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Analysis of factors responsible for life degradation of LED traffic indicators in the state of Missouri

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ANALYSIS OF FACTORS RESPONSIBLE FOR LIFE DEGRADATION OF LED TRAFFIC INDICATORS IN THE STATE OF MISSOURI

by

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ABSTRACT

Traffic lights using state-of-the-art LED illumination use 90 percent less electricity and offer a much longer service life and durability than their incandescent counterparts. Taking advantage of the countless benefits, cities around the country have been replacing traditional filament-based traffic signal bulbs with LEDs for years. However, the degradation of LEDs and hence the replacement strategy, are a concern which is faced by most of the Departments of Transportation. The thesis work sponsored by MoDOT, presents the replacement strategy developed based on the field study of LED indicators in Missouri. Three types of analysis are performed with multiple data point collection – Intensity analysis, manufacturer analysis and temperature analysis.

This thesis is an effort to provide decision support for MoDOT regarding the prudent choice of manufacturer, with regards to temperature dependency. Along with the extension of 2010 study at Missouri University of Science and Technology, the work presented also addresses the unresolved issue about performance of red lights and improves the intensity analysis method.

ACKNOWLEDGMENTS

This is indeed a great pleasure and moment of immense satisfaction for me to express my sense of profound gratitude towards my thesis advisor, Dr. Mariesa L. Crow, whose knowledge and support was the source of inspiration for me. I am extremely thankful to her.

I would also like to thank Dr. Suzanna Long and Dr. C. H. Wu for serving on my committee and taking time to review my thesis. Thank you for always being there to answer all my questions.

This research would not have been possible without the generous funding of the Missouri Department of Transportation. I would like to thank MoDOT for supplying all the necessary information for my thesis.

I would like to especially thank Mr. Kamlesh Joshi, for his endless support, constant inspiration, and taking care of my demands with all means possible.

At last, I am obliged to show gratitude towards my parents (Aai & Baba) who supported me academically, financially and emotionally throughout my entire US journey. Many thanks to them for showing confidence in my decisions. My little sister, Saumya has entertained me and trusted me in my hard times. Thanks are also due to her!

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NOMENCLATURE

Symbol	Description
DOT	Department of Transportation
MoDOT	Missouri Department of Transportation
ITE	Institute of Transportation Engineers
LED	Light Emitting Diode
GE	General Electric
SI	International System of Units
USB	Universal Service Bus
Lux	Unit of Light Illuminance

1. INTRODUCTION

Traffic lighting is an important part of the transportation system and rapid developments in lighting technologies demand new approaches for more efficient and effective use of energy. Traditionally, incandescent and halogen bulbs were used for traffic lights. However, because of the low efficiency of light output and a single point of failure (filament burnout), the Missouri Department of Transportation is increasingly retrofitting traffic signals with LED arrays that consume less power, have increased light output, last significantly longer, and in the event of an individual LED failure, still operate albeit with a reduced light output. The spectral power distribution of an LED is fairly narrow, with half-bandwidths of around 20 to 50 nm, depending upon the substrate material. This means that LEDs produce highly saturated, focused and nearly monochromatic light.

Several companies manufacture traffic signals using LEDs. The usual strategy with these signals is to package hundreds of LEDs together with reflectors or lenses to create the high-luminance signal face that is required by specifications of the Institute for Transportation Engineers (ITE). The LED arrangement in traffic lights is of two types:

1. LED lights distributed in an array (older style)
2. LED light projected through convex lens

Figure 1.1 represents two types of manufacturing styles for LED traffic lights.

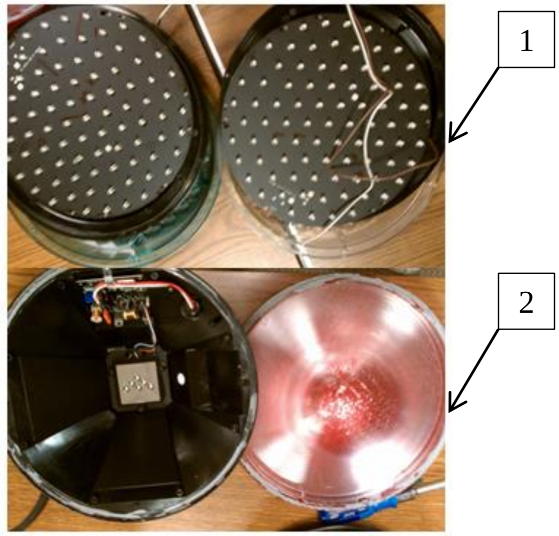

Figure 1.1 Manufacturing patterns for LED traffic lights [2]

The LED light cluster is sealed on a panel and then assembled to the LED panel with a heat sink to become an integrated lighting fixture.

Presently, the majority of agencies replace the traffic lights based on a spot basis or when they receive a complaint. Some of them also follow the generic replacement schedule given by manufacturers` warranties. However, this is not the most cost effective approach. Also, early replacement of traffic lights increases the cost to tax payers. Hence, it is important to decide the replacement strategy only when the intensity degrades out of specification.

The thesis targets a field study and three types of analysis based on:
1) intensity 2) manufacturer and 3) temperature. The analysis is performed on the data collected during field study for the Missouri Department of Transportation. The thesis is an extension of the 2010 study done through the research activities by Missouri University of Science and Technology. In the present thesis work, the impact on behavior of traffic lights is evaluated based upon distance, directional view, color, manufacturer

and temperature. Through an intensity analysis, MoDOT will be able to observe the behavior of specific lights and can target their attention on the lights that exhibit erratic output. The manufacturer analysis section will guide MoDOT regarding the performance of traffic lights belonging to different manufacturers which will help them in choosing appropriate manufacturers. A novel method of Percentage Effectiveness is introduced to show the performance of available manufacturers. Complementing the manufacturer analysis, a temperature analysis is performed to express the effect of temperature on intensity degradation of lights. The thesis provides the complete assessment of field study done as a part of research project assigned to Missouri University of Science and Technology by MoDOT.

The remainder of the thesis is organized as follows: Section 2 provides a varied literature review relevant to the work presented in this thesis. Section 3 presents the lab analysis performed on red, green and yellow lights provided by MoDOT and manufactured by General Electric to validate the instrument and obtain the ideal inverse square law curve which is further used in the intensity analysis section. It also contains information regarding data collection and the sorting method followed by defining a new approach used for analysis. Section 4 contributes to the detailed study of field data through intensity, manufacturer and temperature analysis. Finally the thesis concludes in Section 5 suggesting the future work in area.

2. LITERATURE REVIEW

LED traffic signal modules have gained popularity in the U.S. primarily because they consume far less energy than incandescent lamps - 85% less, on average [1]. Because of these energy savings, the U.S Environmental Protection Agency (EPA) recognized LED traffic signal modules as an ENERGY STAR product in 2000, and then Congress mandated that as of January 2006, all red and green traffic signal modules must meet the energy consumption specifications stipulated by the ENERGY STAR requirements [6].

Noll presented detailed findings on LED traffic light replacement to the State Department of Transportation [2]. He used a deterministic time regression model to calculate the useful life of each type of indicator under study. The data collection methodology was different than the present work. Noll carried cross functional analysis for data collection with one data point for one light and the present work deals with longitudinal analysis collecting multiple data points for each indicator under study. The unconventional behavior of red light was one of the main concerns in his thesis work, which now in the present work is resolved. Noll also expressed a possibility of manufacturer analysis as a future scope in his work which as well is satisfied in present study.

Noble highlighted the issues of maintenance of LED traffic lights and suggested some of the maintenance strategies according to ITE standards [3]. He concluded that phased replacement of signalized intersections is better than system wide replacement due to budget and resource reasons. Bullough presented the results from a study of the photometric requirements, measurement and maintenance of traffic signal modules using light emitting diodes [4]. Based upon the module failure rate of LED traffic lights, some primary guidelines were drawn for when group replacement of LED indicators is provided in the concluding remarks. Urbanik [5] reviewed the results of a survey conducted by the Institute of Transportation Engineers (ITE) [7] [8] in 2006, of transportation agencies regarding their experience and practices with LED traffic signals.

Behura [9] reported an observation that the use of LED traffic signals had been expected to reduce the lifetime cost per module compared with incandescent modules. He stated that many agencies had not implemented appropriate maintenance programs for LED signal modules. A study by Bullough et al. [10] showed that under simulated daylight viewing conditions, LED and incandescent modules of the same nominal color, luminance, and onset time resulted in no statistically significant differences in mean reaction times, percentages of missed signals, color identification accuracy, and subjective brightness ratings.

Cohn et al. [17], and later extended and complemented by Bullough [11], concluded that the visibility of red LED modules and red incandescent signal modules was about equal under daylight conditions, and confirmed that the pixilated appearance of some LED signals might actually provide a visual benefit.

Suozzo [12] examined the feasibility and appropriateness of market intervention strategies to increase the penetration of LED traffic signals, which offer large energy savings and other benefits relative to existing incandescent traffic signals. Relevant replacement strategies includes [13], [14], [15] and [16], which showed that LED traffic lights have equal or better functionality compared to traditional incandescent traffic lights and that LED traffic light replacement has a payback period about 2 years and will save millions of dollars after certain time. Wu, et al. [18], presented economic and environmental effects of solar powered LED on LED traffic lights suggesting low relamping and low maintenance cost.

Hochstein [19], in his patent explained the heat dissipation of LED traffic lights. The invention provides two important features to solve the heat dissipation problem of LED traffic light which can be utilized in combination or separately to open the restriction of heat flow from LED to heat sink and to extend the heat sink from close proximity to LEDs and to the ambient air. Some literature mentioning about highly efficient AlGaInP technology in LED traffic lights [20], reviewed the recent progress of AlGaInP high brightness light-emitting diodes. After the discussion of some basic material properties and the general problem of light extraction they discussed several approaches of high efficiency devices. In conjunction with AlGaInP technology, Hong and Narendran [21] discussed and investigated the non-invasive method to determine the junction temperature of AlGaInP based LED traffic lights. Currently the life of LED lights determined by the manufacturer is based on average life of a single LED under certain laboratory conditions. Hong specifically discussed their non-invasive method as a way to calculate useful life of LED under practical considerations.

Narendran and Gu [22] experimented with several white LEDs from the same manufacturer to test life span at different ambient temperatures. The study concludes that the exponential decay of light output as a function of time provides a convenient method to rapidly estimate life by data extrapolation. In second experiment, several high powered bright lights were tested under similar life tests condition. The results conveyed that different LED products of different manufacturers have slightly different life values in terms of exponential decay. In a study done by Burmen et al. [23], survey of number of factors affecting the quality of LED products is done and corresponding methods for their assessment is suggested. The dependence of the intensity and color on the ambient (junction) temperature has been found to be critical if a stable intensity or a stable color must be maintained.

The topics presented in the thesis have utilized the concepts used in these studies to analyze the results of the approaches discussed in the following sections. The primary objective of the present work is to provide a concrete LED traffic light replacement strategy to MoDOT according to manufacturer, based on the factors of degradation with respect to change in distance, age, color, directional view and temperature and the referred literatures have provided a background for the subsequent sections of analysis and observations.

3. APPROACH

3.1. LAB ANALYSIS

An original field testing instrument was developed for collecting illuminance readings from the intersections across the state of Missouri by Missouri University of Science and Technology in the study provided to MoDOT in 2010 [2]. The instrument works on the technology of Fresnel lens. The Fresnel lens focuses the light emitted from LED traffic indicators into a concentrated beam. The light meter used is HD450 Data logging light meter. It is placed behind the Fresnel lens at its focal length so that it effectively captures all the light emitted into the opening of the cylindrical casing. The light meter by itself would be incapable of measuring the illuminance of a LED traffic indicator from far out distances because the ambient light would impact the measured light output from the LED. The device also has a laser pointer to properly point at the maximum intensity capturing position of LED traffic indicators. The distance is measured by a commerical distance meter. The output of the light meter is ported to the data recorder a USB port. The interface software is provided by the light meter manufacturer.

Laboratory analysis is performed using red, green, and yellow LED traffic indicators provided by MoDOT for testing purpose of intensity measuring instrument and light meter. The readings are recorded in the intervals of 10 ft., using a range between 10-120 ft. and 5-6 samples are taken at the rate of one sample per second. Care of accurate readings is taken by focusing the attached laser pointer.

Figure 3.1 and 3.2 facilitates the overview of the intensity readings obtained for red, green, and yellow LED traffic indicators.

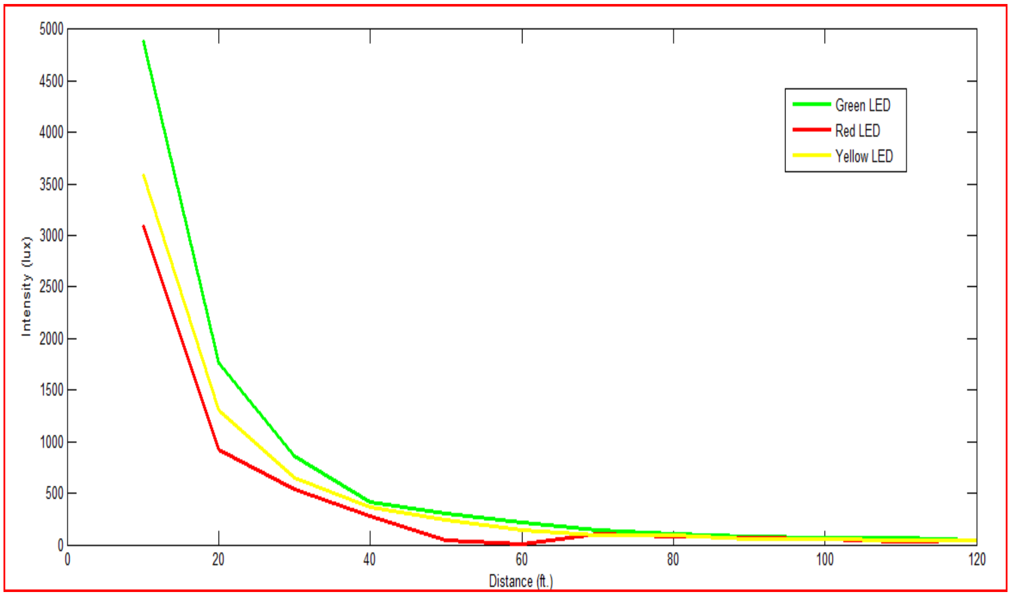

Figure 3.1 Average intensity in Lux versus distance in ft. for lab analysis

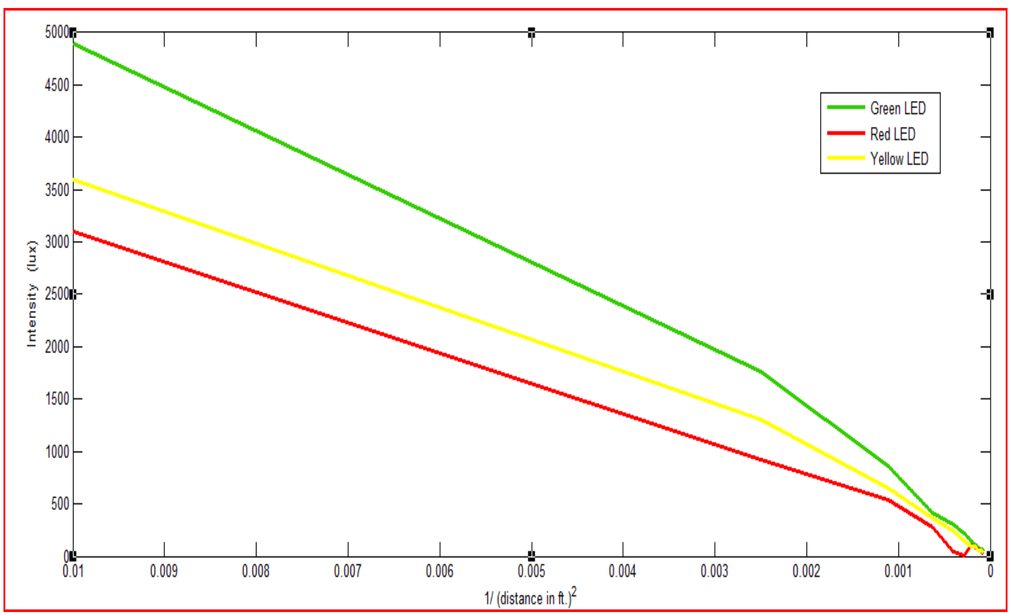

Figure 3.2 Inverse square law curve for lab analysis

The ambient light measured for the lab testing is 7.46 Lux.

A pattern can be observed in the intensity readings for green and yellow lights.

Also, as the distance increases, the intensity of the light is decreasing, as expected. The behavior of LED traffic lights is nearly identical to the ideal and hence can be used for future reference in analysis section.

3.2. LUX TO CANDELA CONVERSION

The laboratory analysis is performed with the intensity being measured in Lux. However, Lux to Candela conversion is important for analysis. Lux measures the intensity when the light strikes the surface. It is the unit for luminous emittance, whereas candela is the unit for luminous intensity. It measures the apparent intensity of light source in a specific direction. It should be noted that the traffic indicators can be considered as the point source which spreads the light in the form of sphere and the area of a sphere is $4\pi r^2$.

$$1\ Lux = \frac{1\ Lumen}{(meter)^2}$$

$$1\ Lumen = \frac{1 Candela}{Steradian}$$

Steradian is the SI unit for a solid angle and is equal to ¼*π of the entire sphere.

This implies,

$$1\ Lux = \frac{1\ Candela * Steradian}{(meter)^2}$$

And

$$1\ Candela = \frac{1\ Lux * (meter)^2}{Steradian}$$

Hence, further anlysis presented in the thesis is done with the intensity measured in Lux but converted to Candela.

3.3. DATA COLLECTION

The detailed list of intersections chosen for data collection is provided by MoDOT along with the manufacturer and installation date details. Data collection is completed for fall 2012 and spring and summer 2013 till the date which is used in the analysis portion.

The intensity readings are recorded at multiple distance points. Five readings in 8-15 ft. intervals for each traffic signal are taped. Through the interface software, each reading produces a unique text file. For each traffic indicator, the maximum reading is identified manually and entered in the excel sheet.

To perform a temperature analysis, the data collection is conducted during different seasons.

The intersections covered for data collection are given in Table 3.1.

Table 3.1 Intersection List for Data Collection

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

3.4. DATA SORTING

Data sorting is the most time consuming portion of the project as the data is recorded in text file for each cycle for each light at each intersection. While sorting, the maximum intensity point is to be identified for each light and entered in the Excel sheet in the format as represented in Table 3.2. The following information found in Table 3.2 is recorded for each reading: street intersection, direction of travel (northbound, southbound, eastbound, or westbound), indicator head number (1-5), indicator type (red, yellow, green and circular or arrow), illuminance (Lux) and distance (meters) measured from light.

The data is sorted by the age and manufacturer and a database is maintained for future reference. The data is marked with different manufacturers by color coding it. This helped in the analysis portion to compare the lights which are on the same platform.

Table 3.2 . Data Collection Database Sample

Age ' x' years									
Intersection	*Direction*	*Indicator Head*	*Indicator Red*		*Indicator Green*		*Indicator Yellow*		……
			Intensity	Distance	Intensity	Distance	Intensity	Distance	…..
									…..
									…..
									…..

where,

Yellow represents GE manufactured lights

Green represents Dial manufactured lights

Blue represents LTEK manufactured lights

and Red represents Philips manufactured lights

3.5. METHODOLOGY

This project is inspired by the previous work performed in 2010 by Missouri University of Science and Technology, but the method used is different. The inverse square law approach is used for intensity analysis. The inverse-square law generally applies when some force, energy, or other conserved quantity is radiated outward radially in three-dimensional space from a point source. Since the surface area of a sphere (which is $4\pi r^2$) is proportional to the square of the radius, as the emitted radiation gets farther from the source, it is spread out over an area that is increasing in proportion to the square of the distance from the source. Hence, the intensity of radiation passing through any unit area (directly facing the point source) is inversely proportional to the square of the distance from the point source.

