LED Traffic Signal Lifespan and Replacement Assessment

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William Rasdorf, Ph.D.
Department of Civil, Construction, and
Environmental Engineering
North Carolina State University

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16. Abstract

Recent advances in LED Module technology for traffic signals have created an opportunity for transportation agencies to increase the efficiency and effectiveness of their LED Module and Signal Head replacement operations. However, as the warranty period for new LED Modules has dramatically increased, from 5-years to 15, there are few new modules in the field from which to collect data related to service life. This research aims to identify a set of potential replacement strategies which may be implemented in the future utilizing new technology. To evaluate the alternative strategies, qualitative and quantitative research methods were utilized to estimate future needs based on current practices and available data.

A novel simulation was developed utilizing data from informational interviews with NCDOT personnel and manufacturer representatives, as well as results of data analysis performed on NCDOT's current signal tracking database, the Division Traffic System (DTS). Monte Carlo methods combined with object-oriented programming were used to create a simulation which provides estimates of cost and labor hour requirements for various replacement strategies. Throughout this research, current practices of NCDOT were accounted for when considering potential solutions for the future.

Findings from the study have been compiled in the form of a discussion of the advantages and disadvantages of each of the presented replacement strategies. The researchers recognize that there is not a one-size-fits-all solution and therefore have made a strategy recommendation while acknowledging the positives and negatives associated with each alternative. Ultimately, NCDOT, or each of the 14 Divisions, can select the replacement strategy most suitable for use among the landscape of their current budgetary, personnel, and policy needs.

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  - Chris Stewart
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  - Mark Aldridge
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  - John Couch
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- Division 13
  - Tyler Nix
  - Randy Ray
  - Steven Wyatt

Manufacturers:

- Dialight
  - John Castner
  - Toni Smith
- Leotek
  - Thor Scordelis
  - Eric Zhao

Other Steering Committee Members:

- Auref Aslami
- Kevin Lacy
- Neil Mastin
- Meredith McDiarmid
- Lisa Penny
- John Stephenson

Executive Summary

LED Module technology has advanced considerably since it originated in the late 2000s. Most recently, the product warranty period for LED Modules has tripled, increasing from 5-years to 15-years as of 2022. With this advancement in technology, it is important to understand how management and operations of traffic signals should be updated. As good stewards of their resources, NCDOT and a research team from NC State set out to determine what replacement strategies are available, and which ones may be best suited for implementation.

This report will expand on the work completed by the research team as they reviewed current literature, documented current practices (including data and interviews), developed a simulation, and compared various replacement alternatives.

Due to the recent nature of the warranty increase, the literature found on the topics of LED Traffic Module lifespan and replacement practices was determined to be out of date. It focused on modules with a 5-year warranty and was largely conducted a decade ago. However, important lessons can be taken from the literature that was reviewed:

- LED Modules have a lifespan in the field that exceeds their warrantied life. (True lifespan of the new 15-year warrantied LED Modules will need to be determined by additional research in the future).
- Many transportation agencies do not have standardized practices for replacement of LED Modules and/or Signal Heads.
- Needs based budgeting can ensure that agencies are providing the necessary resources to their personnel for accomplishing operations and maintenance tasks in a timely and safe manner.

Current practices for NCDOT were then documented via a combination of informational interviews and analysis of available quantitative data. Interviews were conducted with NCDOT personnel at many stages within the Traffic Signal management process – from technicians regularly in the field, to Division engineers and employees at the central office. The traffic signal management database (DTS) and appropriate GIS data were made available by NCDOT, along with inventory and purchasing data from the central warehouse. The research team was able to able to meet with LED Module manufacturers to discuss expected lifespan and failure rates.

Insights gained from these interviews, in conjunction with findings from data analysis indicated that an ideal operational mode for NCDOT was to replace each of the LED Modules in place once they reach 5 years of age (with the use of 5-year modules, prior to the introduction of 15-year modules). This is not possible in all Division across the state due to lack of available personnel or funding. Therefore, some combination of blanket and spot replacement has been taking place.

Looking forward, an opportunity has arisen for NCDOT to implement a new set of standard practices which take advantage of the new 15-year warrantied lifespan of LED Modules. A set of 9 alternative module and signal head replacement scenarios were developed. These alternatives are comprised of various replacement combinations: independent replacement (only LED Modules included in blanket replacement) or joint replacement (both LED Modules and Signal Heads included in blanket replacement). Alternatives also examined various replacement periods (the time of active blanket replacement). There is one scenario which does not utilize blanket replacement, while the remainder incorporate a one-year, five-year, or fifteen-year replacement period.

It was necessary to develop a simulation to observe the impact that each of the alternative replacement scenarios may have on the cost and labor required for its implementation. The simulation presented in this

report is a novel simulation developed specifically for the purpose of estimating the various costs and labor requirements of replacement scenarios over time. Monte Carlo methods were utilized, along with input parameters based on manufacturer information and NCDOT data. Results from running each of the replacement alternatives in the simulation were then compared to determine the benefits and drawbacks of each and to assess which of the alternatives may provide the most benefit to NCDOT.

