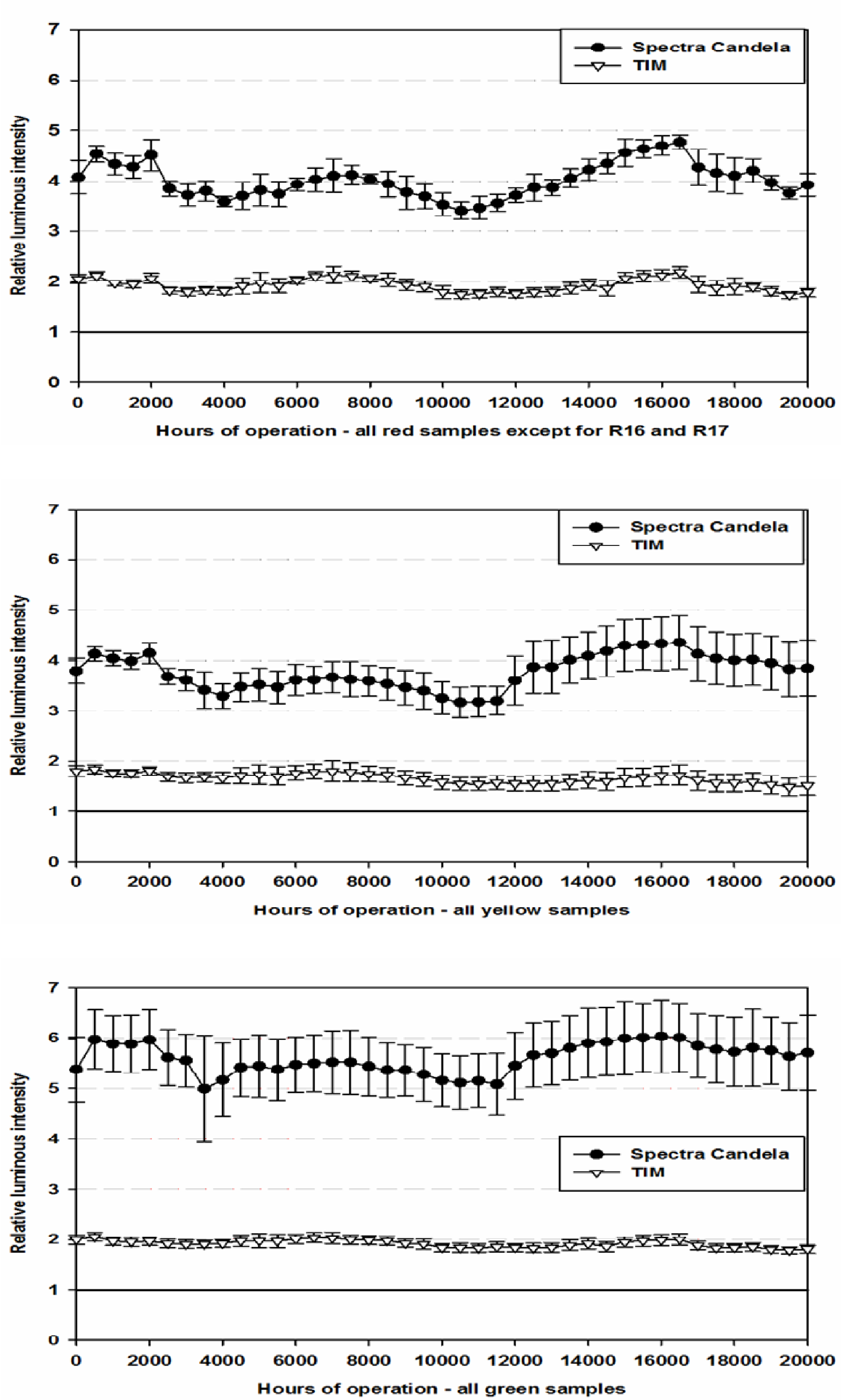


Figure 20
Mean and sample standard deviation of red, yellow, and green modules

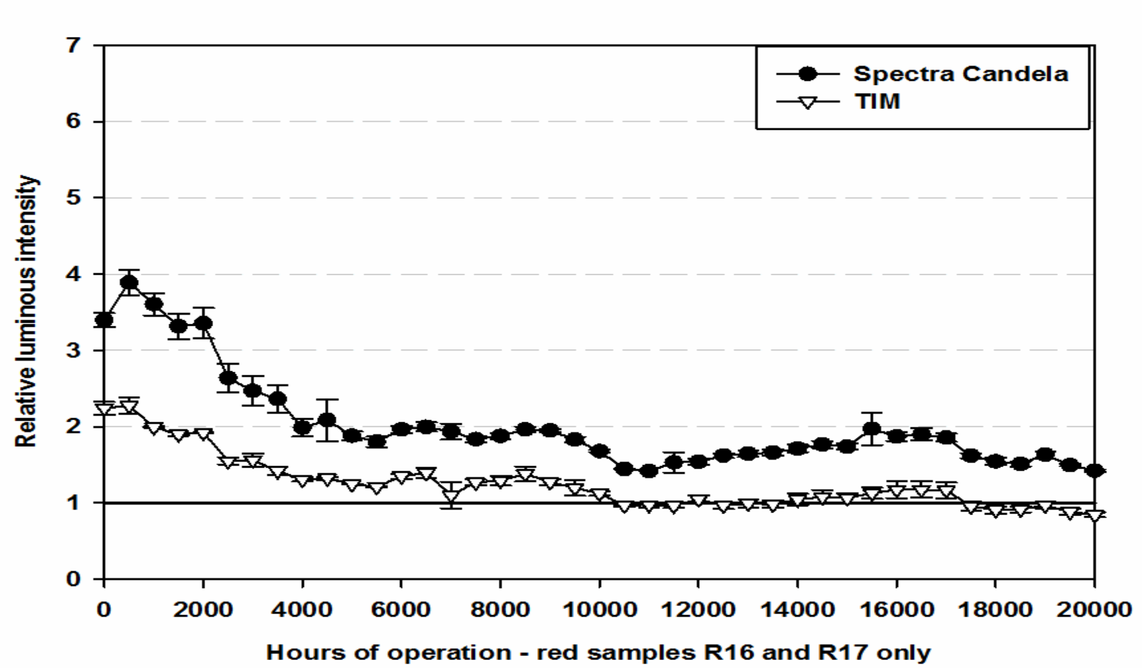


Figure 21