In [2] the inverse square law characteristics was plotted for one intensity reading at one distance measured for one light at one intersection, as the data was collected in that way. With the present data collection strategy, multiple data points at multiple distances are collected for a light at each intersection. Data collection at multiple distances is advantageous over the previous method, as intensity is a concern at various distances as well as age.

The new approach is to group the data based on age and then plot the average intensity readings against distances (inverse square law characteristics) for that group.

This will indicate whether the lights are following the standard pattern of inverse square law characteristics. Also, the age grouping strategy will avoid comparing the intensity of lights belonging to different ages and hence, will help in proper justified analysis. The ideal inverse square law characteristic is as shown in Figure 3.3. [26]

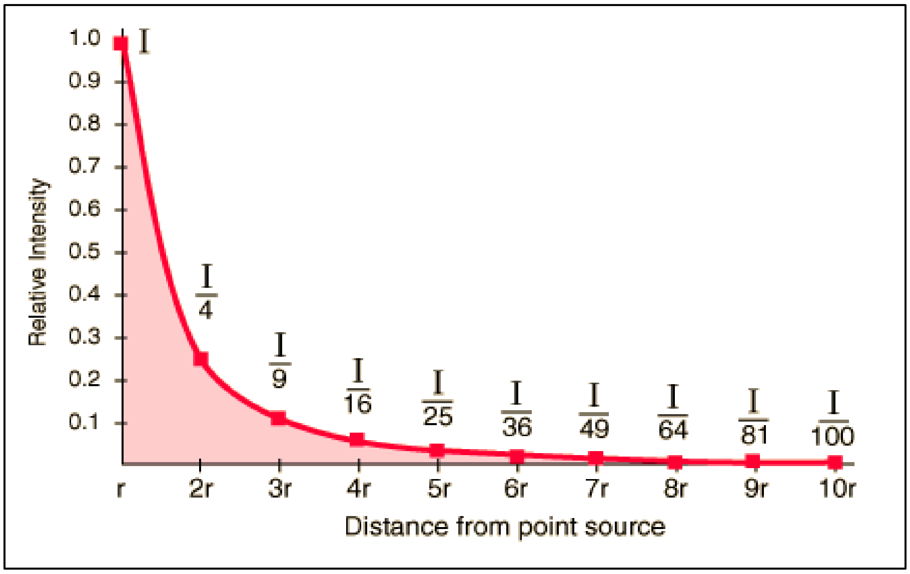

Figure 3.3 Ideal Inverse Square Law Curve

After that, sorting of the data is done based on manufacturer. The different manufacturers are color coded in the database for ease of representation. The preferred manufacturer is chosen based on three factors – data availability, contiguity and slope value. This gives an indication regarding which company at what age is giving which intensity plot, which will also guide MoDOT in choosing the manufacturer.

Lastly, the temperature analysis is performed to determine the effect of temperature changes on the intensity of LED traffic lights. Since the data is collected in two sets at extreme different temperatures, the effect of temperature change is conspicuoulsy visible in the plots represented in future sections. Slope difference is the criteria used to determine the effect of temeperature which also symbolizes the intensity degradation. It is also be coupled with the manufacturer analysis, because the intensity degradation due to temperature is different for different manufacturers.

The thesis is modeled on these three aproaches and the results obtained are presented in the next section.

4. RESULTS AND ANALYSIS

4.1. INTENSITY ANALYSIS

As proposed previously in Section 3, grouping of the data based on same age is done to avoid an averaging over a large range of intensity readings. This strategy will eliminate any possible errors in the analysis. The data is sorted based on the age groups of 5 months, 6 months, 1year, 2 years, 3 years, 4 years, 5 years, 6 years, 7 years, 8 years, 9 years, 10 years, 11 years, 12 years, 13 years and 15 years. The ages are calculated based on the information provided by MoDOT.

To eliminate any possible confusion rising out of plotting the data of all ages on one graph and to achieve proper representation the ages are grouped in 3 groups as given in Table 4.1.

Table 4.1 Grouping of Ages for Intensity Analysis

Group No.	Ages
Group 1	5 months, 6 months, 1 year, 2 years, 3 years
Group 2	4 years, 5 years, 6 years, 7 years, 8 years
Group 3	9 years, 10 years, 11 years, 12 years, 13 years and 15 years.

The large set of data is segregated to avoid comparison of two remote ages. For example, plotting the intensity degradation of age 1 year with age 13 years will be unhelpful.

The data is plotted using MATLAB software. Plots are obtained for intensity in Candela versus inverse squared distance in meters as a representation of inverse square law characteristics for available LED lights and linear fit is applied for proper assessment of slope. The linear fit is applied consistently for all succeeding analyses.

Plots of intensity versus distance obtained for group 1 will be represented in subsequent figures. Figure 4.1 represents plot for circular red light of set1 and group 1.

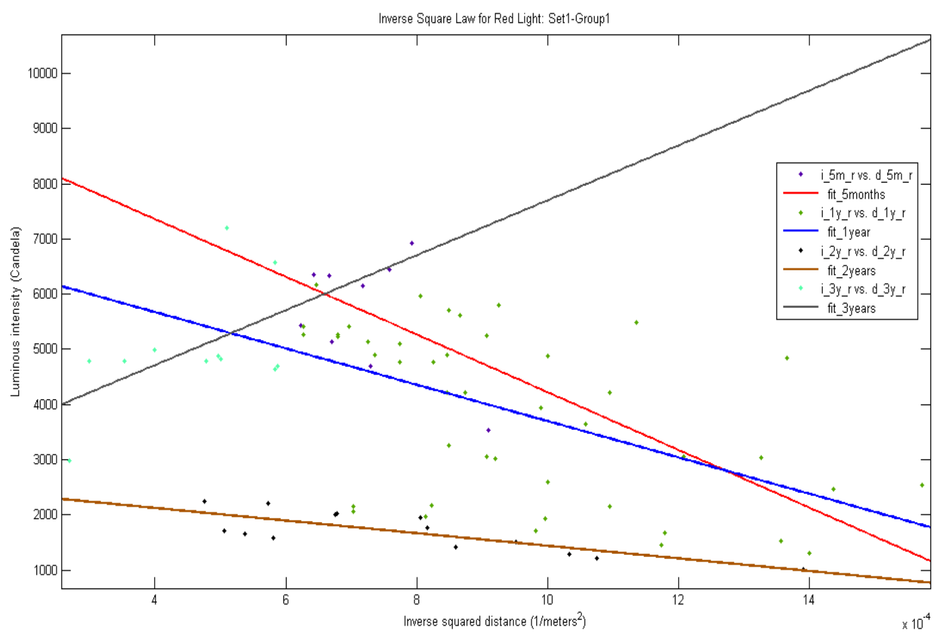

Figure 4.1 Inverse Square Law Characteristic for Red Light: Set1 – Group1

The predicted behavior of ideal inverse square law characteristic which is discussed in Section 3 is followed in 5 months, 1 year and 2years fit. The fit for 3 years which is black colored is completely disobeying the ideal characteristic and can be listed as the consequence of insufficient data.

Figure 4.2 – 4.6 represents the inverse square law characteristic for different lights of set1 and group 1.

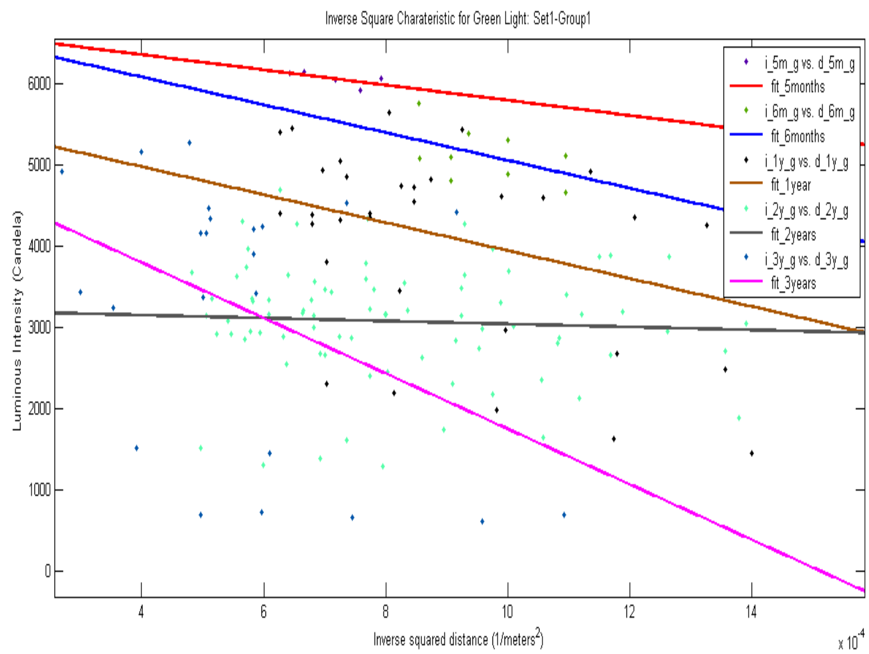

Figure 4.2 Inverse Square Law Characteristic for Green Light: Set1 – Group1

The inverse square law characteristic for green light belonging to group 1 and set 1 is appropriate for every age displayed. The data available is sufficient and nicely spread along the fit. This shows the importance of data availability.

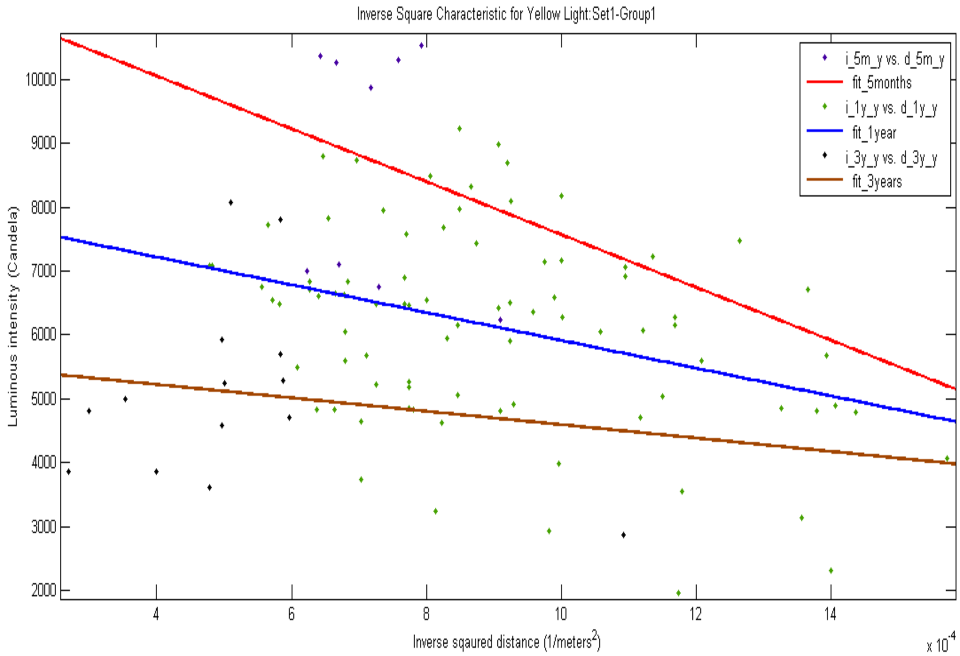

Figure 4.3 Inverse Square Law Characteristic for Yellow Light: Set1 – Group1

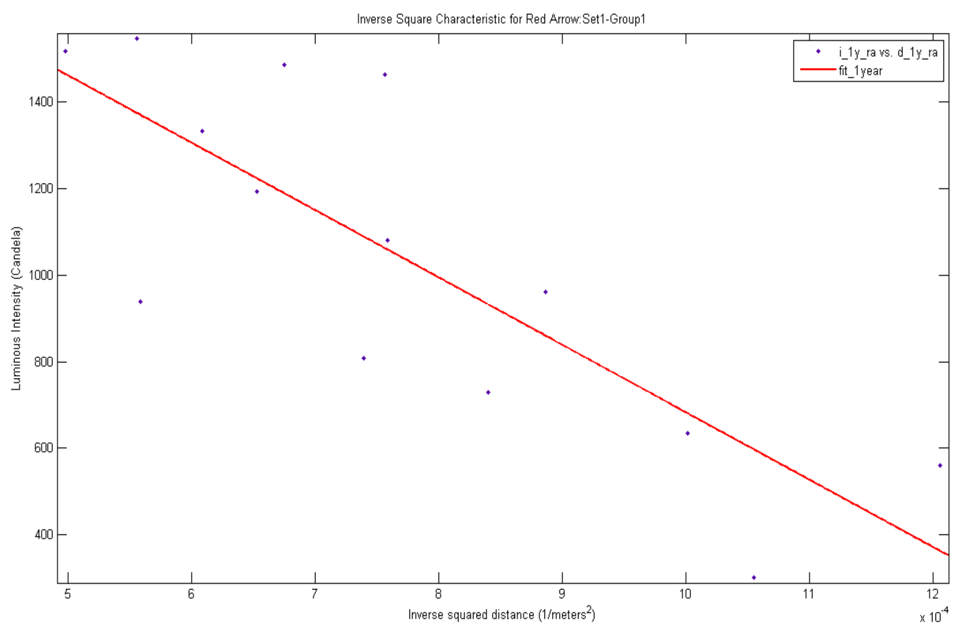

Figure 4.4 Inverse Square Law Characteristic for Red Arrow: Set1 – Group1

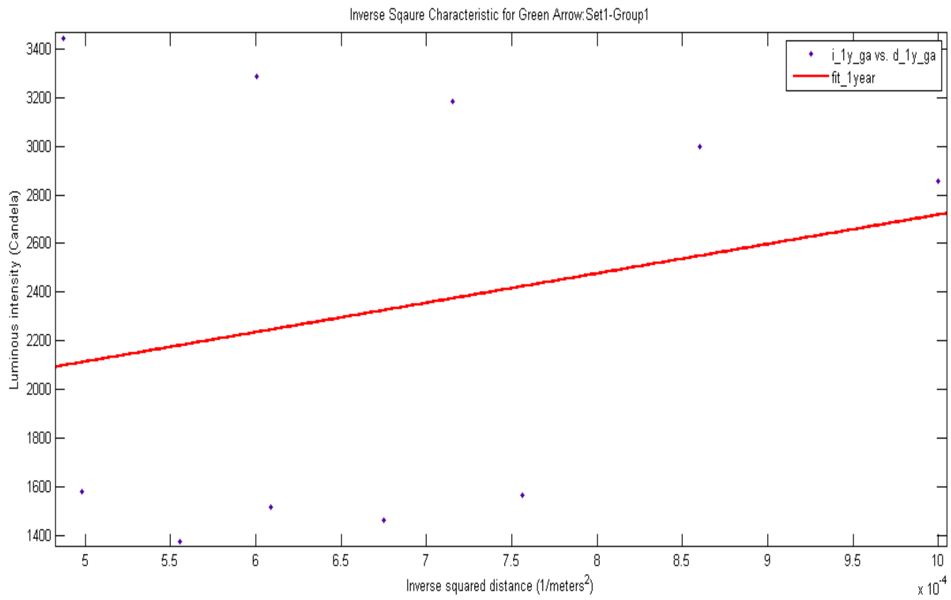

Figure 4.5 Inverse Square Law Characteristic for Green Arrow: Set1 – Group1

The plot for green arrow of set 1 and group 1 is inconclusive due to lack of sufficient data.

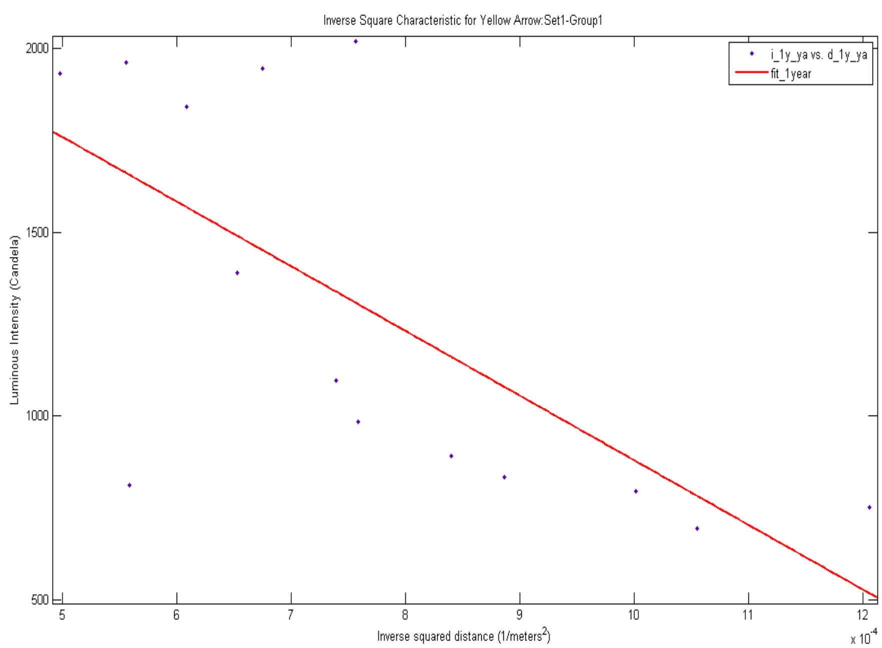

Figure 4.6 Inverse Square Law Characteristic for Yellow Arrow: Set1 – Group1

Figure 4.7 – 4.12 represents the inverse square law characteristic for different lights of set1 and group 2.

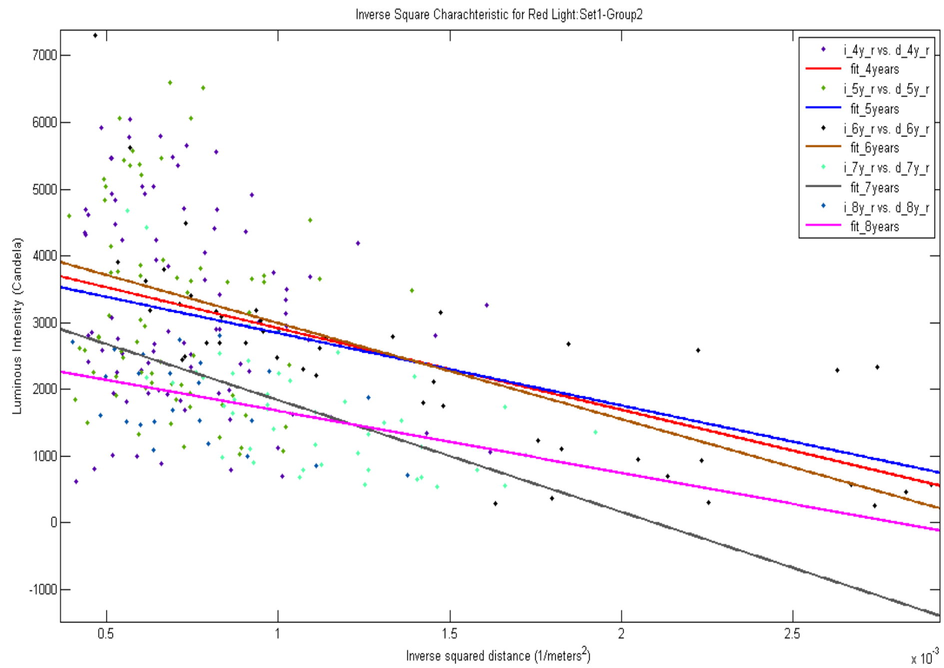

Figure 4.7 Inverse Square Law Characteristic for Red Light: Set1 – Group2

Here, it can be observed that the fit for all the data belonging to group 2 is following the desired shape. Ample data is obtained for these lights and hence this justifies the importance of data collection phase. Also, the luminous intensity is observed to be reduced as compared to group 1.