The results indicate that as the blanket replacement period shortened, the overall costs for replacement were found to decrease. This can be attributed to a lower number of spot replacements required among the LED Modules which are currently in the field. Overall, joint replacement alternatives were slightly more costly than independent alternatives. Upon simulation of each of the alternatives, the recommended alternative for NCDOT moving forward is the one-year period, independent replacement alternative. This alternative resulted in low overall replacement costs and a low amount of NCDOT labor hours required for implementation, freeing up both financial and personnel resources for other uses during the remainder of the replacement cycle. Even more importantly this alterative gets all the work done very quickly. Ultimately, the recommendation resulting from this research is that NCDOT identify a replacement alternative which they find to be most beneficial, implement it, and track the impact that it has on traffic signal replacement operations over time. Doing so establishes NCDOT as a leader in traffic signal safety and management.

This work is important because, in this time of ever improving technology, it is critical that transportation agencies act as good stewards of the resources provided to them, minimizing waste, and making impactful investments. In developing a simulation to test various LED Module replacement scenarios, this work provides transportation agencies with the information needed to make decisions about future replacement policies. Their operations and management practices and policies can be made more efficient as new technologies arise. However, implementing positive change requires taking the time to understand how to appropriately move forward. The work completed here provides a valuable tool to aid that process.

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1.0 Introduction

1.1 Narrative Synopsis

1.1.1 Origins

North Carolina Department of Transportation (NCDOT) began replacing incandescent traffic signal modules with LED Modules in about 2010. The impetus for this study were the questions, "How long do these new LED Modules really last, when should they be replaced, and what will that cost?" These questions arose in May of 2019 and initiated a preliminary study that resulted in a proposal to the NCDOT research office that was submitted in September of 2019 and approve in May of 2020. However, the COVID pandemic delayed the project start to January of 2021 and delayed project progress by a full year such that the project was not complete until the end of December 2023.

Prior to the beginning of the project, the product warranty on all LED Modules was 5 years. NCDOT adopted this warranty as a reasonable estimate of the lifespan of the modules. As a result, a replacement schedule for LED Modules was initiated based on a 5-year cycle. Interestingly, between the time of the initial questions that precipitated this study and its initiation, manufacturers extended their LED Module product warranties to 15 years. In the authors' experience this was a rather revolutionary change.

One of the initial goals of this study was to determine the true lifespan of the 5-year LED Modules, in common use at that time, to see how long those modules lasted in the field. The hope was to use this data to extend the length of the replacement cycle thereby reducing labor needs and costs. But the need to assess 5-year module lifespan was eliminated by the emergence of the new 15-year modules which were reasonably priced and lasted longer. NCDOT purchases recently switched entirely to 15-year modules.

These developments, prompted by significant LED technological improvements, changed the nature of the research study. Because of the long lifespan of the new LED Modules, it was no longer necessary to focus on lifespan. Although, based on the authors' prior and current research we believe the new Modules are likely to last up to between 18 and 20 years. However, with few to no new 15-year LED Modules in the field, it is not possible to conduct a field-study to verify that prediction. As a result, the research team assumed and adopted a 15-year lifespan for the LED Modules.

During the study of LED Modules, the question arose of how long the Signal Heads (in which the modules are embedded) would last. Our interaction with NCDOT personnel in coastal divisions revealed significant deterioration of heads in some locations and this observation prompted the question. We were able to find no prior research or literature to answer it. Further interaction with NCDOT personnel yielded a 30-year lifespan based on their experience, which we used in our model.

At this point the original research goal of answering the question "how long do the new LED Modules last, when should they be replaced, and what would that cost?" evolved to "How should the new Modules and Signal Heads be replaced and what would that cost?" assuming 15 and 30-year lifespans for the modules and heads, respectively.

1.1.2 Replacement Strategies

To understand and document NCDOT's current replacement strategy, the research team consulted with NCDOT personnel and studied field practices and procedures. Strategies for replacement differ across the state, as each Division is dealing with their own combination of limitations related to budget and available personnel. However, largely the Divisions are utilizing a spot-only replacement strategy in which LED Modules are replaced once they go dark or are noticeably dim. Those Divisions who have been able to provide their Signals teams with sufficient fundings have continued blanket replacements on a 5-year cycle.

To compare replacement strategies for the future, a variety of replacement combinations and expected replacement periods was used. There are two replacement combinations: Independent, meaning that only the LED Modules are included in the blanket replacement, Signal Heads are spot replaced upon failure; and Joint, meaning that the LED Modules and Signal Heads are replaced together during blanket replacement. The three replacement periods include, 15 years, 5 years, and 1 year. The replacement period is the time during which active blanket replacement is occurring. The replacement cycle for each strategy considered is 15 years, or the expected time for an LED Module to meet ITE standards in the field (based on warranty length). Additionally, a replacement strategy of continuing spot replacements only has been considered.

A one-year replacement period is simple, fast, and will completely replace all LED Module (possibly Signal Heads) within year. It will require significant up-front funds, however, a one-year replacement will also free up NCDOT personnel for the remaining 14 years of the cycle to complete other critical work. The 5-year replacement period mimics NCDOT's current field replacement schedule. The pattern is familiar and may result in a normalcy of operations. A 15-year replacement cycle mimics NCDOT's current field replacement uniformity. This replacement strategy would spread the need for blanket replacements evenly over the entire replacement cycle (15 years).

Each of these strategies has both positive and negative aspects. The 1-year strategy requires a large initial influx of funding. It is likely that bringing in a contractor would be required simply due to the quantity of labor hours required to replace all modules within the state in a one-year period. It would also provide NCDOT with a fresh 'reset' and may simplify the recording of data moving forward. As mentioned above, a one-year replacement period will also free up NCDOT personnel for the following 14 years.