Mean and sample standard deviation of red samples R16 and R17 only

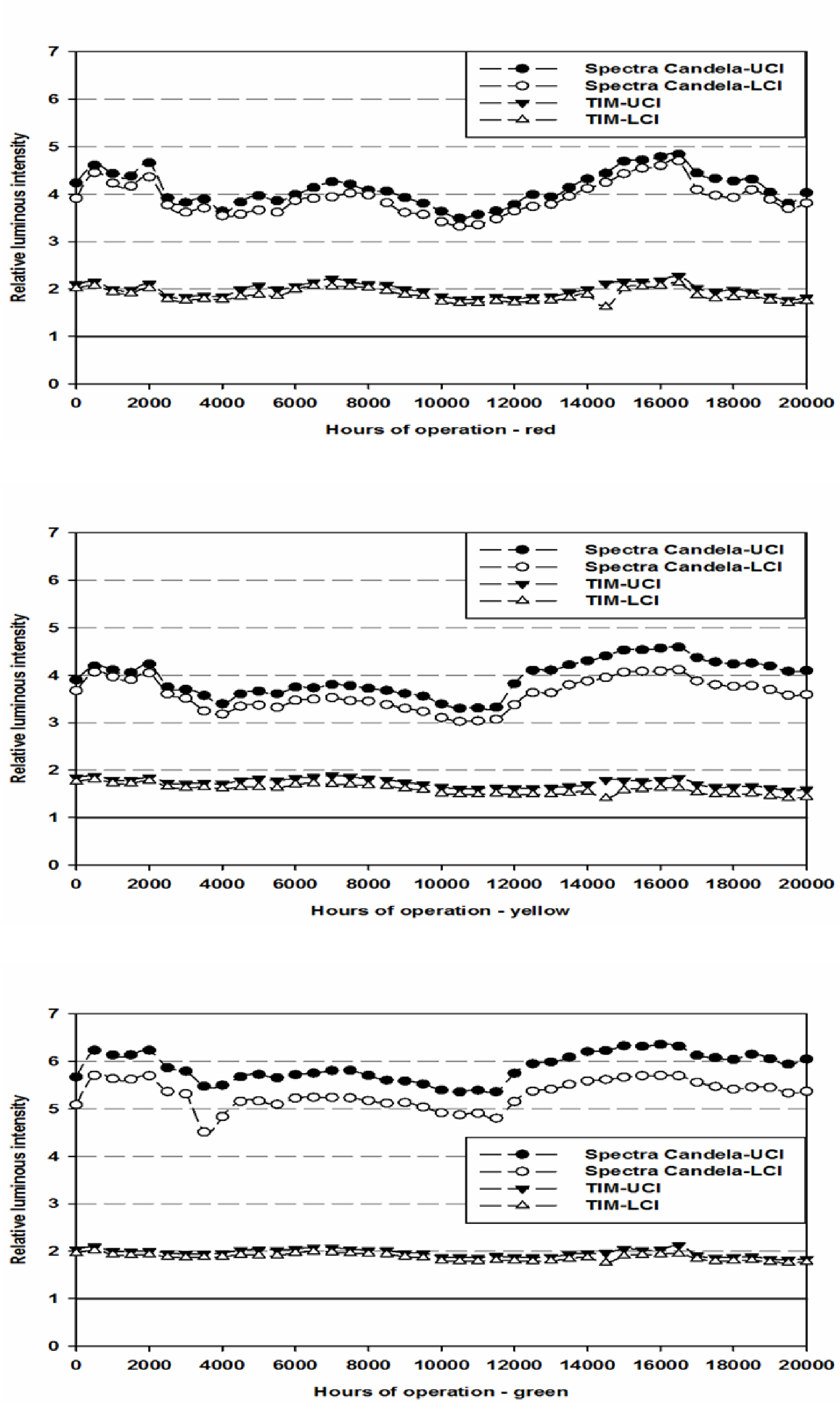


Figure 22

Confidence intervals of each handheld device for red, yellow, and green modules – 95% CI