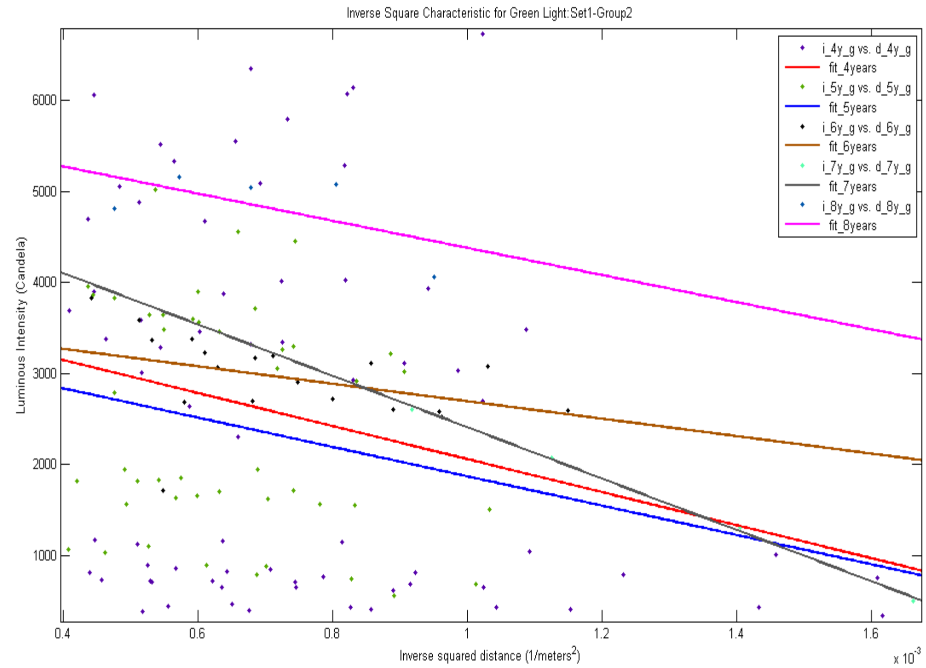

Figure 4.8 Inverse Square Law Characteristic for Green Light: Set1 – Group2

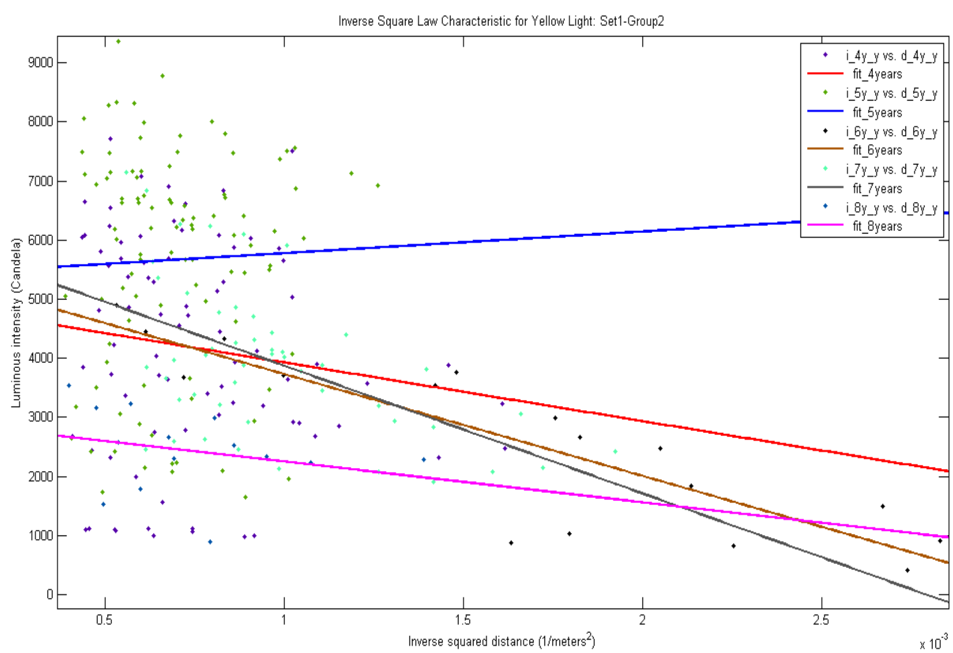

Figure 4.9 Inverse Square Law Characteristic for Yellow Light: Set1 – Group2

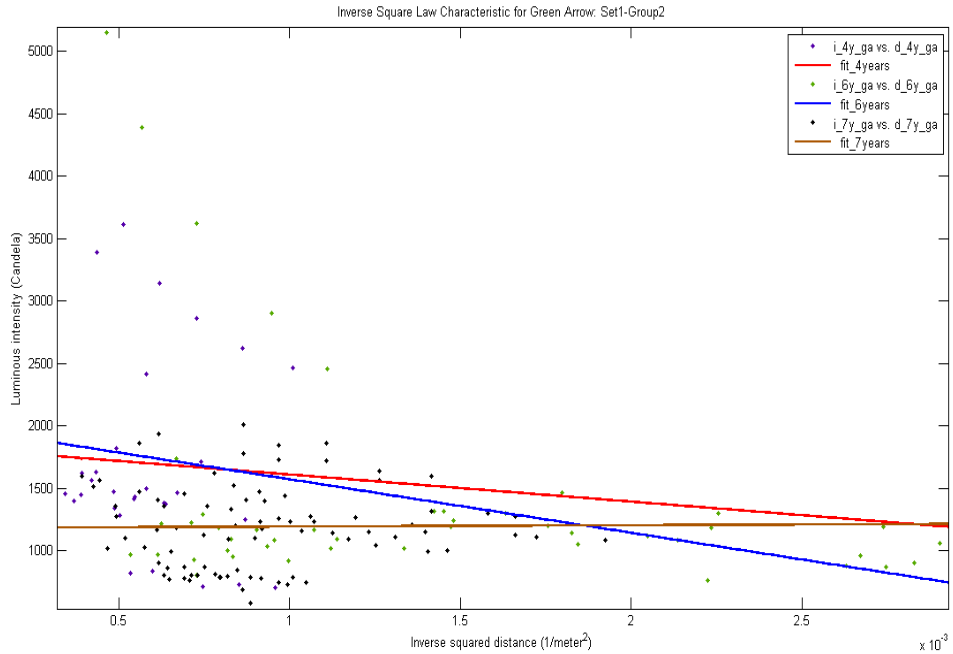

Figure 4.10 Inverse Square Law Characteristic for Green Arrow: Set1 – Group2

It can be noticed that the behavior of inverse law characteristic for the green arrow of group 2 is much better than group 1 with very little degradation of intensity with respect to age.

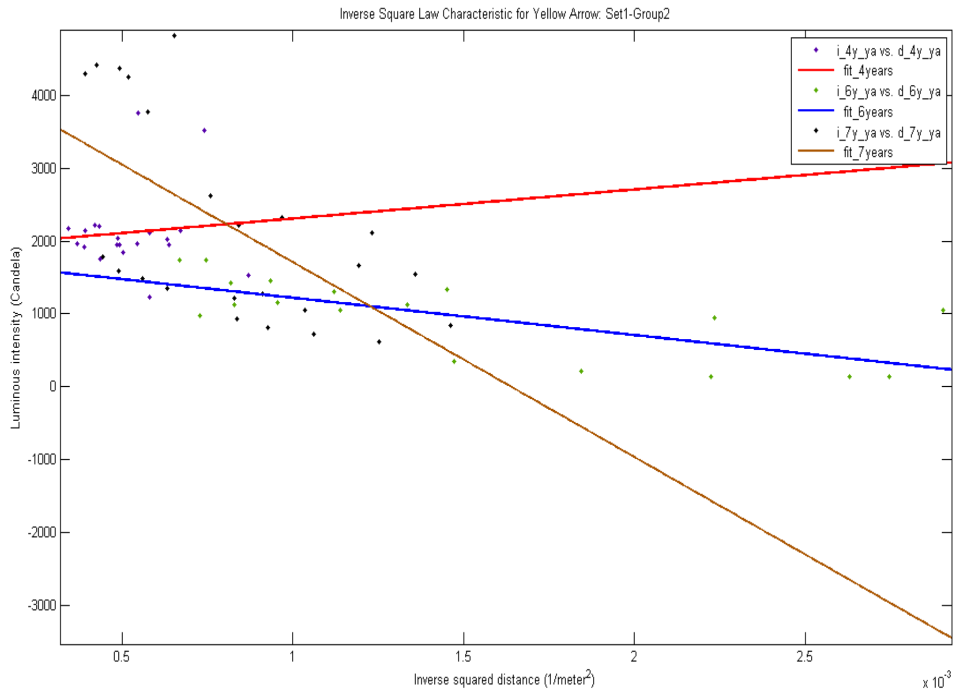

Figure 4.11 Inverse Square Law Characteristic for Yellow Arrow: Set1 – Group2

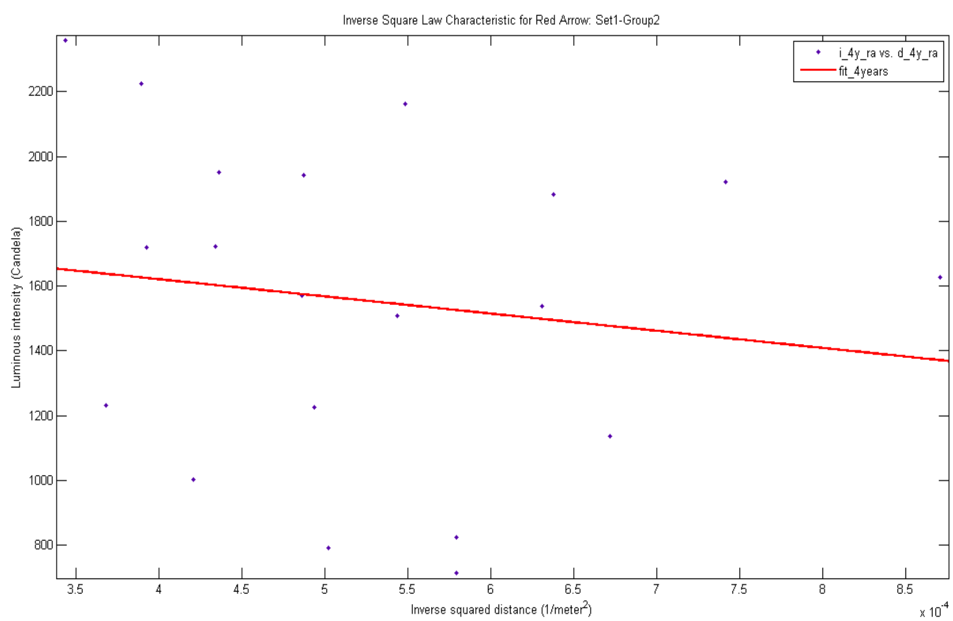

Figure 4.12 Inverse Square Law Characteristic for Red Arrow: Set1 – Group2

Very less data is available for red arrow, but the fit resembles the ideal inverse square law characteristic curve. Figure 4.13 – 4.17 represents the inverse square law characteristic for different lights of set1 and group 3.

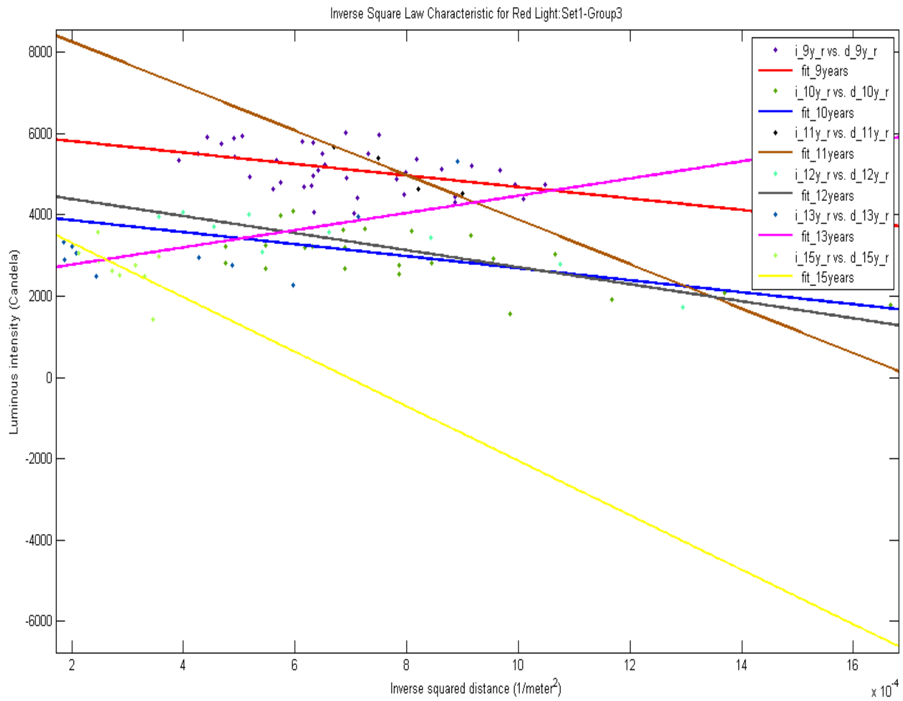

Figure 4.13 Inverse Square Law Characteristic for Red Light: Set1 – Group3

The inverse square law characteristic for red lights in group 3 is similar to the ideal except for age 13 years represented by pink colored fit. This light definitely needs the attention for manufacturer and more data collection, so as to deduct the cause of this unconvincing behavior.

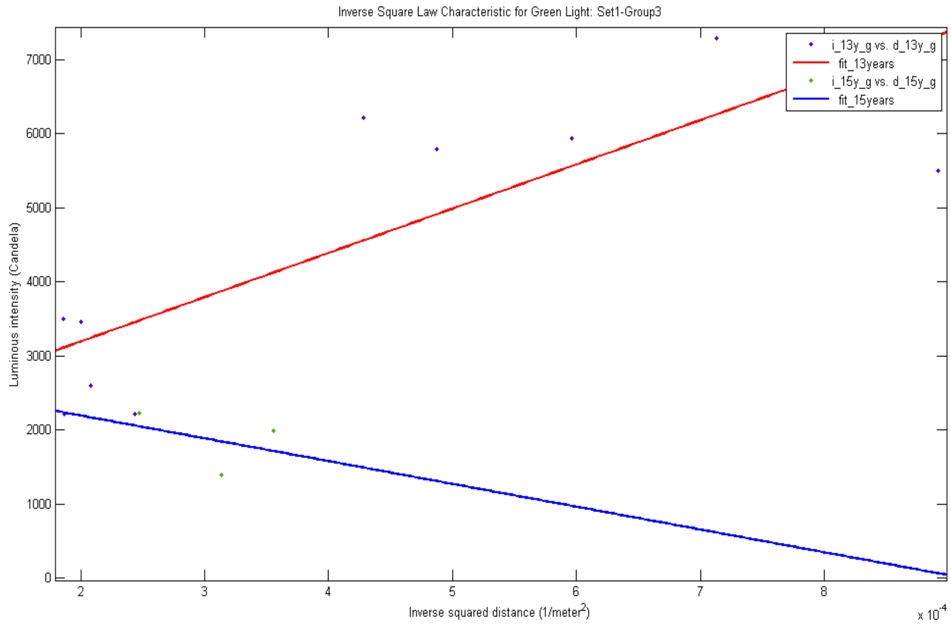

Figure 4.14 Inverse Square Law Characteristic for Green Light: Set1 – Group3

The impact of insufficient data for green light of ages 13 and 15 is clearly visible in the above plot.

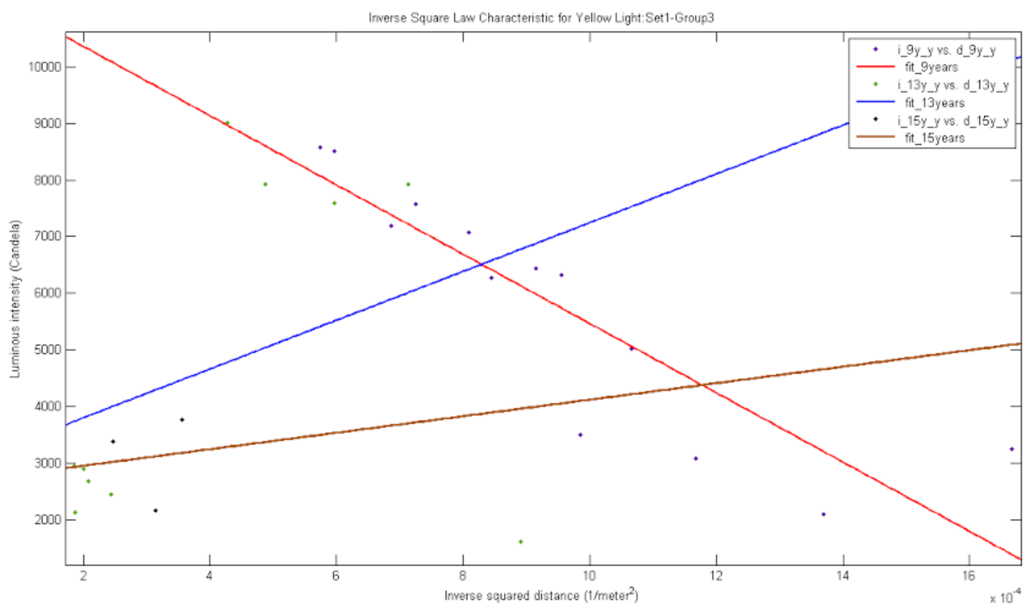

Figure 4.15 Inverse Square Law Characteristic for Yellow Light: Set1 – Group3

Yellow lights of age 13 and 15 years needs more data collection.