The 5-year strategy yields a high spot replacement cost because the old 5-year modules are already at or beyond their warranty period and spreading replacement over five more years will result in some old 5-year modules being in operation for over a decade. Many of them will fail, causing high spot replacement rates over the initial five-year period of replacement work. This is further complicated by the fact that the spot replaced Modules will be replaced with new 15-year Modules. If this is done before the intersection in question is subject to blanket replacement, care will need to be taken not to replace the new Modules, which could now be anywhere from 1 to 5 years old, again. Using a five-year replacement period will free up NCDOT personnel for the following 10 years of the replacement cycle.

To avoid replacement of already replaced modules will require the establishment of a way to track replacements. The simplest way to do so will be to place a date stamp on the Signal Head signifying the date of replacement of the head and of the modules. Alternatively, a database could be developed documenting the replacements or could be combined with one of NCDOT's existing databases. In either case, paper replacement record keeping is imperative.

The 15-year replacement strategy results in high spot replacement costs. In this scenario, some existing 5-year Modules may not be replaced until year 15, resulting in their being at least 20 years old. More likely, they would have already been spot replaced with a new 15-year module well before the blanket replacement cycle even gets to them. Thus, this 15-year blanket replacement strategy will encounter far more modules that have already been replaced necessitating clear markings and/or record keeping to ensure that already replaced 15-year modules are not replaced again. This 15-year replacement strategy will also require careful record keeping of the sequency of areas replaced and that sequency must be maintained over the second and future replacement cycles.

Utilizing spot only replacement results in low overall costs. When only spot replacement is considered, there is no uniformity or consistency that develops over time meaning that the cost per year is different for each of the 30 years observed. Variable costs are more difficult to plan for, in terms of both budget and labor, than consistent costs. The spot only strategy is dependent only upon the Module and Signal Head lifespans and failure rates provided. This means any updates to those values, based on newly acquired data, may drastically alter the cost estimates found. Additionally, due to the way LED Modules degrade over time rather than going dark at the end of their useful period, without proper training of NCDOT personnel, there is the risk that many LED Modules will remain in the field which have fallen below Institute for Transportation Engineer's (ITE) required illuminance minimums.

1.1.3 Caveat

This research study models a 30-year replacement timeframe. The authors believe that it is impractical to consider further analysis, and possibly not even a second 15-year cycle, due to the high likelihood of further technological advances in lighting. The authors' recommendation is for NCDOT to select a replacement strategy now, carry it out, live through a single total replacement cycle, assess module deterioration, maintain detailed records of replacement locations and dates, and make a new strategic decision 15 to 20 years from now on how to proceed further at that time given new technology, further experience with field practices and procedures, and any changes that have occurred in funding.

1.2 Background

The North Carolina Department of Transportation (NCDOT) is responsible for the installation, inspection, repair, and replacement of traffic signals across the state. As of 2022, an estimated inventory included 155,000 LED Modules, in 43,500 Signal Heads, covering 8,200 intersections per the Division Traffic System, provided by NCDOT.

1.2.1 Specification History

In 1982, the Institute of Transportation Engineers (ITE) published a Manual of Traffic Signal Design. This manual dictated the visibility requirements (as a measure of distance) for traffic signals. (Institute of Transportation Engineers 1982) An announcement was published in 1998 indicating that initial studies into LED Traffic Signals were taking place and an interim purchasing specification was published to accommodate these advancements. ("Interim LED Signal Head Specification Adopted" 1998) With the completion of further research into the use of LED bulbs in traffic signals, two specifications were issued by ITE with the intent of updating performance requirements. These specifications are *Vehicle Traffic Control Signal Heads – Light Emitting Diode (LED) Circular Signal Supplement*, and *Vehicle Traffic Control Signal Heads – Light Emitting Diode (LED) Vehicle Arrow Traffic Signal Supplement*, published in 2005 and 2007 respectively. Both the Circular and Arrow supplements provide information about the physical and mechanical requirements of LED signals.

ITE has specified the luminous intensity, uniformity, and distribution of the modules. (Joint Industry and Traffic Engineering Council Committee 2005; LED Committee of the Traffic Engineering Council 2007) ITE requires that the modules meet these minimum standards for 60 months, or five years. Equations are provided to ensure consistent test measurements of luminous intensity. Minimum acceptable luminous intensity values are also provided. While these specifications provide ample information regarding the performance requirements of LED traffic signals, they do not address methods for field tracking of signal degradation, nor do they address methods for systematic replacement of modules as they age past five years.

1.2.2 NCDOT Context

LED Module and Signal Head inventory for NCDOT are maintained by the purchasing office. Orders are placed with approved vendors and deliveries are made to the central warehouse (also known as the Depot). Upon request by the Divisions, materials are transported from storage at the NCDOT Depot across the state to the Divisions to be stored locally.

Current policy at NCDOT is to replace LED Modules every five years, coinciding with the material warranty and ITE standards. Damage to modules is rare, but can occur – modules can catastrophically fail, become visibly dim, flicker, exhibit intermittent bright flashes, or other behaviors that cause them to need replacement. Poles can be damaged by a crash, lights can be turned, and the ground loops can fail. Signal Heads and Modules can be damaged by lightning. Wind and salt can also pose significant problems for Signal Heads.