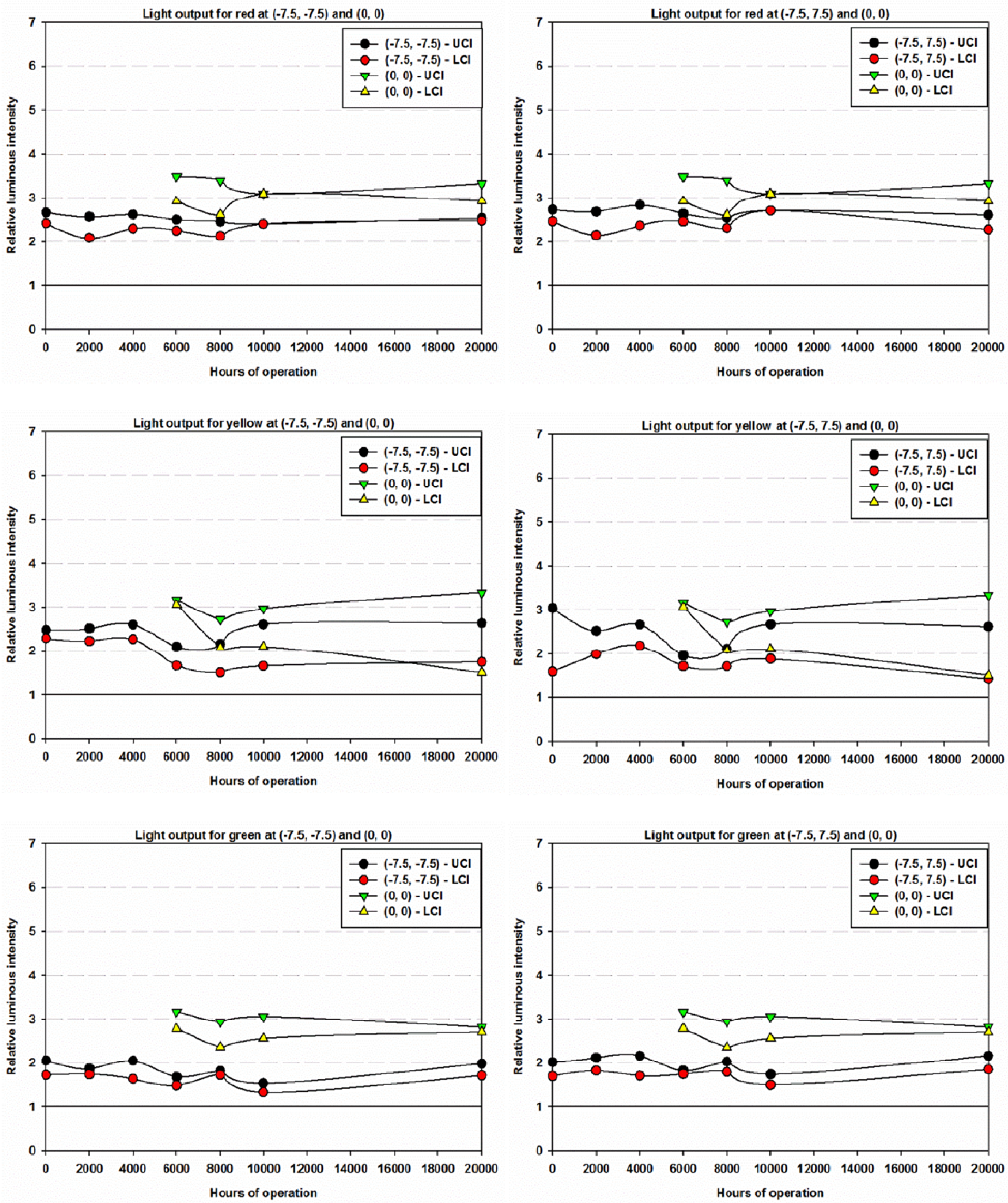


Figure 23
Comparison between the confidence intervals of lab measurements at (-7.5, -7.5) and at (0, 0) (left) and at (-7.5, 7.5) and at (0, 0) (right) for red, yellow, and green modules – 95% CI

CONCLUSIONS

The first objective of this research was to establish lifetime curves for the LED traffic signal modules that DOTD was contracted for at the time this study was initiated. The lab luminous intensity measurements serve as the basis of the lifetime curves. The relative luminous intensity presented failure, i.e., it decreased below 1, for too few coordinates in order to establish the lifetime curve. There were some early life failures and, as expected, they followed the bathtub failure distribution curve. The 20,000-hour results are starting to show some failures as well indicating that the appropriate failure distribution is in fact the bathtub failure distribution. However, it appears that the 20,000 hours is only the beginning of the increase in failures. As of yet, it is unknown whether the failures will start to accumulate rapidly or whether there will be a long, slow decline. Because of this, it is recommended that this study be continued for another 24,000 hours to determine the definitive recommended replacement time for LED traffic signal modules.

Other research has shown how the duty cycle affects the longevity of LEDs *[4]*. This other research shows negligible impact of duty cycle up to 10,000 hours. The data is then projected out to 100, 000 hours where it shows an impact of approximately a 5% decrease between continuous operation and a duty cycle operation. In reference to on-off duty cycles, it is recommended that a parallel study with these cycles be conducted as well.