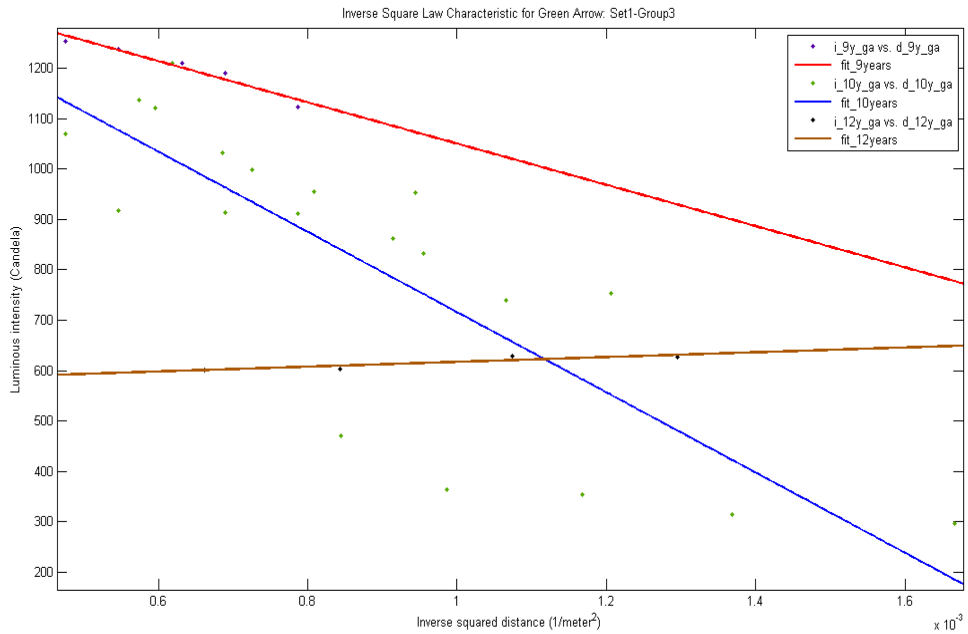

Figure 4.16 Inverse Square Law Characteristic for Green Arrow : Set1 – Group3

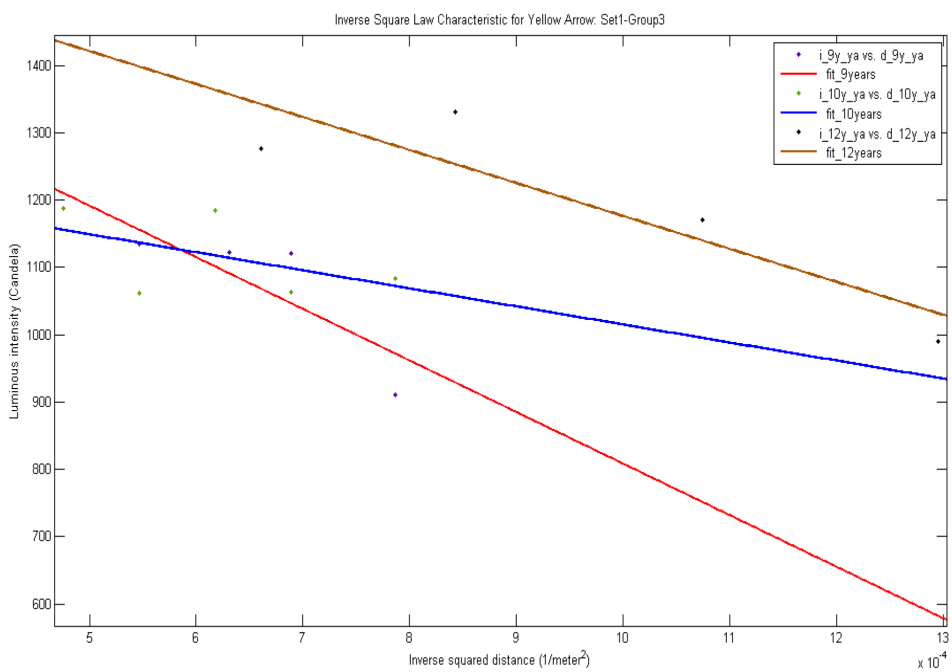

Figure 4.17 Inverse Square Law Characteristic for Yellow Arrow : Set1 – Group3

Similarly, inverse square law characteristics are obtained for set 2 which are represented in the following figures. The comparison of set 1 and set 2 done in the temperature analysis will show the difference in the intensities recorded in these two sets.

Figure 4.18 represents plot for circular red light belonging to set2 and group 1.

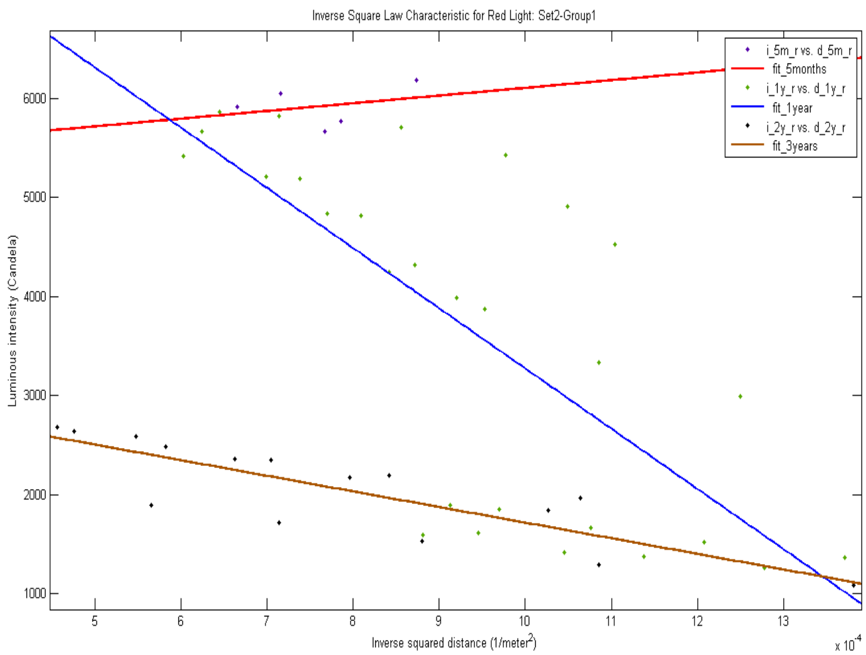

Figure 4.18 Inverse Square Law Characteristic for Red Light : Set2 – Group1

The erratic behavior of red lights can be observed in the above plot. The fit for 5 months is not appropriate as compared to other fits belonging to group 1. Also, the behavior of 5 months data collected in set 2 does not match with set 1. Here, it should be noted that since the data collected is equal in both the sets for red light, human error in data collection process may have led to this nonmatching behavior between set 1 and set 2

Figure 4.19 – 4.21 represents the inverse square law characteristic for different lights of set 2 and group 1.

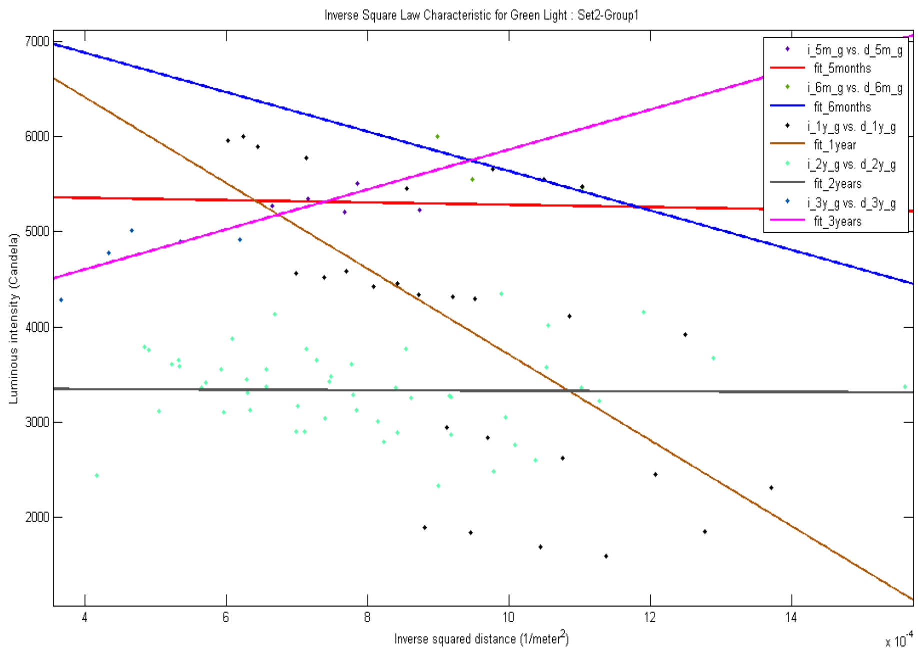

Figure 4.19 Inverse Square Law Characteristic for Green Light : Set2 – Group1

The behavior of green light belonging to age 3 years is not as desired which shows the need of more data collection or attention to manufacturing details of the particular lights.

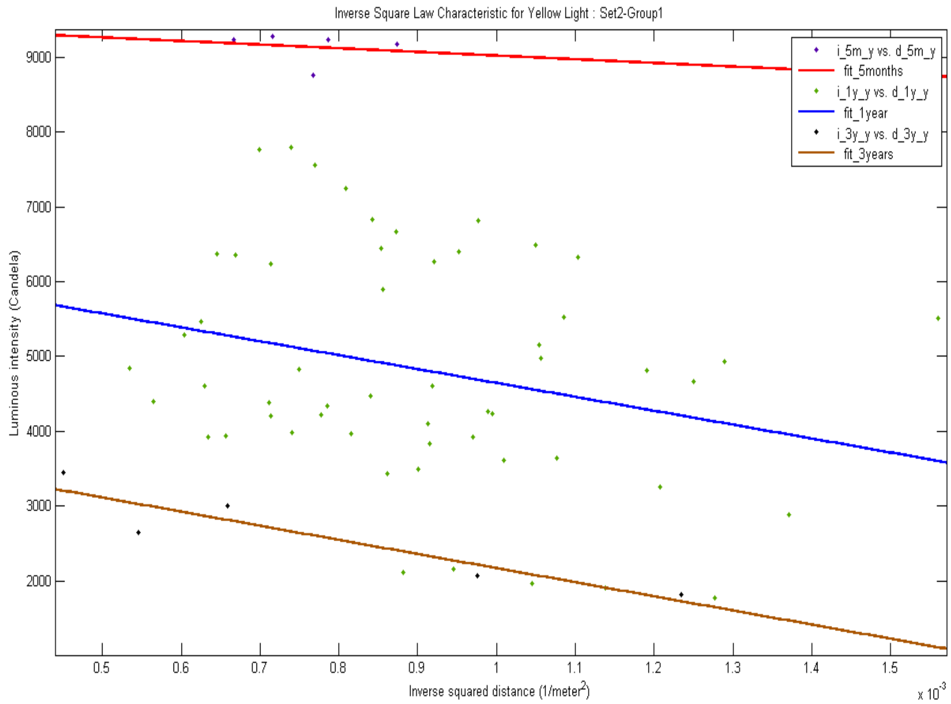

Figure 4.20 Inverse Square Law Characteristic for Yellow Light : Set2 – Group1

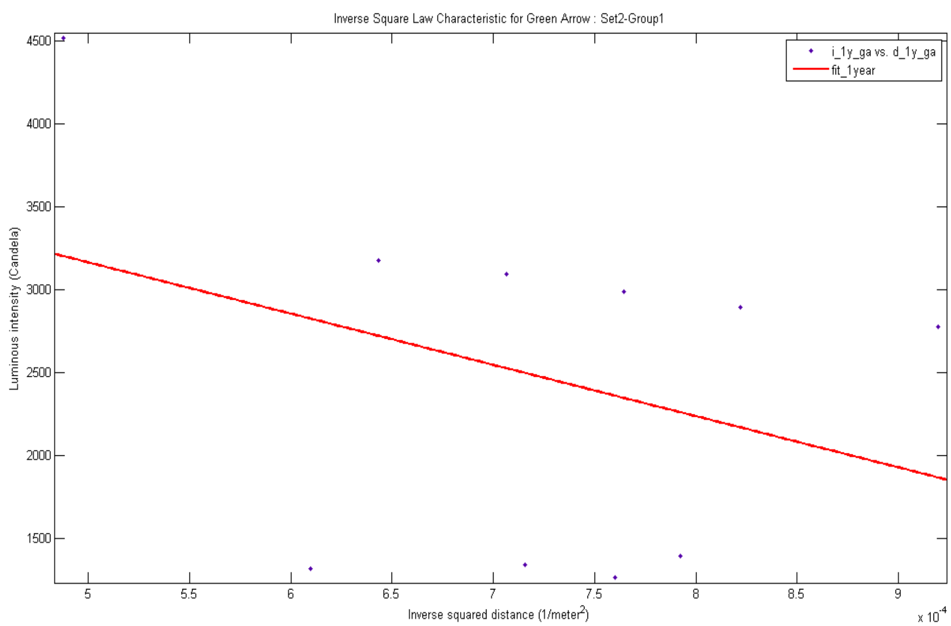

Figure 4.21 Inverse Square Law Characteristic for Green Arrow : Set2 – Group1

Figure 4.22 – 4.26 represents the inverse square law characteristic for different lights of set 2 and group 2.

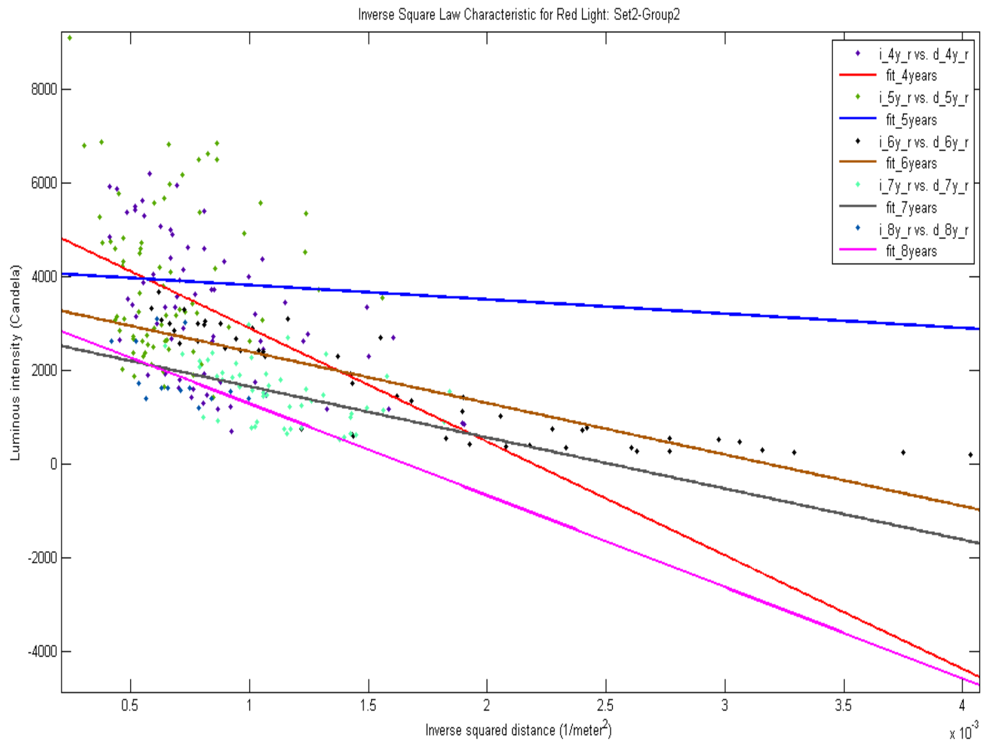

Figure 4.22 Inverse Square Law Characteristic for Red Light : Set2 – Group2

The above figure is in accordance with Figure 4.7 representing red light behavior for set 1 – group 2.

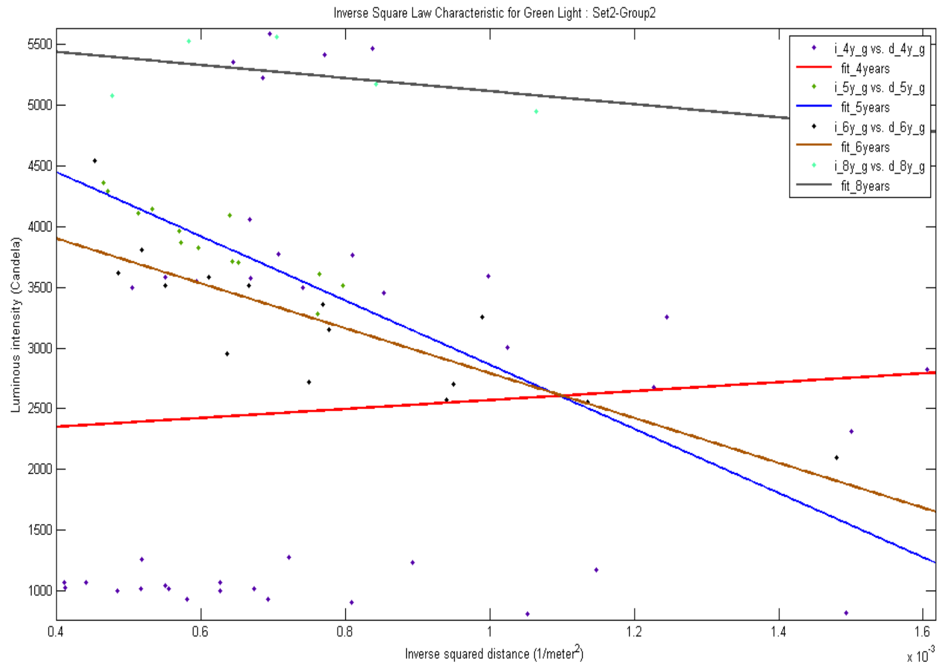

Figure 4.23 Inverse Square Law Characteristic for Green Light : Set2 – Group2

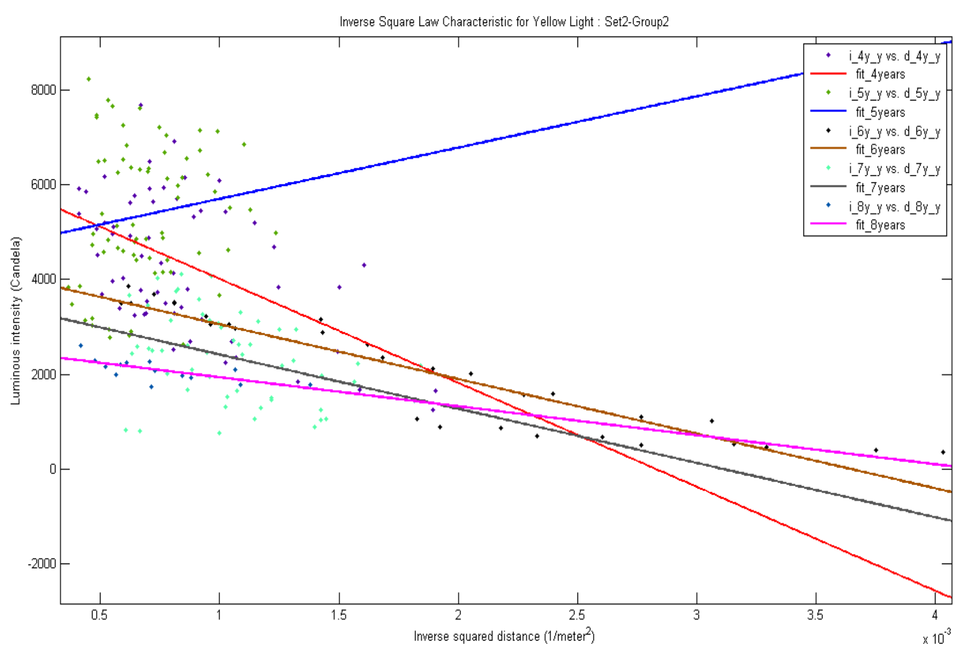

Figure 4.24 Inverse Square Law Characteristic for Yellow Light : Set2 – Group2

Figure 4.24 is in agreement with Figure 4. 9 which are representing the behavior of yellow light belonging to set 1- group 2. However, for age 5 years represented by blue color has the data available for the very less distance range. On observance of curve, it will be noticed that data is not spread equally along the fit and hence needs more data collection.