Material cost is not typically an issue with respect to replacement for LED Modules (with new 15-year-warrantied modules averaging around $35 USD per unit), labor, cost, and safety are the main concerns. Replacement can require lane closure and special equipment. There are few differences with regard to replacement between primary and secondary roads or rural versus urban locales, other than traffic volumes and the quantity of Signal Heads and Modules at each intersection. Equipment, personnel, and overall replacement procedures remain the same. With respect to region, Signal Heads and Modules are exposed to wide temperature variation in the mountains, hurricane level winds on the coast, and salt exposure in both areas (related to snow and ice prevention in the mountains and sea-air on the coast).

1.2.3 Definitions

Though drivers utilize traffic signals every day, to provide clarification throughout this research, a list of definitions has been provided below to explain and distinguish between technical terms in the work. Also identified are other commonly used terms that are intended to have the same meaning. We are standardizing terminology to simplify, clarify, and enhance understanding.

Chromaticity: an objective specification of the quality of a color regardless of its luminance.

Illuminance: the amount of light incident on (striking) a surface; measurements expressed in foot-candles, or lux; 1fc = 1lm/ft^2; lux is the SI unit, 1fc = 10.764 lx or 1 lx = 0.0929 fc.

LED: a light-emitting diode (a semiconductor diode which glows when a voltage is applied).

LED Package: a plastic casing that carries an LED chip and phosphor. The LED chip is the semiconductor material that emits light (blue light) and the phosphor material converts some of this light into green and red wavelengths.

Luminance: the amount of light leaving an object; the reflected illuminance; can be expressed as candelas per unit area or lumens per unit area; candela per square meter (cd/m^2).

Luminous Flux: the measure of the perceived power of light expressed in lumens (lm).

Luminous Intensity: the power emitted by a light source in a particular direction; candela (cd) is the SI unit of luminous intensity.

Module: the individual unit within a traffic signal which houses the LEDs. The most typical three modules in a traffic signal are one red, one yellow, and one green. *Other terms identified: signal, indicator*

Signal Head: the casing which contains and protects the modules which make up a traffic signal. *Other terms identified: signal, traffic light*

Traffic Signal: a set of automatically operated colored lights, typically red, yellows, and green, for controlling traffic at road junctions and crosswalks. *Other terms identified: signal, intersection, indicator, traffic light*

Figure 1.1 visually identifies the parts of a traffic signal as described in the definitions, it specifically distinguishes between an intersection, a Traffic Signal, the Signal Head, and the three Modules shown. A three-section signal is shown, identifying the signal head as separate from the individual modules it contains.

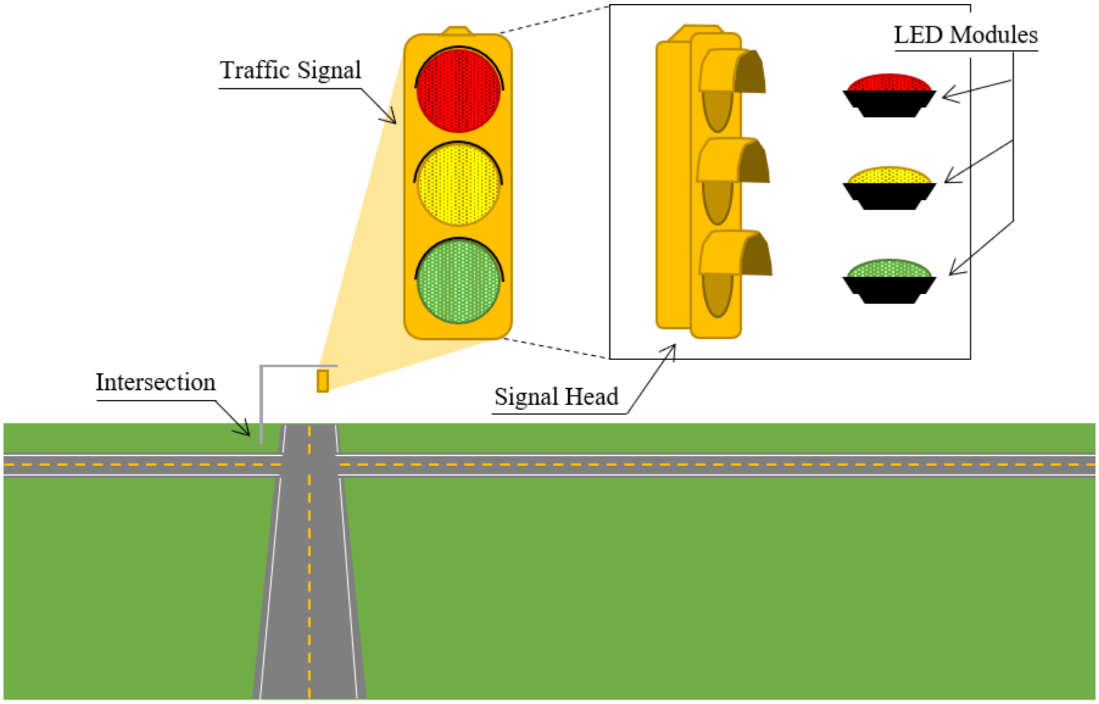


Figure 1.1 Diagram Identifying Signal Components

1.2.4 Importance of Maintaining LED Traffic Signals

Traffic signals are an important feature of any traffic system. Drivers utilize them for safe traveling, while traffic engineers and transportation planners count on them for management of traffic flow and congestion. ITE standards specify that modules meet their minimum standards for maintained luminous intensity for 60 months [five years] (Joint Industry and Traffic Engineering Council Committee 2005; LED Committee of the Traffic Engineering Council 2007). An example of this standard is shown in Table 1.1. Note that both a vertical and horizontal viewing angle are specified for each of the values shown. Provided angles are the degrees above and below the horizontal plane from which the luminous intensity measurement is taken. These standards are intended to ensure clear visibility of LED Modules to drivers interacting with them on the road. When these minimum values are no longer met, the intent is for the LED Module to be replaced.