The second objective of this report was to evaluate the accuracy and precision of two handheld luminous intensity measuring devices, the Spectra Candela and TIM. Results show the following: Spectra Candela appears to be inaccurate and imprecise; however, TIM appears to be precise and inaccurate. The limitations referred to include the fact that there was only a single TIM device and a single Spectra Candela device measuring on the order of 21 test points per time interval. The limitations also included the fact that lab measurements comprised typically only 3 test points per time interval. Thus, it is undetermined if these devices are able to replace lab measurements once the implementation phase is underway. In order to further explore the issue of accuracy and precision of the handheld devices, it is recommended that any extension of this study includes considerable more handheld measurements with more handheld devices.

RECOMMENDATIONS

The 20,000-hour duration of this study approximates a five-year time span for red and green LED modules. This research has shown that the average LED modules in the sample has a longer life span than this. What remains unknown is exactly how long the actual life span is. If, as expected, the LED module failures follow a bathtub curve (Figure 6), then there will be a surge in the hazard rate at the end of life failures part of this curve. It is recommended that this research continue for another 24,000 hours to determine the actual failure time of LED modules and to confirm or deny the failure distribution. It is also recommended to increase the frequency of lab readings to every 1,000 hours and to maintain the handheld readings at every 500 hours. As of now, columns C1 to C6 of LED modules remain turned on at Traffic Services (see Figure 8). With a 24,000-hour extension and a 1,000-hour interval between lab readings, each column will have 4 lab readings.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

cd	candela
DDOT	District Department of Transportation
DOTD	Department of Transportation and Development
ITE	Institute of Transportation Engineers
LED	Light Emitting Diode
LTRC	Louisiana Transportation Research Center
MoDOT	Missouri Department of Transportation
PRC	Project Research Committee
TIM	Traffic Light Intensity Meter
WIPO	World Intellectual Property Organization