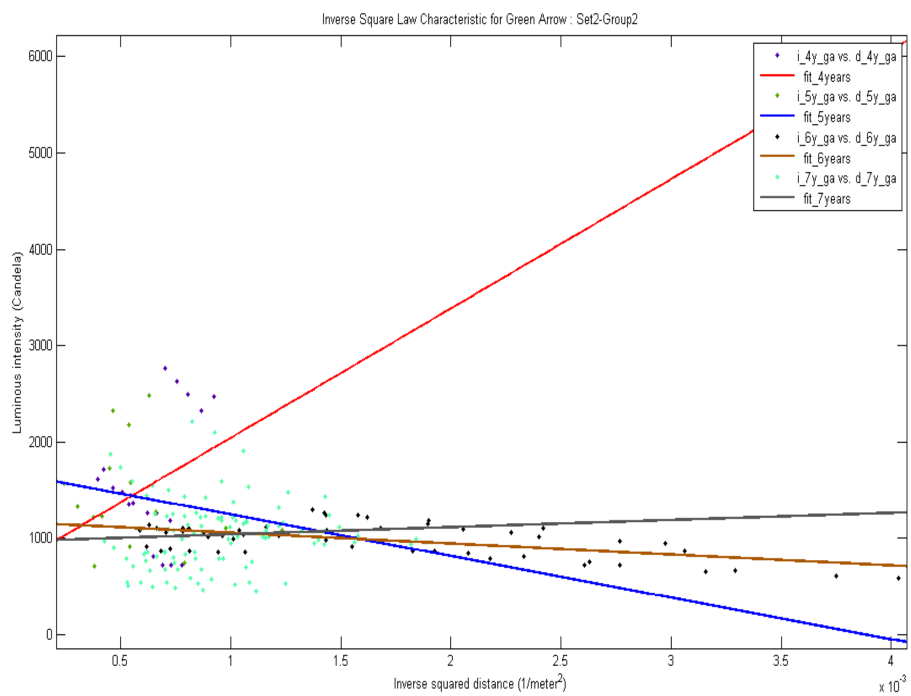

Figure 4.25 Inverse Square Law Characteristic for Green Arrow : Set2 – Group2

Similarly, for green arrow of age 4years, data available is concentrated only in the beginning of fit and hence needs more data collection with more than 5 distance points for correct judgment.

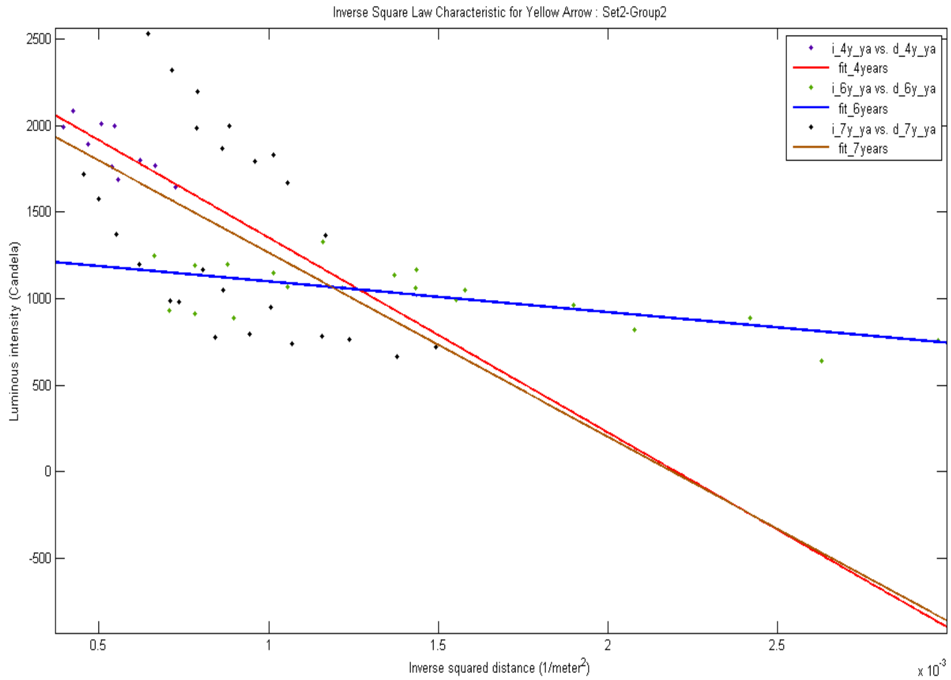

Figure 4.26 Inverse Square Law Characteristic for Yellow Arrow : Set2 – Group2

Figure 4.27 – 4.30 represents the inverse square law characteristic for different lights of set2 and group 3.

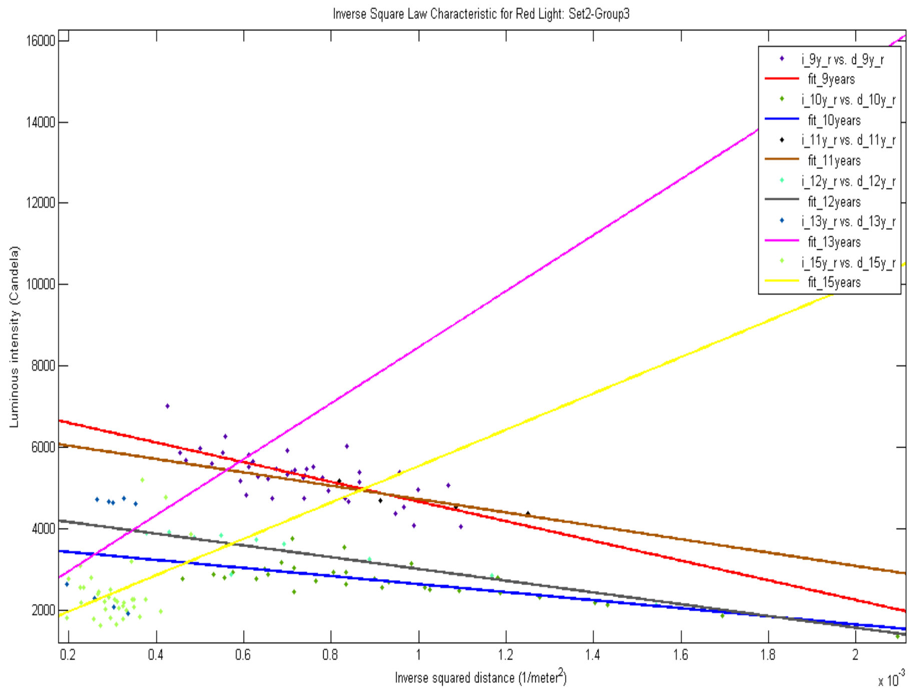

Figure 4.27 Inverse Square Law Characteristic for Red Light : Set2 – Group3

The unconvincing behavior of red lights belonging to ages 13 and 15 is consequence of insufficient available for analysis which is consistent from set 1.

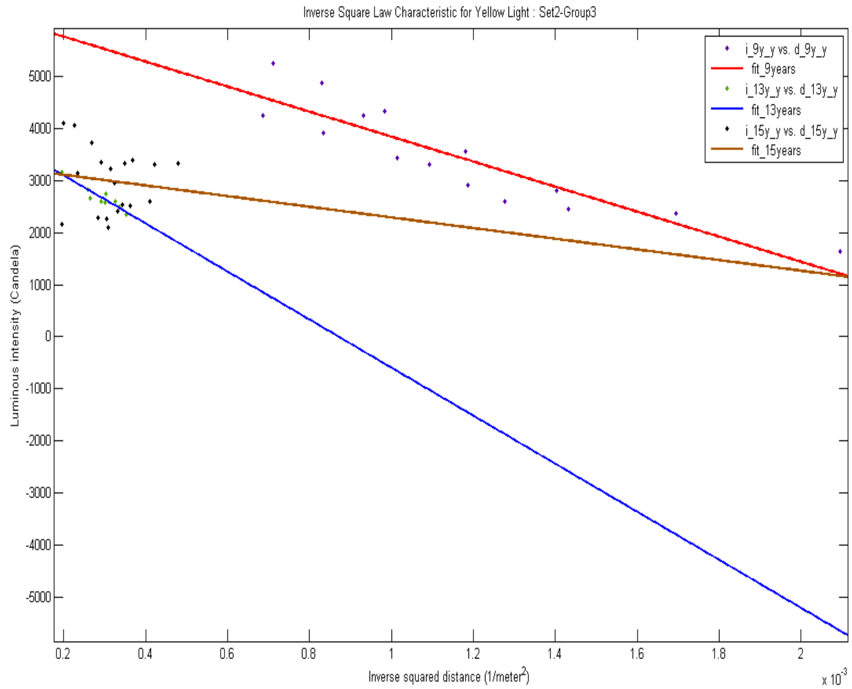

Figure 4.28 Inverse Square Law Characteristic for Yellow Light : Set2 – Group3

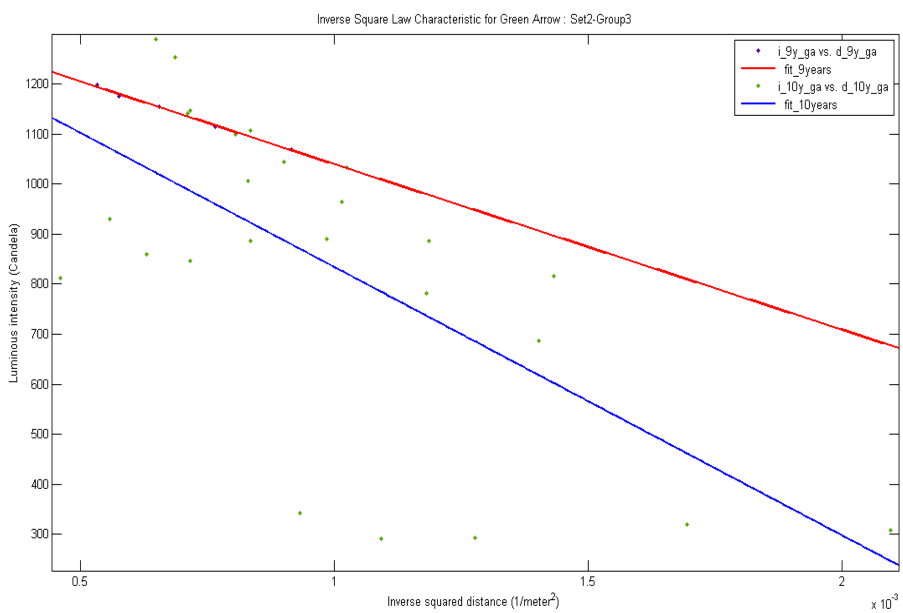

Figure 4.29 Inverse Square Law Characteristic for Green Arrow : Set2 – Group3

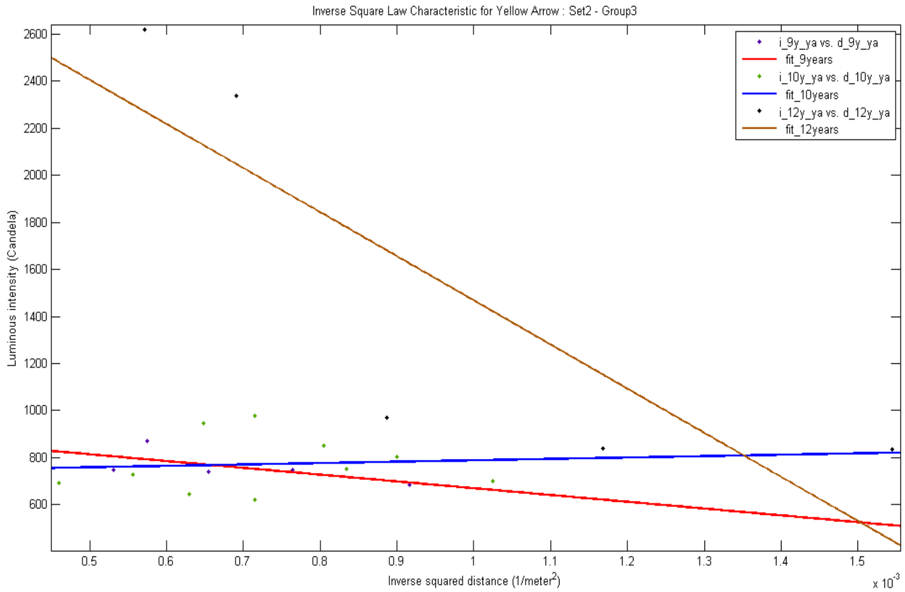

Figure 4.30 Inverse Square Law Characteristic for Yellow Arrow : Set2 – Group3

A considerable role of data sorting per age is observed in intensity analysis; as there are fewer cases of unconventional behavior in the data for both the sets as compared to the previous study in 2010.

Through the intensity analysis, it can be concluded that the unconventional behavior seen in some of the lights is may be because of insufficient data collection. Data should be taken for more than five distance points in the range of 8 – 25 ft. This will help to see the contiguity of data point to the fit. Also, a good methodology is needed to avoid human errors in data collection.

Because of inconsistent data available for set 1 and set 2 there is disagreement in certain graphs obtained for these two sets. However, in certain cases, though the data available is same in both the sets, there is a disagreement which encourages proceeding further with the manufacturer analysis in the thesis.

4.2. MANUFACTURER ANALYSIS

The intensity analysis concluded to segregate the available data according to age as well as manufacturer. The intensity degradation rate may vary as per the manufacturer and hence, to study the poor performance of some of lights, a manufacturer analysis is presented in this section of thesis.

The data sorted previously with respect to age is now sorted again by manufacturer provided by MoDOT. The prominent manufacturers of available LED lights are GE, LTEK, Dial and Philips. The following Tables 4.2 and 4.3 represents the available LED lights with same age and having two or more than two manufacturers for set1 and set 2 respectively.

Table 4.2. Data available in Set 1 for Manufacturer Analysis

Ages \ Lights	Red	Green	Yellow	Green Arrow	Yellow Arrow
1 year			LTEK GE		
5 years	GE Dial	Dial GE	LTEK GE Dial		
7 years				Dial GE	Dial GE
8 years	Philips Dial				

Table 4.3 Data available in Set 2 for Manufacturer Analysis

Ages \ Lights	Red	Yellow	Green Arrow	Yellow Arrow
1 year		LTEK GE		
5 years	GE Dial	GE LTEK Dial		
7 years			GE Dial	GE Dial
8 years	Philips Dial			
9 years		GE Dial		

For better analysis by manufacturer, three factors are considered in the order listed below.

1. Data available
2. Data contiguity to the fit
3. Absolute value of slope

In the event of confusion when all the above mentioned three points are aproximately equal, deviation in the terminal points is considered as a tie breaker.

Figures 4. 31 – 4.37 represents the inverse square law characteristic for lights belonging to different manufacturers of the same ages in set 1 as listed in Table 4.2 .

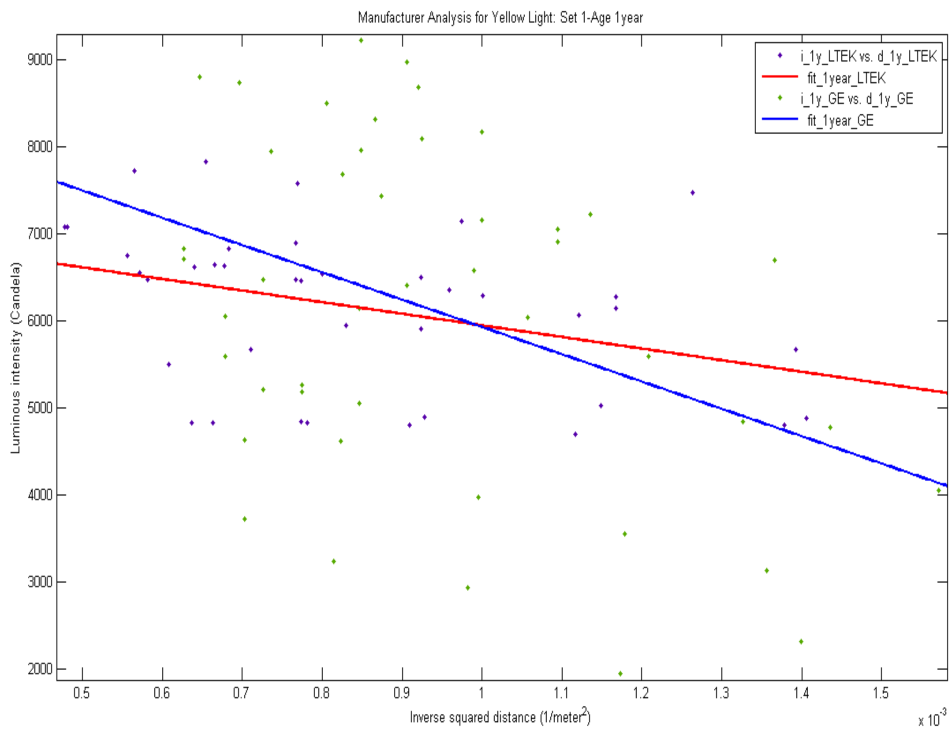

Figure 4.31. Manufacturer Analysis for Yellow light: Set 1- Age 1 year

In this figure, the available data is almost the same. Data contiguity to the fit is also similar. However, the absolute value of slope for LTEK is 1.3 X 10^6 and for GE is 3.1 X 10^6. The smaller the slope value, the slower is the intensity degradation and the longer is the expected life, which is desirable. Based upon these three factors, it can be concluded that LTEK is better option than GE for the given data of yellow light at age 1.

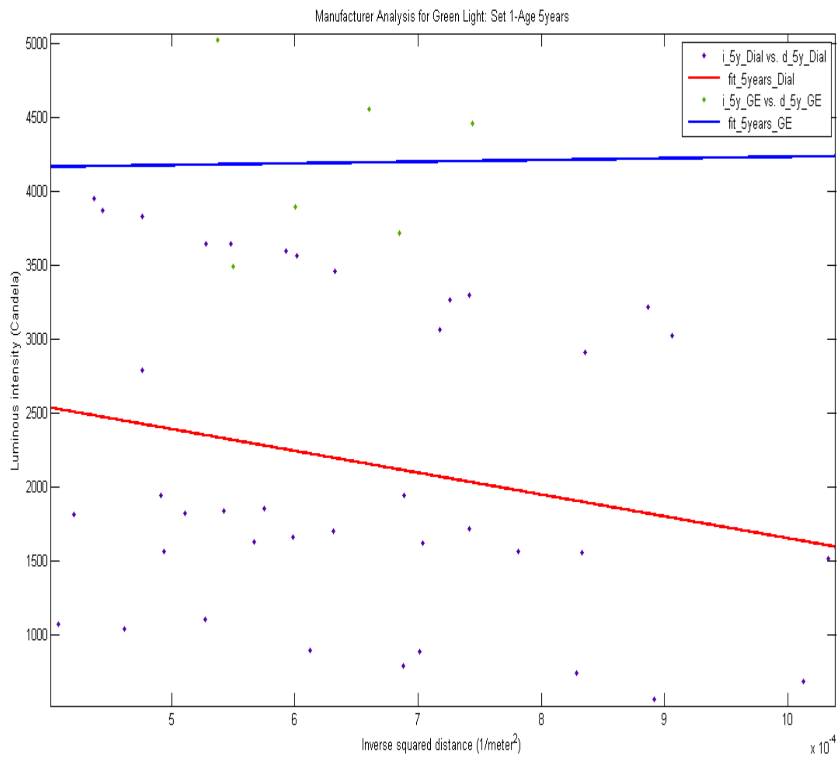

Figure 4.32 Manufacturer Analysis for Green Light: Set 1- Age 5 years

In this case, slope of GE is positive as compared to negative slope of Dial. There is a possibility that because of slight error in data collection for green light at age 5 years of GE, the slope may have a slight positive value. If this slight error value is neglected, performance of GE is almost same with the increasing distance.