While these specifications provide ample information regarding the performance requirements of LED Modules, they do not specific strategies for inspections, repair, or replacement of said modules. Thus, transportation agencies are tasked with developing LED Module and Signal Head installation, inspection, repair, and replacement strategies that best fit their resources and needs while complying with ITE requirements.

Table 1.1 Minimum Maintained Luminous Intensity Values
VTCSH LED Circular Signal (excerpt)

Vertical Angle	Horizontal Angle	Luminous Intensity (candela)					
		200 mm (8-in) Diameter			300 mm (12-in) Diameter		
		Red	Yellow	Green	Red	Yellow	Green
+12.5	2.5	17	41	22	37	91	48
	7.5	13	33	17	29	73	38
-7.5	2.5	127	316	166	281	701	366
	7.5	106	262	138	234	582	304
	12.5	71	176	92	157	391	204
	17.5	41	103	54	91	228	119
	22.5	21	53	28	47	118	62
	27.5	12	29	15	26	64	33

1.3 Problem Statement

Though the use of LEDs in traffic signals is now standard practice across the United States, there are, to date, no official guidelines regarding the systematic replacement of these Modules and the Signal Heads that house them. As a result, users cannot know whether the timeline that they are using for replacement is optimizing the use of new longer-lasting modules. As of 2020, LED Module manufacturers have released an upgraded LED Module with a warranty life of fifteen years. There are also no official guidelines outlining optimal transition procedures from five-year modules to fifteen-year modules. One of the key goals of this research is to fill in this missing knowledge gap by providing such guidelines.

1.4 Objective

The objective of this research is to determine a set of possible LED Module and Signal Head replacement strategies for NCDOT to implement across divisions, optimizing manpower, budget, and the lifespan of the LED Modules and Signal Heads.

NCDOT had a need to assess and determine LED Module lifespan and to define a potential set of systematic and cost-effective LED Module and Signal Head replacement strategies. The presented set of strategies was determined by a thorough analysis of possible replacement periods, their estimated costs, and potential for waste. Because many past LED Module-lifespan models are becoming outdated, and replacement models specific to this asset have not been developed, a novel simulation that related manufacturer warranty and the cost of labor and equipment was required. Running a variety of replacement strategies through the model assisted in determining a subset of the more effective LED Module and Signal Head replacement strategies. This subset of strategies can be considered for adoption by NCDOT in the future.

The first goal of this research was to analyze available data to determine a clear picture of current practices implemented across the state of North Carolina. This included benchmarking costs, module lifespan, inspection rates, and other variables to fully understand and clearly explain the replacement process currently used across the state.

The second goal was to determine a set of effective LED Module and Signal Head replacement strategies, or to identify replacement strategy enhancements suitable to NCDOT that efficiently balance costs and aid planners in deciding which signals will be replaced and when. Various strategy options were defined. Each alternative was simulated over a timespan of thirty years. Costs and labor hours were determined for both in-house NCDOT work as well as contracted work. The outputs were compared across alternatives, identifying the advantages and disadvantages of each.

A third goal of this research was to develop recommendations for future data collection. These recommendations will touch on the types of data recorded, as well as their frequency.

This study will answer the questions:

1. What are available, effective methods for the transition from five-year warrantied modules to fifteen-year warrantied modules, which minimize waste and maximize resources?
2. Once the transition period is complete, what is the most suitable replacement strategy for prioritizing available resources while maintaining field safety?

1.5 Scope

The scope of this project included the analysis of available literature, determination of LED Module lifespan, documentation of the inspection, repair, and replacement practices currently operating within NCDOT, and suggested methods for moving forward with the most effective, cost-saving, and efficient replacement practices available. These methods were based on analysis of available data as well as statistical modeling.

The scope of this project did not include any long-term experimentation with LEDs or Signal Heads, and is not presently intended to provide field data related to the state of the LED Modules themselves.

The completed research includes:

1. An assessment of different LED Module and Signal Head replacement strategies to be adopted by NCDOT Divisions to manage LED Modules and Signal Heads within their purview,
2. Development and use of a Monte Carlo simulation model in predicting future LED Module and Signal Head replacement needs. This includes an estimation of budgets based on LED Module warranty life, LED Module and Signal Head replacement rates, and operating costs.

These estimates will then be used by NCDOT to improve costs efficiency and facilitate more informed LED traffic signal management decisions for maintaining the required level of LED Module condition and performance. The completed research included the following steps:

1. **Conduct a Literature Review**

The first step in this research project was to identify relevant technical reports, journal articles, manufacturer data and specifications, warranties, etc. on previous LED Module and Signal Head degradation and lifespan. This provided a review of the progress previously made by researchers and state DOTs. See Chapter 2.0 for detailed discussion of the Literature Review.