REFERENCES

1. Philips LUMILEDs. “Evaluating the Lifetime Behavior of LED Systems.” White Paper WP15, 20150609.
2. Institute of Transportation Engineers. “Vehicle Traffic Control Signal Heads: Light Emitting Diode (LED) Circular Signal Supplement. Publication No. ST-052.” Washington, DC, June 27, 2005.
3. Illuminating Engineering Society of North America. “Technical Memorandum on Light Emitting Diode (LED) Sources and Systems.” IESNA TM-16-05, April 11, 2005.
4. Avago Technologies. “Projected Long Term HTOL Light Output Degradation of Precision Optical Performance AlInGaP LEDs.” Application Brief I-018. October 18, 2010.
5. Giacomo, P. “News from the BIPM.” Metrologia 16, 55-61 (1980)
6. Long, S., Qin, R., Gosavi, A, Wu, C.H., Ryan, T., and Noll, C. “Life Expectancy Evaluation and Development of a Replacement Schedule for LED Traffic Signals.” Report No. OR 11.015, March 2011.
7. Long, S., Gosavi, A., Qin, R., and Noll, C. “Evaluating Useful Life and Developing Replacement Schedules for LED Traffic Signals: Statistical Methodology and a Field Study.” *Engineering Management Journal*, Vol. 24 No. 3, September, 2012.
8. Arhin, S., Bellamy, T., Cheeks, Jr, J., and Harvey, A. “Evaluation of Life Expectancy of LED Traffic Signals and Development of a Replacement Schedule in the District of Columbia.” Report No. SAMMATT01-20011, June 3, 2011.
9. O’Connor, P. D. T. and Kleyner, A. “Practical Reliability Engineering – 5th ed.” John Wiley & Sons, Ltd., The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom.
10. Elsayed, Elsayed A. “Reliability Engineering – 2nd ed.” John Wiley & Sons, Inc., Hoboken, New Jersey.
11. Kapur, K. C. and Pecht, M. “Reliability Engineering,” John Wiley & Sons, Inc., Hoboken, New Jersey.
12. McPherson, J. W. “Reliability Physics and Engineering – Time-to-Failure Modeling – 2nd ed.” Springer Cham Heidelberg New York Dordrecht London.
13. Moubray, J. “Reliability-centered Maintenance,” Industrial Press Inc., New York, New York.
14. ETAP NV. “LED Lifetime in Practice – The ETAP Approach.” White Paper.
15. Instrument Systems GmbH – Optronik Division. “Goniophotometer Systems.”
16. http://www.spectracine.com/Product_6.html
17. United States Patent. “Portable Traffic Light Signal Light Photometer.” Patent Number:

5,185,637. Date of Patent: Feb. 9, 1993.

18. World Intellectual Property Organization. "Apparatus and Method for Determining the Light Intensity of a Traffic Signal Head." International Publication Number: WO 2005/026672 A1. International Publication Date: March 24, 2005
19. Ott, L. "An Introduction to Statistical Methods and Data Analysis – 4^{th} ed." Wadsworth Publishing Company, Belmont, California.

APPENDIX

Agency types that responded to the survey:

State: 18 (CO, CT, IA, LA, ME, MN, MS, NC, NH, NJ, NY, OH, OR, PA, SC, TX, WI, WY)

Municipality (in Louisiana only): 4 (Houma, Lafayette, Norwood, West Monroe)

Province: 1 (BC)

Inventory

1A - How many intersections are managed by your agency?
None: 3
3: 1
13: 1
30: 1
189: 1
285: 1
403: 1
700: 1
980: 1
1,000: 1
1,200: 1
1,300: 1
1,500: 2
2,550: 1
3,300: 1
3,500: 1
3,700: 1
6,000: 2
8,900: 1

1B - How many LED circular traffic signal modules are typically installed per intersection as managed by your agency?
12: 1
24: 5
30: 2
30 to 35: 1
34: 2
36: 3
42: 1
77: 1
All: 4
N/A: 2
Blank response: 1

1C - What is the typical manpower costs concerning replacement of LED circular traffic signal modules installed per intersection as managed by your agency?
$160: 1
$185: 1
$200: 2

$250: 1
S340: 1
$450: 1
$500: 1
$800: 2
$1,000: 1
N/A: 3
Blank response: 9

1C - How long does it typically take a crew to replace all of the LED circular traffic signals located at a given intersection?
1 hour to 2 hours: 1
2 hours: 2
3 hours: 3
3 ½ hours: 1
3.6 hours: 1
6 hours: 1
8 hour: 3
10 hours: 1
N/A: 3
Blank response: 7