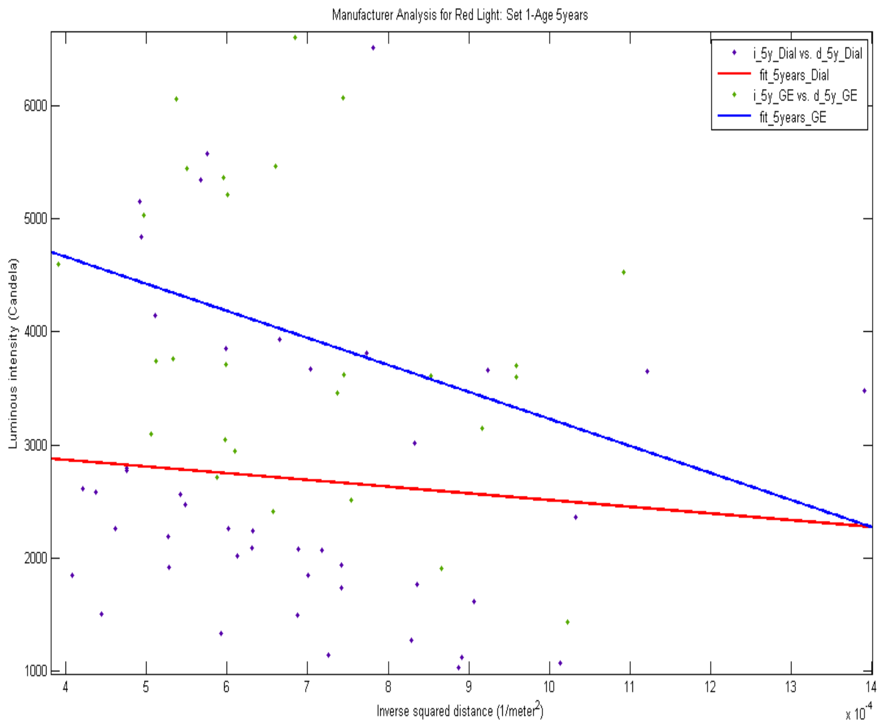

Figure 4.33 Manufacturer Analysis for Red Light: Set 1- Age 5 years

In this figure, the data available and contiguity of data to fit is almost equal in both the cases, however, the absolute value of slope for Dial is 5.9 X 10^5 and for GE is 2.4 X 10^6. This indicates that GE is may have the possibility of higher intensity degradation rate over Dial for the given data for Red light at age 5.

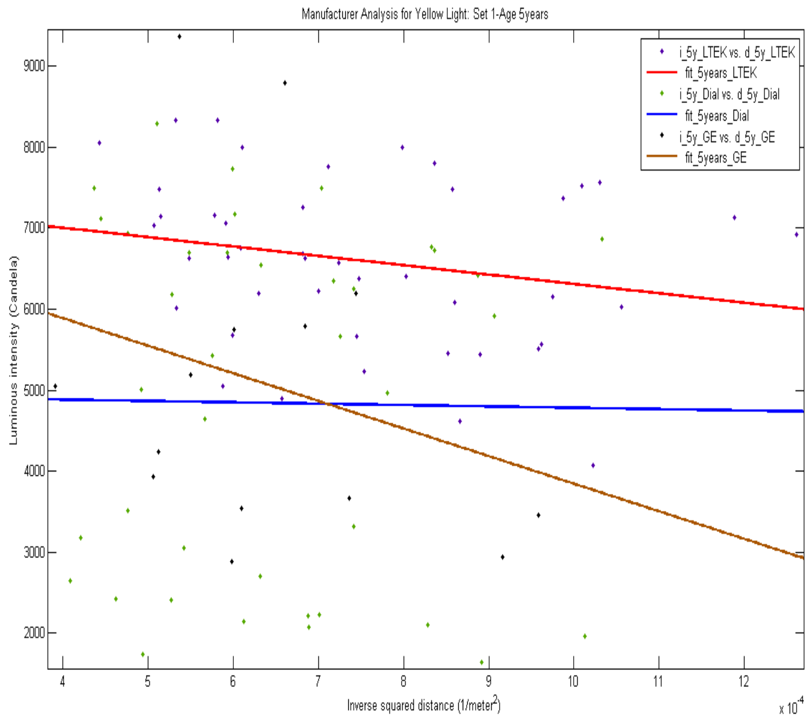

Figure 4.34 Manufacturer Analysis for Yellow Light: Set 1- Age 5 years

In this scenario, slope value of Dial has a very slight positive value, which can be affected even if a single data point is changed.

When the comparison is between GE and LTEK, based upon the absolute slope value of 1.2 X 10^6 for LTEK versus 3.4 X 10^6 for GE, LTEK shows slower intensity degradation with increasing distance.

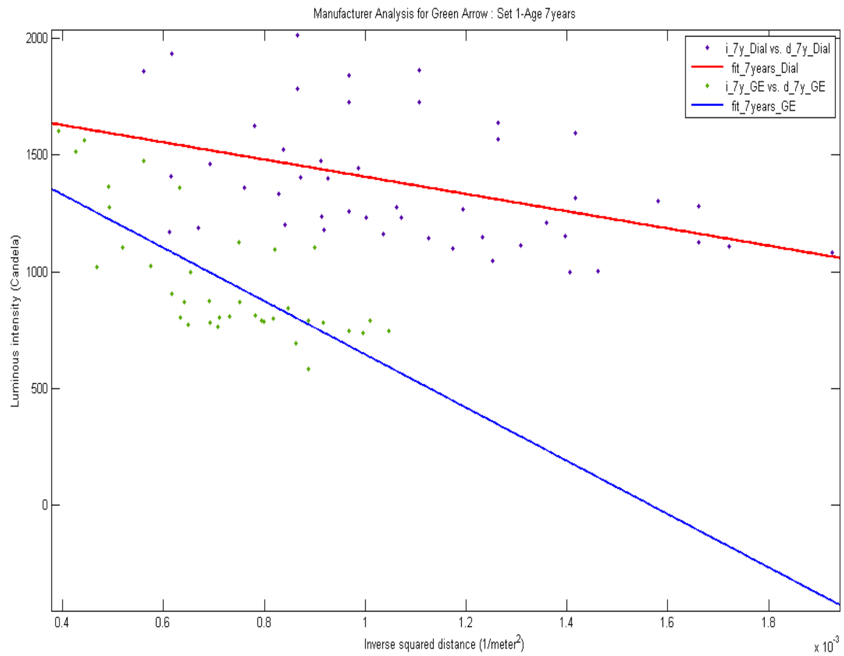

Figure 4.35 Manufacturer Analysis for Green Arrow: Set 1- Age 7 years

In this case, since the first two factors of data availability and proximity to the fit are almost equal, the slope of two curves is a noticing factor. The slope of Dial is less with an absolute value of 3.7 X 10^5 over GE with a slope value of 1.1 X 10^6.

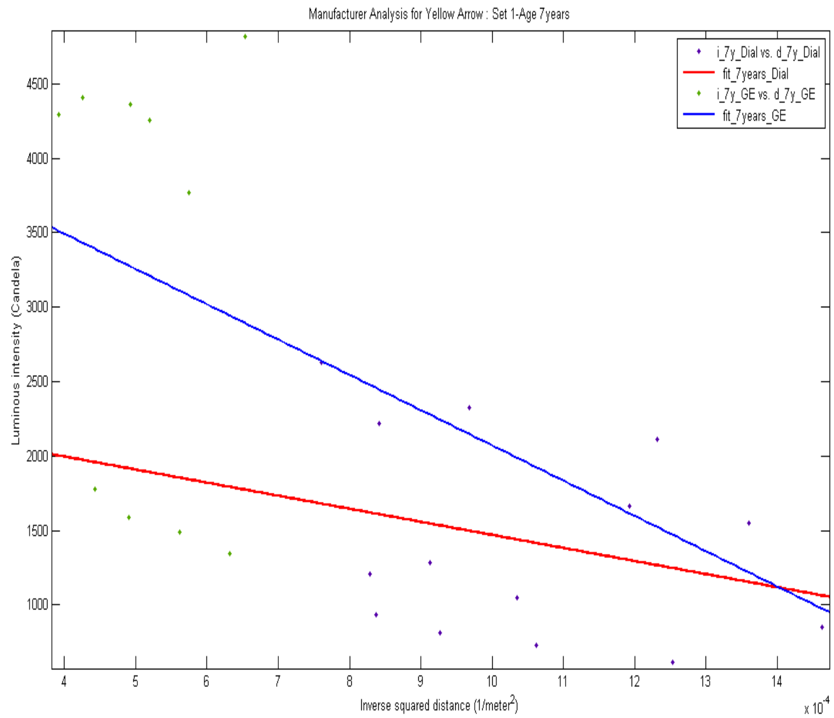

Figure 4.36 Manufacturer Analysis for Yellow Arrow: Set 1- Age 7 years

In this case, as the available data for Dial is more than GE, it has a little advantage of the better fit. Also, the proximity of data to the fit is observed more in Dial. The absolute value of slope for Dial is 8.8 X 10^5 and for GE is 2.4 X 10^6. Hence, with present factors expected life degradation is slower in Dial.

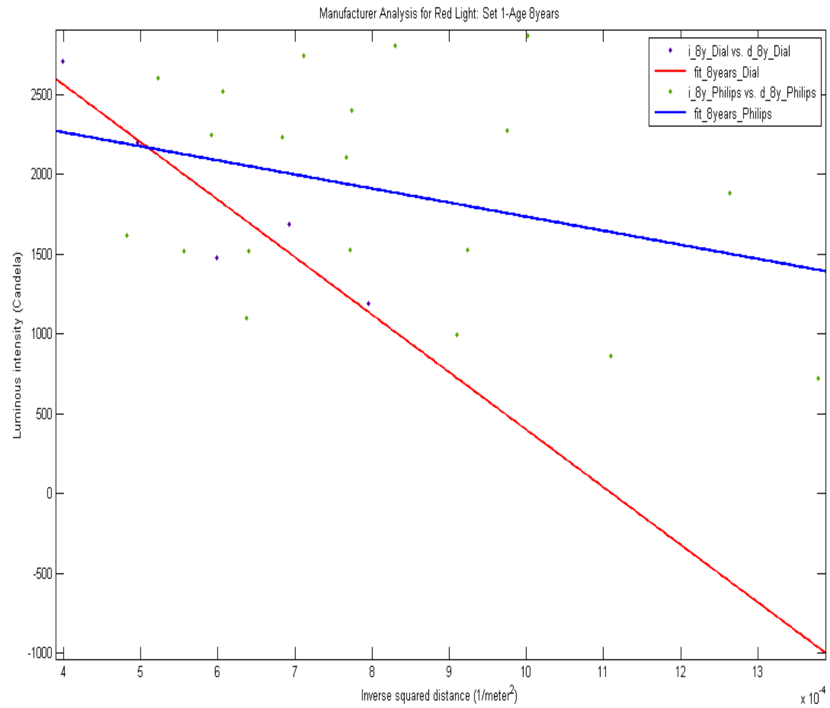

Figure 4.37 Manufacturer Analysis for Red Light: Set 1- Age 8 years

With larger available data, more contiguity and better absolute value of slope which is $8.8 * 10^5$ over $3.6 * 10^6$ of Dial, Philips is a recommended option.

Now, similarly for set 2, the Figures 4. 38 – 4.44 represents inverse square law characteristic for lights belonging to different manufacturers and of same ages in set 2 as listed in table 4.3.

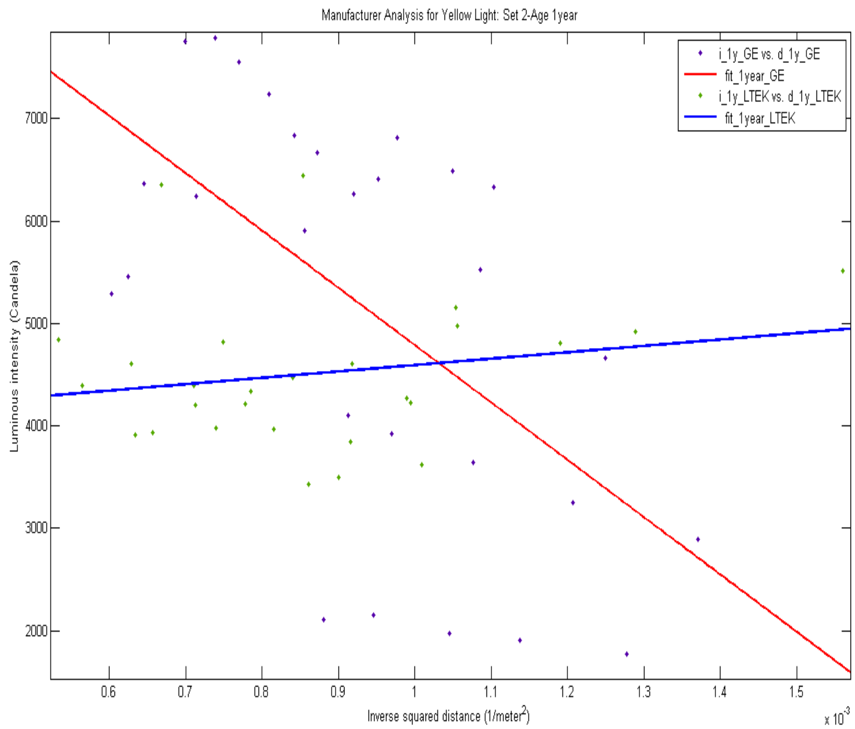

Figure 4.38 Manufacturer Analysis for Yellow Light: Set 2- Age 1 year

Based on previously discussed factors, it can be noticed that the data available for analysis and its proximity to the fit is almost similar for both the manufacturers. However, for GE the intensity value is increasing with distance which does not match with the laboratory analysis.

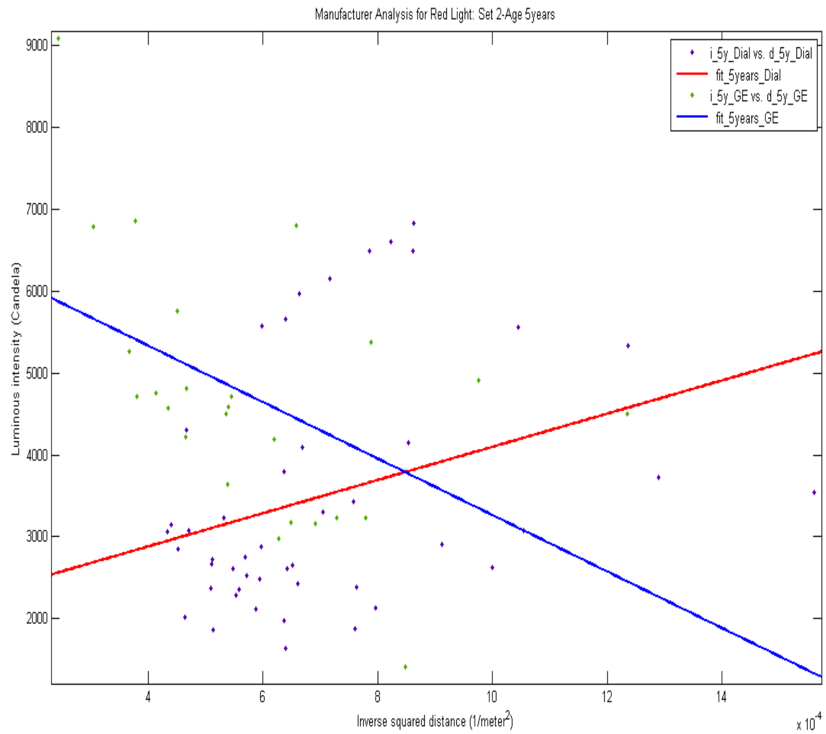

Figure 4.39 Manufacturer Analysis for Red Light: Set 2- Age 5 years

It can be clearly noticed that because of increasing slope value which symbolizes more intensity degradation rate, GE has better performance choice over Dial for given data for red light at age 5 years.

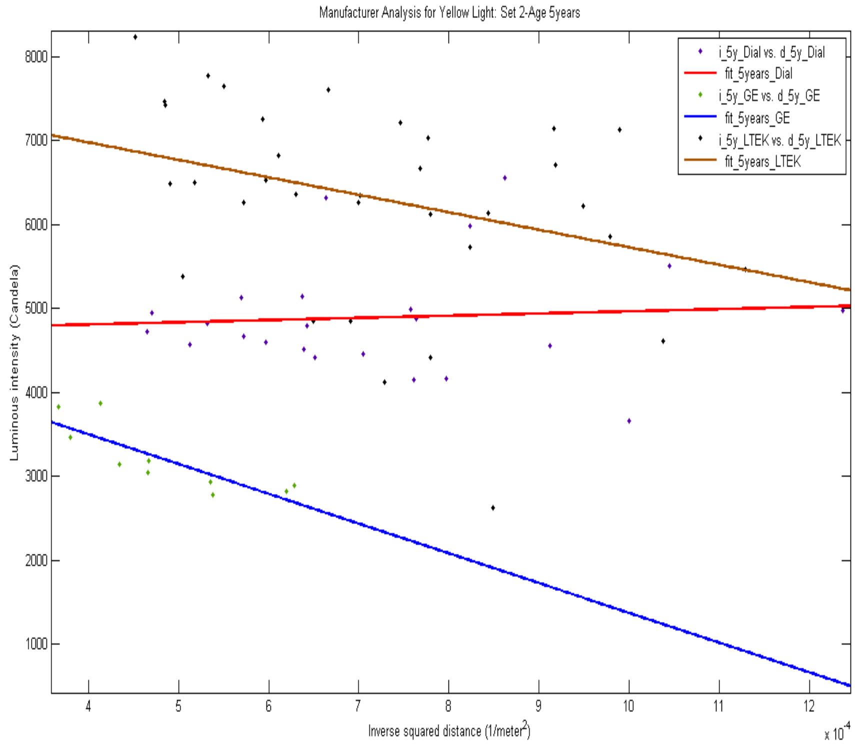

Figure 4.40 Manufacturer Analysis for Yellow Light: Set 2- Age 5 years

Here, the slope value of Dial is positive which represents increase in intensity with respect to distance. Similar to set 1 result, in the comparison is between GE and LTEK, based upon the absolute slope value of 2.1 X 10^6 for LTEK versus 3.5 X 10^6 for GE, LTEK has slower intensity degradation than GE and Dial.

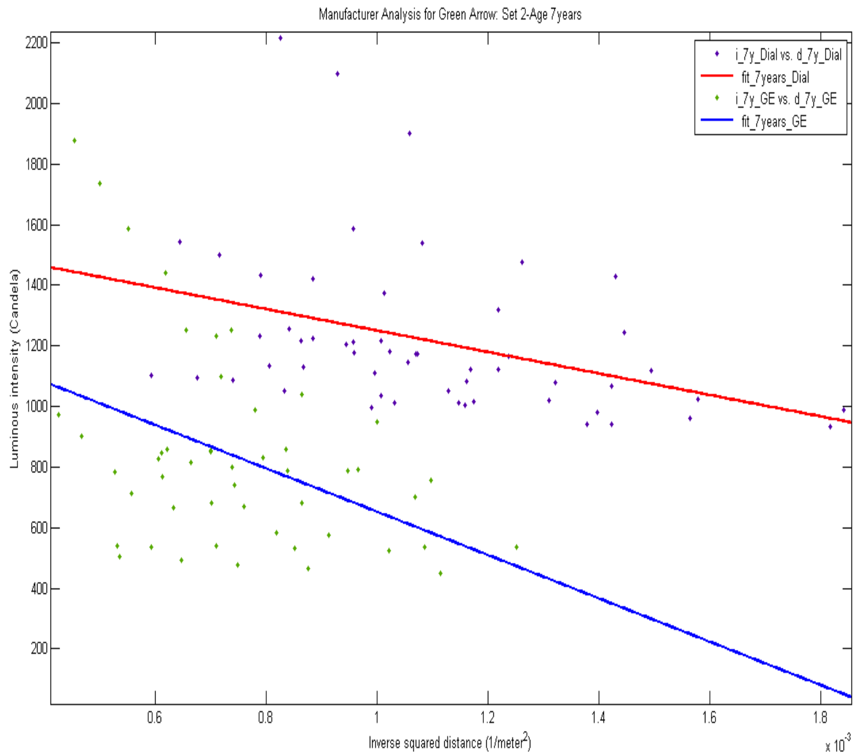

Figure 4.41 Manufacturer Analysis for Green Arrow: Set 2- Age 7 years

In this case, since the first two factors of data availability and proximity to the fit are almost equal, the slope of two curves is an important factor. The slope of Dial proves to be better with an absolute value of 3.5 X 10^5 over GE with a slope value of 7.2 X 10^5. This result matches with the set 1 observance for green arrow at 7 years.