2. **Acquire Traffic Signal Field Performance and Cost Data**

Available LED Module and Signal Head data was acquired from a variety of sources, including those mentioned in the following list.

- Manufacturer Product Specifications
- Literature Results
- NCDOT Databases
    - Division Traffic System (DTS)
    - GIS (Geographic Information System)
- Purchasing and Distribution Records

Meetings were held with NCDOT engineers, technicians, and other related personnel to ensure that the data acquired represented their experiences in the field. Data acquired during this phase of the project was utilized to determine:

- LED Module and Signal Head replacement sequence
- LED Module replacement rate
- LED Module and Signal Head replacement costs

For additional discussion of the data acquired and used throughout this research, see Chapter 3.0 Data Sources.

3. Document Current NCDOT Signal Practices

This research has identified variances among NCDOT's current replacement strategies. Working with the ITS and Signals Management Section of NCDOT, selected NCDOT Divisions, and other NCDOT personnel, the current LED Module and Signal Head replacement strategy has been understood. This is the result of informational interviews and ride-a-longs with the above-mentioned personnel. See Chapter 4.0 for detailed discussion of Current Practices.

4. Identify Realistic Strategy Alternatives

A set of replacement strategy alternatives was identified. Using each of these replacement strategies to run the simulation allows for determination of effective methods. Careful consideration has been given to NCDOT field practices and procedures. All strategy alternatives have been built from current practices so that all alternatives can be fully implemented. For a detailed discussion of the alternatives see Chapter 5.0 Development of Replacement Strategy Alternatives.

5. Develop LED Module and Signal Head Replacement Model

One of the objectives of this research was to "determine a set of effective LED Module and Signal Head replacement strategies, or to identify replacement strategy enhancements suitable to NCDOT that efficiently balance costs and aid planners in deciding which signals will be replaced and when." A Monte Carlo simulation was developed for this purpose. The model provides estimates related to quantity of materials, cost of both materials and labor, and labor hours for each replacement activity. The results of the simulation have been used to compare LED Module and Signal Heads replacement strategy alternatives, allowing NCDOT to make replacement strategy decisions. Additional discussion of the simulation structure, inputs, and outputs can be found in Chapter 6.0 Development of Model.

6. Discuss, Benchmark, and Assess Model's Validity

Simulation validity was developed throughout the research process by maintaining contact with NCDOT personnel, subject experts, and the use of sound statistical practices in model development. A sensitivity analysis was conducted to provide insight into the factors most strongly influencing the model. See Chapter 7.0 Validation for further discussion of model validity.

7. Compare Strategy Alternatives Using Simulation

Output from the simulation for each strategy alternative can be found in Chapter 8.0 Results. These results allowed the research team to compare alternative strategies based on estimated cost (annual and overall) as well as the quantity of labor hours required for each. See Section 9.1 Conclusions for detailed comparison. Section 9.2 Recommendations, contains the authors' recommendation for strategy selection, along with recommendations for future work, data collection, and data management.

8. Results, Presentation, and Project Reporting

Throughout this project, detailed and comprehensive quarterly reports were provided on a timely basis. The final report and presentation will be the end of a series of meetings with the steering committee. Regular interim meetings were held for the duration of the project to obtain NCDOT feedback and guidance, also to provide NCDOT with a clear understanding of our objectives, goals, and plans. NCDOT will be provided with copies of any publications that are produced related to this work.

2.0 Literature Review

The first step in this research project was examination of the current literature. To what extent has similar work been attempted and what progress was made by previous researchers and other DOTs? The literature review is organized by topics that are relevant to the present work: LED Module degradation, existing degradation models, LED Signal operations (i.e., inspections, repair, and replacement procedures), budgeting, future directions for this research, and finally, a meta-analysis of the available literature.

2.1 Degradation

2.1.1 LED Module Degradation

Though catastrophic failure is not the typical failure mode for LEDs, it can occasionally occur. This is the subject of Bullough, 2009, which determined that the most common modes of catastrophic failure in LEDs will be: (a) failure of the startup ("boot strap") circuit in the driver integrated circuit (IC), (b) head produced by a power resistor degrading adjacent LEDs, (c) failure of a Schottky diode, and a category listed as (d) "general LED failure." (Bullough et al. 2009)

Specified in the most recent ITE standards, the current method for determining end of life of an LED Module is the point in time at which the illuminance drops below acceptable standards. Table 2.1 shows the average lifespan of various LED Module types (with a five-year warranty) based on the estimates provided in literature. Dialight and GE were the most studied module manufacturers and therefore that data has been disaggregated. The Overall average lifespan was developed to include the estimates not tied to a specific manufacturer. The spaces labeled N/A indicate that not enough data was provided in the literature for a lifespan estimate to be developed. The estimates used to develop this table were based on degradation rates. LED degradation rates are based on rates of illuminance loss.