1D - Which manufacturers do typically provide your agency with LED circular traffic signal modules?
Act One: 1
Dialight: 13
Duralight: 2
Excellence Opto: 6
GE Lighting Solutions: 10
Gelcore: 3
Leotek: 13
Precision Solar: 1
Swarco: 1
TraStar: 6
N/A: 2
Blank response: 4

1D - What are the unit costs of these traffic signals?
$26 to $34: 1
$28 to $36:1
$32 to $40: 1
$32 to $72: 1
$36 to $54: 1
$37 to $56: 1
$39 to $65: 1
$40 to $59: 1
$42 to $47: 1
$45 to $80: 1
$50 to $80: 1
$50 to $105: 1
$50 to $150: 1
N/A: 2
Blank response: 8

Luminous Intensity of LED Circular Traffic Signal Modules

2A - Does your agency monitor the luminous intensity degradation for its inventory of LED traffic signal modules?
No: 18
Yes: 3
N/A: 2

2B - If so, what is your agency's method of monitoring the luminous intensity degradation?
Handheld equipment: 2
Measurement of luminous intensity: 1
N/A: 20

2B - How often does your agency monitor the luminous intensity?
As needed: 1
Annually: 2
N/A: 20

2B -What percentage of your agency's inventory of LED circular traffic signals is monitored?
3 intersections: 1
16 intersections: 1
All: 1
N/A: 20

Replacement Practice for LED Circular Traffic Signal Modules

3A - What management practice has your agency adopted to replace LED circular traffic signal modules?
Dim: 5
Duty cycle: 1
Failure: 9
Service time: 7
Warranty: 2
N/A: 4

3B - If your agency has adopted a warranty period based approach to replacement, what method was used to establish the warranty period?
Established by the manufacturer: 1
N/A: 19
Blank: 3

3B - What is the warranty period?
Five years: 11
Blank: 12

3C - If your agency has adopted a practice that was not based on a warranty period, did it comply with ITE requirements for minimum maintained luminous intensity values?
Unknown: 1
N/A: 6
Blank: 16

Unscheduled Replacement of LED Circular Traffic Signal

4A - Have LED circular traffic signal modules from your agency's inventory ever required an unscheduled replacement?
Yes: 16
No: 4
N/A: 3

4B - If so, what were the causes for this unscheduled replacement?
Failure: 12
Weather: 1
Manufacturing defect: 3
Design: 1
Don't know: 1
N/A: 7

4B - What percentage of your agency's inventory of LED circular traffic signals was affected by these causes?
0.1%: 1
1%: 1
2%: 1
Less than 5%: 1
5% to 20%: 1
15%: 1
N/A: 7
Blank: 10

LED Circular Traffic Signal Lifetime curves

5A - If specific lifetime curves for LED circular traffic signals in operation in your agency's geographic region were available, is it likely that your agency would utilize these curves as part of their strategy for LED circular traffic signal replacement?
Yes: 11
Possibly: 7
No: 3
N/A: 1
Blank: 1

5B - What method might your agency use in establishing its own region-specific LED circular traffic signal lifetime curves?
Empirical: 1
Field Testing: 6
Manufacturer: 1
Measurement of luminous intensity: 1
Roadway type: 1
Temperature: 1
Weather: 1
N/A: 5
Blank: 8

5C - Which traffic signal manufacturers would be included in the sample used to establish these lifetime curves?

Approved manufacturers: 3
Available at the warehouse: 1
GE, Dialight, and Leotek: 1
Leading manufacturers: 1
Three manufacturers: 1
All: 5
N/A: 4
Blank: 7

5C - What size would this sample be?
48: 1
50 to 100: 1
Three of each manufacturer: 1
Several hundred: 1
N/A: 4
Blank: 15

Comments

6A - Use this space to add whatever comments you consider relevant concerning LED circular traffic signal replacement that may not be present on this survey.
Lack of policy for replacing the LED traffic signals: 1
LED traffic signals are new to the transportation agency: 1
Maintenance is reactive: 1
Request for the results of the study: 1
The lifetime curves may be impacted by many variables (change in the technology (electronic design), manufacturer (electronic design), and environment (humidity, temperature, and de-icing material), UV): 3
Blank: 16

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