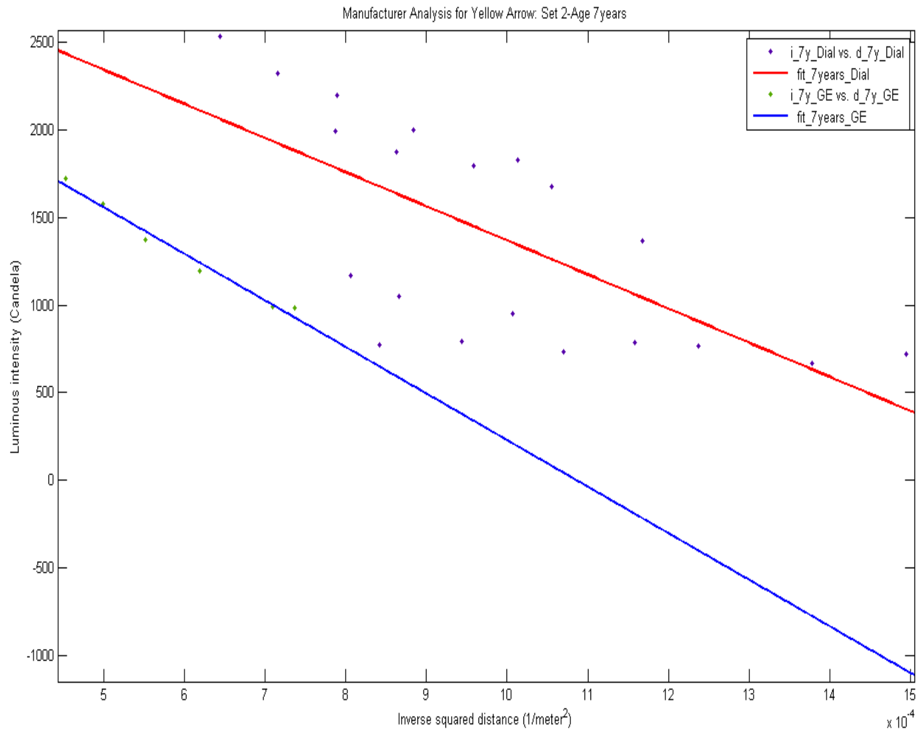

Figure 4.42 Manufacturer Analysis for Yellow Arrow: Set 2- Age 7 years

With better available data, better and ordinated contiguity, and better absolute value of slope which is $1.9 * 10^6$ as compared to $2.7 * 10^6$, Dial is a recommended option.

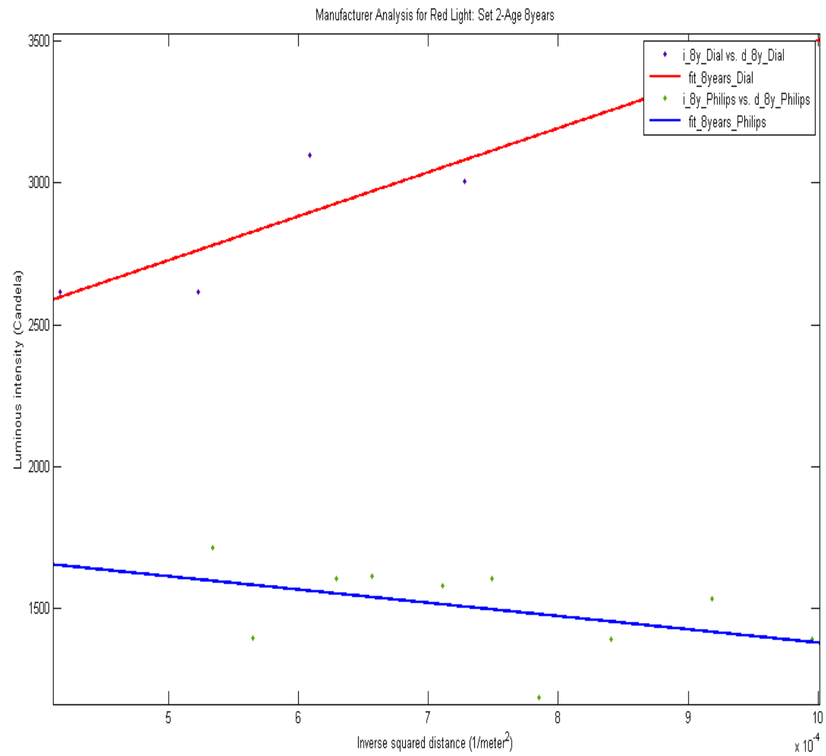

Figure 4.43 Manufacturer Analysis for Red Light: Set 2- Age 8 years

The behavior of Dial manufacturer is not in accordance with the curves obtained from laboratory analysis. Hence, it can be easily concluded that Philips is a good option.

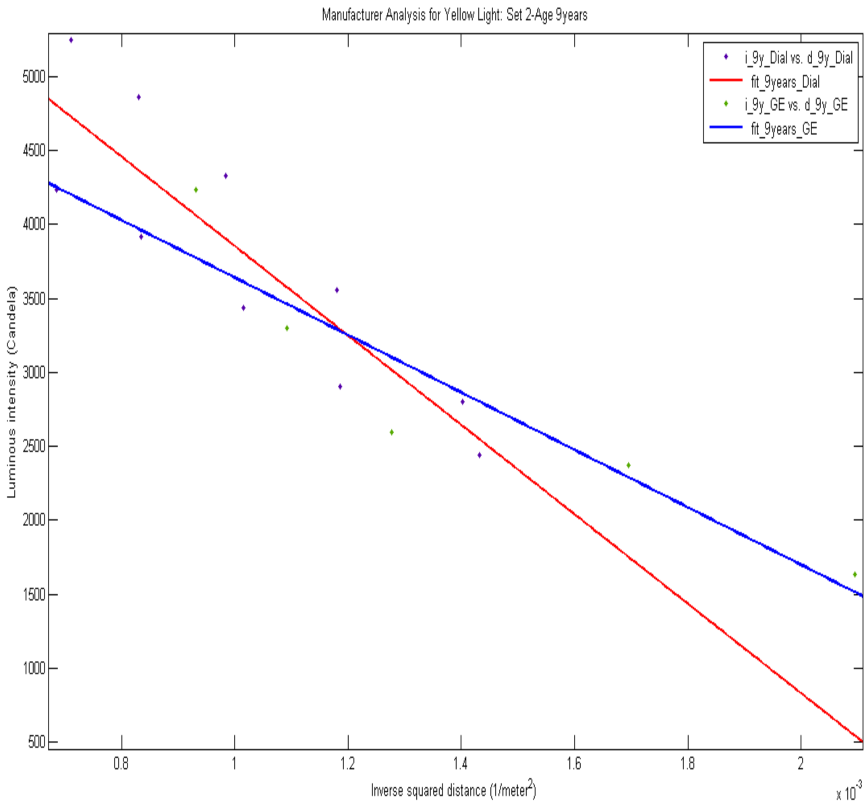

Figure 4.44 Manufacturer Analysis for Yellow Light: Set 2- Age 9 years

In this case, though Dial has larger available data, GE has more contiguity to the fit and better slope value of 1.9 X 10^6 over 3 X 10^6. Hence, GE is recommended over Dial for a given data of yellow light at age 9 years.

Based upon the results obtained, following table summarizes the total number of positive aspects for each manufacturer.

Table 4.4 Total positive factors of manufacturers for considered data

Factors \ Manufacturers	GE	LTEK	Dial	Philips
Data available	6	4	10	0
Contiguity to the fit	3	4	7	2
Absolute value of Slope	1	2	7	0
Total	10	10	24	2

As per the summarized table, Dial is recommended choice with 24 total positive factors. It has been discussed previoulsy in intensity analysis section that data availability has major contribution for better fit. It can be noticed that Dial has more data availaibility over other manufacturers and hence this must have given more weightage for better performance of Dial over rest of the manufacturers. But still, the absolute value of slope shows Dial to be a recommended manufacturer.

To avoid the confusion between GE and LTEK for recommendation, it is important to consider the percentage effectiveness to decide the best available option for future reference. The percentage effectiveness is defined as

$$Percentage\ Effectiveness = \frac{no. of\ efficient\ performances}{no.\ of\ installations}$$

where,

The *no. of efficient performances* are calculated based upon the number of times the manufacturer has shown better performance over others with the available lights mentioned in Tables 4.2 and 4.3 for comparison.

The *no. of installations* are calculated wherever the manufacturers` lights are avaliable for comparison.

Table 4.5 represents the percentage effectiveness calculated for available manufacturers` lights.

Table 4.5 Percentage effectiveness for available manufacturers

Manufacturers	GE	LTEK	Dial	Philips
Percentage Effectiveness	33.33%	75%	41.6%	100%

With the present available data and calcualtion of the positive weightages of factors, Dial is recommended option; but when percentage effectiveness is considered, Philips is 100% effective. However, this result is completely factual and hence cannot be considered as exactly correct. If more data could be available for lights manufactured by Philips, then this analysis would have been more beneficial. This analysis though answers for the confusion between GE and LTEK. The total of positive factors is same for GE and LTEK, but the precentage effectiveness shows LTEK is more effective than GE.

Thus, through the manufacturer analysis, various positive factors of different manufacturers are highlightened. Based on the three factors considered for analysis, Dial has shown more total value of positive points. As a tie breaker and for better analysis, percentage effectiveness is defined and calculated for all manufacturers. Philips has shown 100% effectiveness. However, only two lights are available for Philips manufacturer and hence, this result cannot be considered as reliable. More data is required for this particular manufacturer for better judgement. GE and LTEK manufacturers have equal total number of positive factors, but through the percentage effectiveness calculation, LTEK shows more effectiveness.

4.3. TEMPERATURE ANALYSIS

Since, the data collection is done for two sets in two completely different seasons, an analysis of the effect of temperature on available LED lights was performed. A temperature analysis is done to see the effect of temperature on the behavior of the same lights, of same age, and belonging to same manufacturer. For this purpose, the temperature was recorded when the data collection was done. The following tables represents data collected for two sets with temperatures recorded at that time.

Table 4.6 Temperature Analysis: Data collection for Set 1

Location	Date	Temperature
Rolla		
63 X 72	1/14/2013	-11^{o} C
63 X University	2/3/2013	-9^{o} C
Rolla X 72	1/14/2013	-11^{o} C
Salem X 72	1/13/2013	-12^{o} C
63 X Vichy	3/3/2013	-13^{o} C
Union and Washington		
50 X Prairie Dell	1/15/2013	-8 ^{o} C
50 X Independence	1/14/2013	-8 ^{o} C
47*50E	1/14/2013	-8 ^{o} C
50W * 47	1/14/2013	-8 ^{o} C

Columbia 763 X University 763 X Paris 763 X Big Bear	2/17/2013 2/17/2013 2/17/2013	-2 ^{o} C -2 ^{o} C -2 ^{o} C
Jefferson City 63 X MO	2/15/2013	-8 ^{o} C
Cape Girardeau 74 *Silver Springs 74 *Fountain	3/14/2013 3/15/2013	-6^{o} C -2^{o} C
Jackson D X 34 34 X Main	3/13/2013 3/14/2013	-3^{o} C -6^{o} C
St. Louis Keller X61 Forder X 61 Mehl X 61	3/31/2013 1/4/2013 1/4/2013	8^{o} C 3^{o} C 3^{o} C

Table 4.7 Temperature Analysis: Data collection for Set 2

Location	Date	Temperature
Rolla 63 X 72 63 X University Rolla X 72 Salem X 72	7/15/2013 7/31/2013 4/19/2013 6/13/2013	20^{o} C 16^{o} C 1^{o} C 16^{o} C
Union and Washington 50 X Prairie Dell 50 X Independence 47*50E 50W * 47	6/30/2013 6/14/2013 6/30/2013 6/20/2013	18^{o} C 17^{o} C 18^{o} C 21^{o} C
Columbia 763 X University 763 X Paris	6/8/2013 6/8/2013	12^{o} C 12^{o} C

763 X Big Bear	6/8/2013	12° C
Jefferson City 63 X MO	6/3/2013	12° C
Cape Girardeau 74 *Silver Springs 74 *Fountain	6/21/2013 6/21/2013	22° C 22° C
Jackson D X 34 34 X Main	7/16 /2013 7/25/2013	22° C 13° C
St. Louis Keller X61 Forder X 61 Mehl X 61	6/16/2013 8/13/2013 8/1/2013	21° C 16° C 18° C

For analysis, one graph is plotted per group, as instead of noticing the subtle differences, the effect of temperature will be noticed in conspicous age differences. Also, the age which has maximum data available in the group is chosen for analysis. The graphs are defended based on slope which represents the degradation of lights with respect to temperature.

Figure 4. 45 - 4.47 represents temperature analysis for red colored lights each belonging to same intersections.

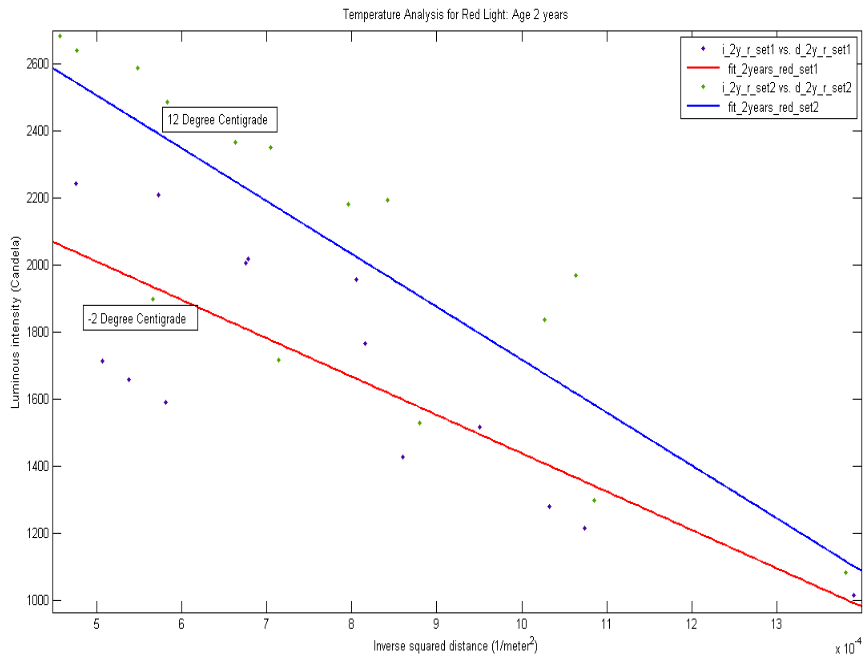

Figure 4.45 Temperature Analysis for Red Light: Age 2 years

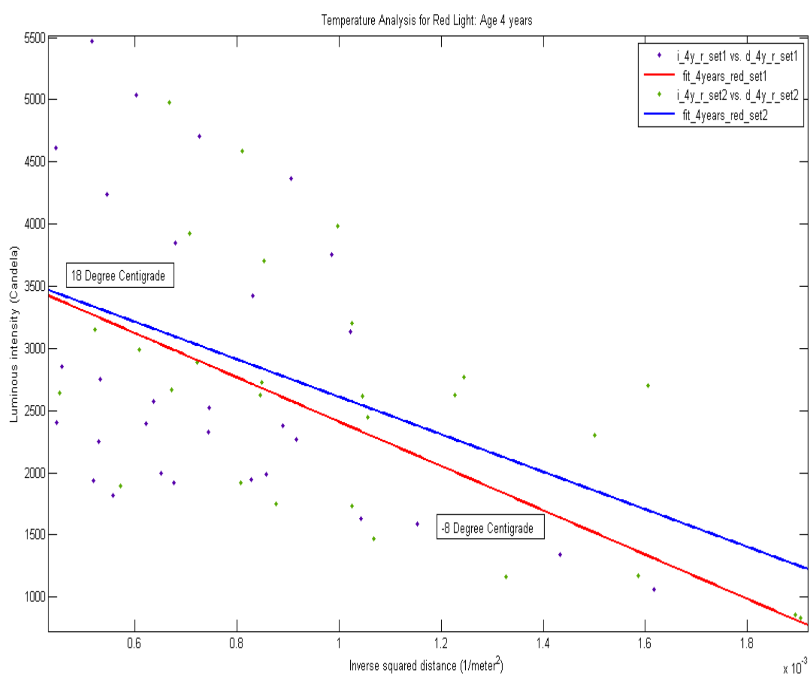

Figure 4.46 Temperature Analysis for Red Light: Age 4 years

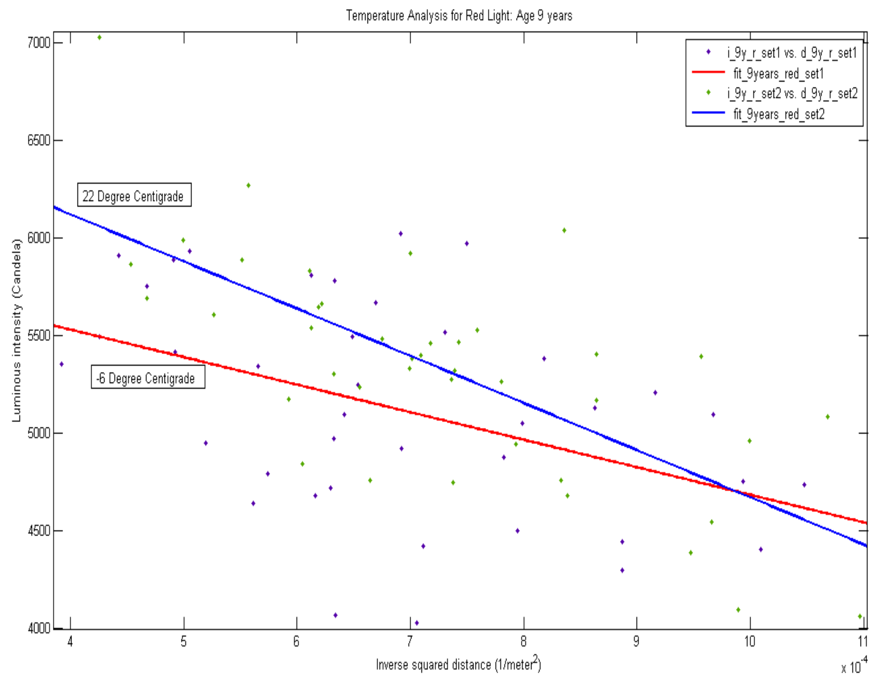

Figure 4.47 Temperature Analysis for Red Light: Age 9 years

Following table 4.8 shows the interpretation of these graphs for red lights at ages 2, 4 and 9 years.

Table 4.8 Temperature Analysis: Slope difference for Red light

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

The table demonstrates the temperature difference between two sets recorded and the significant slope difference obtained because of temperature change. In this case, the behavior of Dial lights is more reliable than GE, since, the slope difference which symbolizes the degradation of intensity is less in Dial as compared to GE at approximately same temperature difference (26^{o} C and 28^{o} C).

Similarly, following figures 4. 48 and 4.49 represents temperature analysis for green colored lights each belonging to same intersections.