Table 2.1 Average Lifespan of an LED Module – from Literature

Manufacturer	Circular Green	Circular Yellow	Circular Red	Arrow Green	Arrow Yellow	Arrow Red
Dialight	8.2	N/A	8.1	10.7	6.4	N/A
GE	5.2	0.4	7.0	7.7	7.2	N/A
Overall*	6.2	4.9	7.6	8.0	6.8	N/A
* the Overall Average incorporates values which were not attributed to a specific manufacturer						

2.1.2 Models from Literature

One 2005 survey by the State of California Energy Commission reported that the estimated age of replacement for their LED Modules ranges from 4.5 to 5 years (Bronson 2005). The remainder of the studies found related to LED Module degradation provide lifespan estimates based on quantitative degradation rates. These studies cover Washington, D.C. and the state of Missouri. Publication dates range from 2011 to 2014, with no more recent research on the topic available. Listed in Table 2.2 are three examples of LED Module degradation models obtained from relevant literature. The full set of 20 models can be found in Appendix A. Regression models available for each color have been provided. Lifespan estimates are provided by:

- Bronson, 2005
- Arhin, et al., 2011
- Long et al., 2012a
- Long et al., 2012b
- Schmidt et al., 2014

Methods for determining degradation were only provided by Long (all sources), Arhin, and Schmidt. Arhin provides the reader with a rate of degradation and a standard deviation for this parameter estimate, however that resource does not provide a model complete with coefficients. Arhin did include the raw data used in the analysis as an appendix of the resource (Arhin et al. 2011). Long and Schmidt provide complete models, the units used in these models vary, but can be converted for ease of comparison. These papers do not provide the raw data used to develop the regression models. (Long et al. 2012a; b; Schmidt et al. 2014).

Table 2.2 identifies each model by a Model ID, then provides a color code, the manufacturer, the literature source of the model, the DOT or company that provided the data, the year of the publication, the quantity of intersections studied, the sample size of the study, the collection method, the degradation as a regression model, the units of the model, and whether the model was used to estimate lifespan (these final estimates provided in Table 2.1).

Color codes used in Table 2.2, and Appendix A: LED Degradation Models Available in Literature, include the following:

- GC – Green Circle
- GA – Green Arrow
- RC – Red Circle
- YC – Yellow Circle
- YA – Yellow Arrow

These regression models show that determination of lifespan is possible with field-collected data. However, due to the timing of this research, new 15-year LED Modules have not been in the field long enough to collect sufficient data. Continued work in this area is suggested if the true lifespan of the 15-year warrantied LED Modules is to be determined.

Table 2.2 LED Degradation Models Available in Literature

Model ID	Color	Brand	Source ID	Data Source	Data Year	Intersections Studied	(n) for total project	Collection Method	Regression Model	Units	Used for Lifespan Estimation?
1	GC	GE	Schmidt, Long 2011	MoDOT	2009	20	328	Collect illuminance intensity from a research vehicle	$y = -28.139x + 386.6$	Age vs Candelas	Yes
2	GC	Dialight	Schmidt, Long 2011	MoDOT	2009	20	328	Collect illuminance intensity from a research vehicle	$y = -32.415x + 531.07$	Age vs Candelas	Yes
3	GA	GE	Schmidt, Long 2011	MoDOT	2009	20	328	Collect illuminance intensity from a research vehicle	$y = -9.8846x + 116.46$	Age vs Candelas	Yes

2.2 LED Traffic Signal Operations

2.2.1 Inspection

By and large the specifics related to LED Signal operations are left for the transportation agencies. The ITE specifications contain requirements for production and testing inspections, however they do not contain guidelines or requirements for the inspection of LED Modules or Signal Heads after installation.

Long, et. al. maintains that "DOTs are still searching for a reliable method to monitor the light output of LEDs which degrade over time." For inspection of the luminance of the Module, typically measurements are taken in a lab setting or in a bucket truck at the signal head in the field. Both methods require that the Module be taken out of service for some period. NYDOT has implemented the use of a portable luminance meter which can be used to take luminance measurements from sidewalks or traffic islands (Long et al. 2012b). Long developed an instrument for measuring luminosity from a vehicle. The instrument developed consisted of a commercial light meter, a custom Fresnel lens, a range finder, and a laser pen. With this device (shown in Figure 2.1), Long was able to conduct the first study measuring the illuminance of the LED Modules from the driver's perspective (Long et al. 2011).

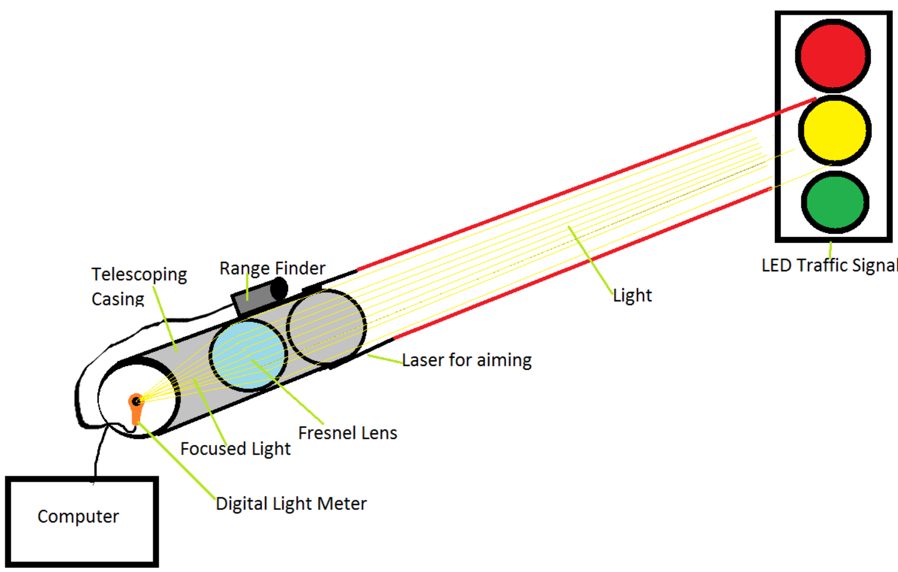


Figure 2.1 Schematic of a Ride-a-Long Illuminance Measuring Device

Due to limitations surrounding the measurement of the illuminance of LED Modules, tracking this data is not part of a typical inspection. Examples of two Traffic Signal Inspection Checklists are provided in Table 2.3. The checklist from Virginia is circa 2009, while the list from Connecticut was more recently published in 2019.