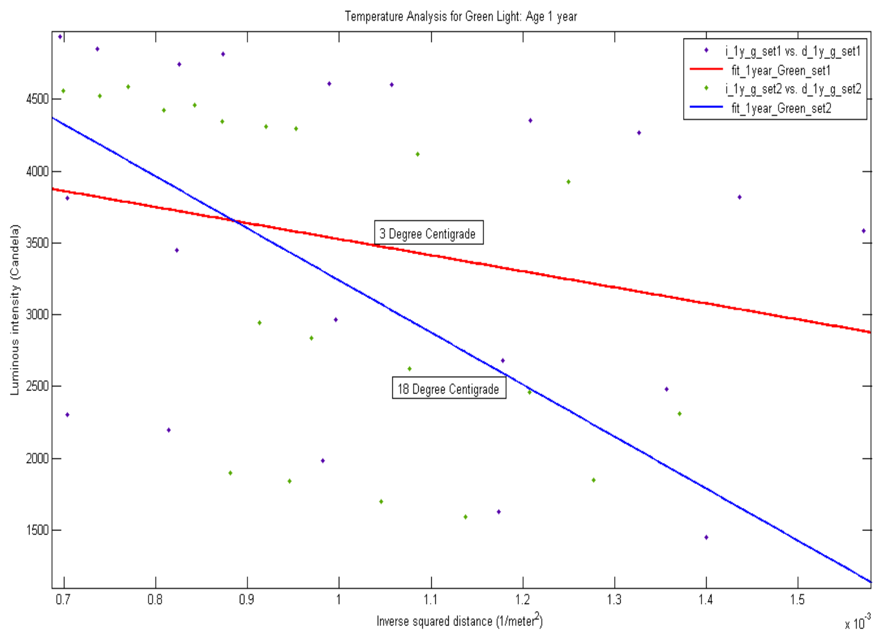

Figure 4.48 Temperature Analysis for Green Light: Age 1 year

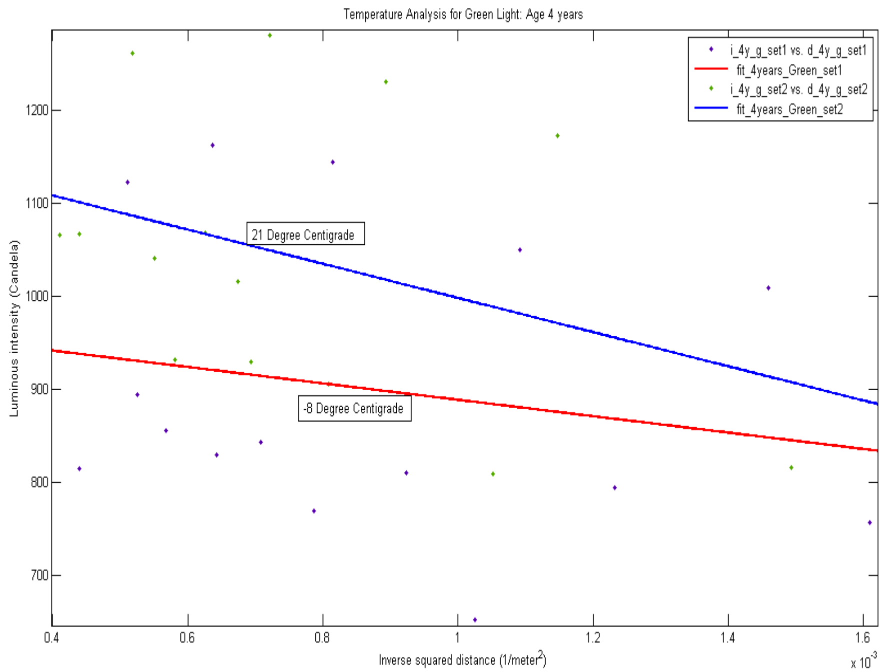

Figure 4.49 Temperature Analysis for Green Light: Age 4 years

Table 4.9 complements the graphs for green lights at ages 1 and 4 years.

Table 4.9 Temperature Analysis: Slope difference for Green light

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

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

Figure 4. 50 and 4.51 represents temperature analysis for yellow colored lights each belonging to same intersections.

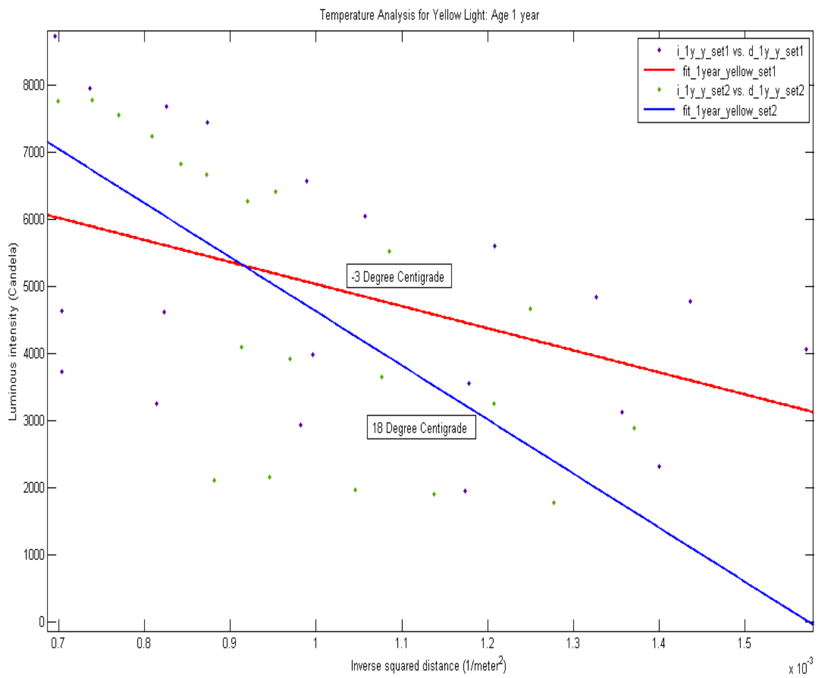

Figure 4.50 Temperature Analysis for Yellow Light: Age 1 year

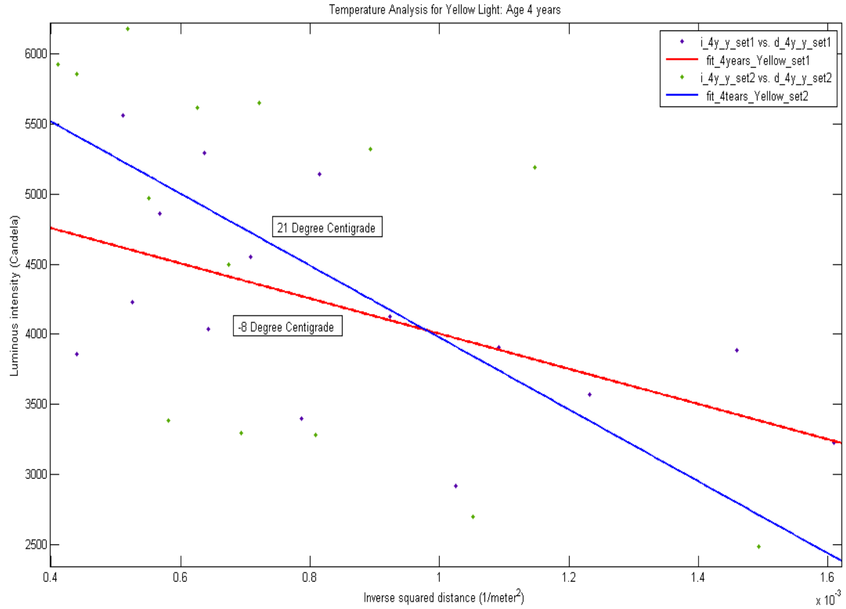

Figure 4.51 Temperature Analysis for Yellow Light: Age 4 years

Table 4.10 complements the graphs for yellow lights at ages 1 and 4 years.

Table 4.10 Temperature Analysis: Slope difference for Yellow light

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

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

Similarly, figures 4. 52 to 4.54 represents temperature analysis for green arrow,each belonging to same intersections.

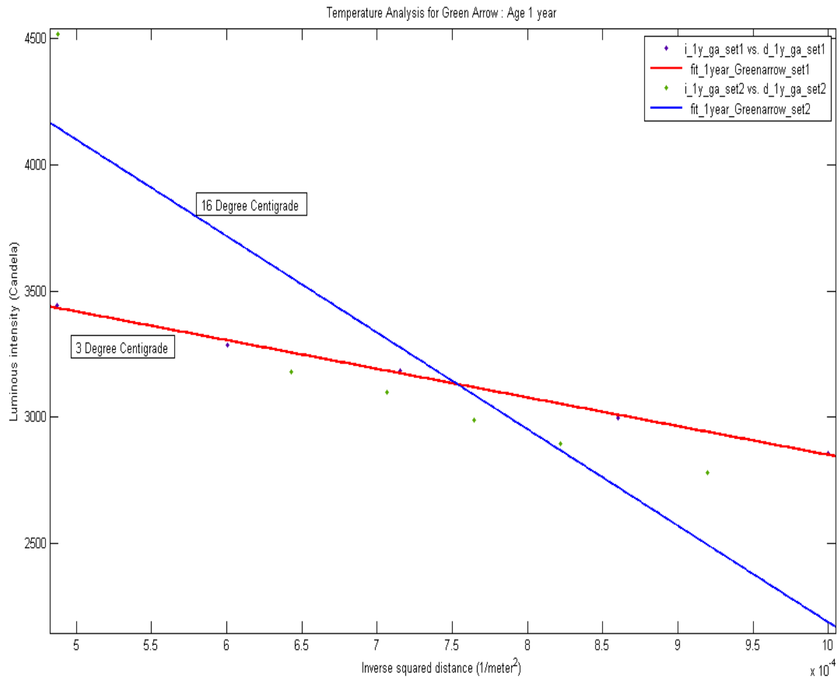

Figure 4.52 Temperature Analysis for Green Arrow: Age 1 year

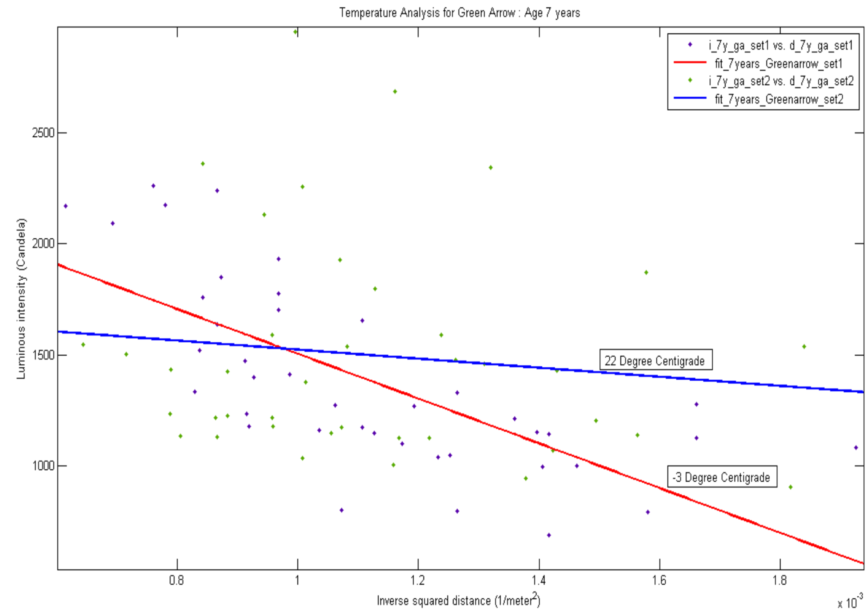

Figure 4.53 Temperature Analysis for Green Arrow: Age 7 years

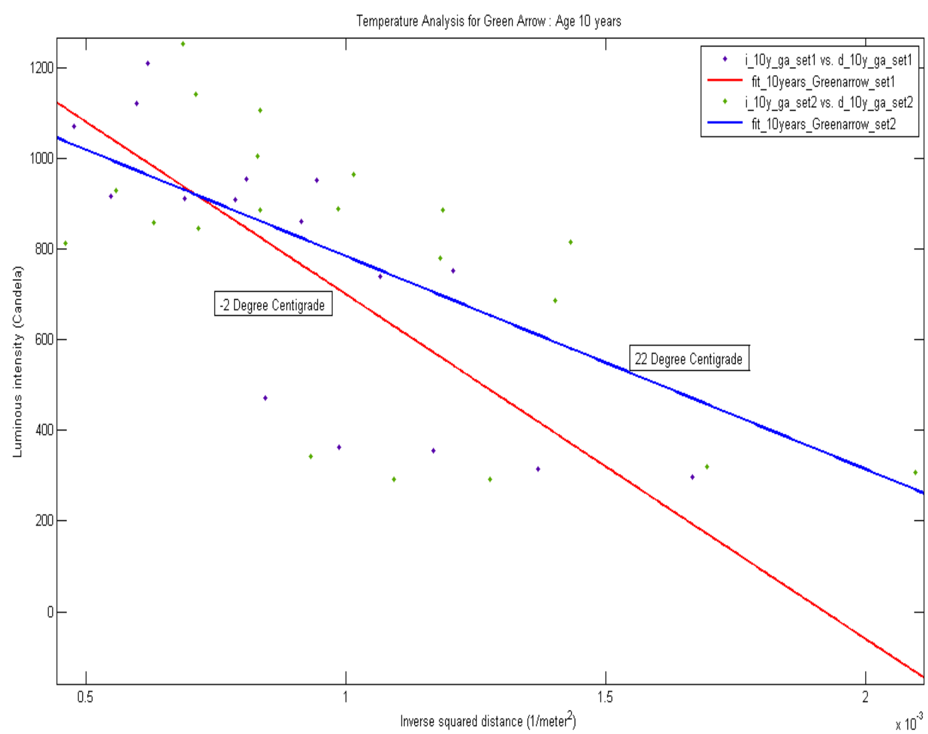

Figure 4.54 Temperature Analysis for Green Arrow: Age 10 years

Table 4.11 interprets the graphs for green arrow at ages 1, 7 and 10 years.

Table 4.11 Temperature Analysis: Slope difference for Green Arrow

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

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

Figure 4. 55 represents temperature analysis for yellow arrow at age 7.

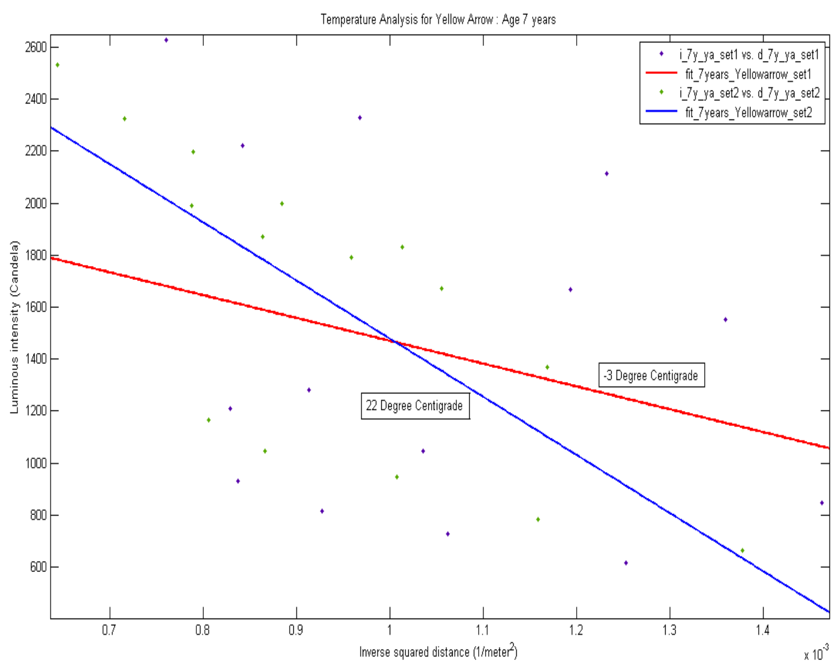

Figure 4.55 Temperature Analysis for Yellow Arrow: Age 7 years

Table 4.12 explains the graph for yellow arrow at age 7 years.

Table 4.12 Temperature Analysis: Slope difference for Yellow Arrow

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

The significant effect of temperature can be observed on the intensity of yellow arrow lights for given data in two sets.

Thus, it can be noticed that with the increase in temperature, intensity value of LED traffic lights is also increasing. This means for better intensity value, temperature should be more. Also, less deviation between maximum intensity value and minimum intensity value is desired for less life degradation. This factor is calculated by measuring the slope value of the fit. It has been observed that Dial shows less slope deviation with significant temperature difference.

5. CONCLUSIONS AND FUTURE SCOPE

Although considered a more sustainable technology, the long-term performance and degradation rates of LEDs have not been thoroughly studied to gain an understanding of their useful lives and appropriate replacement strategy. There exist many stochastic factors that affect LED degradation rates making their analysis complicated. This research extends a previous cross-sectional study done by Missouri University of Science and Technology; funded by the Missouri Department of Transportation (MoDOT) in 2010.

The factors studied in the present thesis work are the impact of distance, directional view, color, manufacturer and temperature on behavior of LED traffic lights. For this purpose, field data is collected from the intersection list provided by MoDOT. A database is created in Microsoft Excel and Microsoft Access for future reference. Three analysis methods are applied on the obtained field data: 1) Intensity analysis, 2) Manufacturer analysis, and 3) Temperature analysis.

In 2010 study, the inverse square law characteristics was plotted for one intensity reading at one distance measured for one light at one intersection and have averaged the readings of Lux belonging to different ages for analysis. This resulted into erratic characteristic of some of the red colored traffic lights. This issue is resolved in the presented thesis work by analyzing the data belonging to same age. Inverse square law characteristic is obtained for red, green, yellow, green arrow, yellow arrow and red arrow traffic lights and it has been observed that some of the lights belonging to some ages need particular attention.

The manufacturer analysis is also a part of future scope of 2010 study. The traffic lights manufacturers` information given by MoDOT is used to sort the collected field data. The preferred manufacturer is determined based on three considerations: 1) Data availability, 2) Data contiguity, and 3) Absolute value of slope. A novel concept of Percentage Effectiveness defined as the ratio of number of efficient performances to number of installations is used to specify the effectiveness of the manufacturer based on present field study. This will help MoDOT to choose the manufacturer. The study recommends Dial as it has more number of total positive factors. However, the results obtained are based on the collected field data and hence is factual. If sufficient data is available the approach of percentage effectiveness can be more useful and dependable.

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

The present work has led path for the important future work in analysis of LED traffic lights. The intensity analysis has some of the lights showing confusing behavior and one of the major reasons is data insufficiency. Future analysis may concentrate on these lights by collecting more intensity data.

Presently, there is no industrial standard defined for manufacturing LED traffic lights. Lab analysis done on various LED traffic lights with different manufacturers may result into a step towards it. The ideal curve of behavior can be obtained and used for comparison with the real time intensity data. Frequency spectrum analysis will be one of the major contributions in the lab investigation.

The data collection can be done with ease and more efficiency, if the design of intensity measuring device is modified with attachment at the bottom to set in the vehicle and adjust its targeting position. This method will play an important role to attain the issue of human error in data collection.

Study on visibility performance of LED traffic lights can also be done. Mechanisms for appropriate dimming of LED traffic signal modules to replace glare and provide modest energy savings could be implemented and perhaps, even to temporarily increase signal intensity during conditions of reduced visibility such as fog or sun phantom. This may require application of sensors.

Power consumption analysis can be done to check if the calculated power by wattmeter method agrees with manufacturers` specifications. The economic burden calculated as watt hour * $/watt hour will be an important portion of this analysis.

This thesis is an effort to fortify the accurate decision support for MoDOT regarding the prudent choice of manufacturer, complementing the temperature dependency. Along with the extension of 2010 study, the work presented also attains the unresolved issue about performance of red lights and improved the intensity analysis method.

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VITA

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