The two inspection lists, developed a full decade apart, consist of mostly the same inspection items. Both lists do include the LED Modules (see task 3), however there is not specific instruction for module data collection. Given that recent research has not provided any updated degradation models, it does not seem that illuminance measurement is a regular part of signal or module inspection. If transportation agencies were maintaining databases full of illuminance measurements over time, the degradation models for the modules could be updated at regular intervals based on this ongoing data collection process.

Table 2.3 Comparison of Traffic Signal Inspection Checklists

Item #	Virginia (2009)	Connecticut (2019)
1	Inspect structures, foundations, mast arms, span (tether wires), and poles	Controller components
2	Inspect control boxes, junction boxes, hand holes, and filters	Cabinet fan and filter
3	Inspect loops, ***signal heads***, pedestrian signals, pole caps, hand-hole covers, and pedestrian buttons	***Vehicular and pedestrian signal heads***
4	Inspect backplates, signal-based signs, and graffiti	Pedestrian push buttons and signs
5	Inspect structure	Signal pole and/or mast arms
6	Check or test conflict monitors, load switches, auxiliary logic	Span wire installations
7	Check or clean cabinet (interior and exterior)	Conduit system and junction boxes
8	Check control box lamps	Cables
9	Check and re-do caulk	Detection systems
10	Check splices	Overhead street name signs
11	Check electromechanical control equipment (dial assemblies, cam assemblies, relays, flashers, disconnect switches, and terminal connections)	UPS (battery backup)
12	Check detectors (sensors, amplifiers, etc.)	Cabinet prints (up to date and in good condition)
13	Preemption test rail crossing (experts will carry out)	
14	Test railroad pedestrian pushbutton devices	
15	Check if all paperwork matches system data	

2.2.2 Repair and Replacement Procedures

This section of the review provides a chronological assessment of the repair and replacement discussions that were found in literature. Publications start in 2007 and end in 2019.

Behura, 2007

A paper by Behura in 2007 provides a succinct summary of the state of traffic module technology and related replacement processes over time (Behura 2007). At this point agencies were beginning to install LED Modules, with little to no experience or guidance to work with. Behura indicates that, based on an ITE survey, a few public transportation agencies at the time had inspection and replacement systems in place for these modules, and even fewer were tracking what could be considered the basic data required to properly maintain these modules. After the Energy Policy Act of 2005, LED Modules were practically required to meet the Energy Star Requirements put in place.

Behura reports on an ITE survey conducted in 2007, showing that a lack of national guidelines on the inspection and replacement of LED Modules and Signal Heads has led to agencies developing or (notably) not developing, their own maintenance systems. This has agencies replacing modules at anywhere from four to ten years based on either the warranty period or the expected lifespan of the module. Behura notes that there was not enough data at the time to know the lifespan of the modules. Often agencies are unequipped to develop a more robust data collection or inspection and replacement plan because of a lack of funding or budgeting for the management of traffic services.

The final recommendation of the paper is to get a data collection, review, and evaluation process in place, and wait to see the results. Because of a lack of current data, agencies cannot know what kinds of adjustments will benefit them when it comes to planning for traffic signal inspection and replacement. Behura concludes by recommending a maintenance program consisting of the following five elements:

1. A good sampling method,
2. Inventory database,
3. Lab Testing Programs,
4. Purchasing of Field-Testing Equipment,
5. Proper Training of Signal Technicians.

Urbanik, 2008

Supplementing the ITE survey data, Urbanik conducted follow up interviews with many of the participants, publishing a paper in 2008 which provided additional details about state DOTs' internal processes (Urbanik 2008). An increase of replacement intervals is discussed in this paper as being inevitable. This being the case due to improvements in LED technology and traffic systems. Once concern voiced by Urbanik is that the resulting increase in time between replacement events will result in a lack of cleaning of the LEDs, in turn leading to a degradation of the light output experienced. Urbanik suggests monitoring the modules for a time to determine whether intermediate cleaning between scheduled preventative maintenance events is required to maintain expected light output levels.

This report does not conclude with an additional set of recommended replacement timelines. Instead, it closes with a list of remaining issues to be addressed along with some ideas for future research.

1. Issues
    a. Definition of a sustainable LED replacement strategy
        i. Determining appropriate replacement schedule
        ii. Determining appropriate funding for replacements
    b. Need for improvement of technical standards
        i. Better failure detection
        ii. Harmonization with related standards
        iii. Ability to further reduce energy consumption
2. Future Research
    a. Detailed studies in LED lifespan and degradation rates
        i. By color, including environments, duty cycles.

Chen, et. al., 2009

In 2009, the Virginia Department of Transportation published a paper in which they outlined the types of data required for development of an LED Signal Maintenance System as well as the maintenance events needed (Chen et al. 2009). Table 2.4 provides the parameters and performance measures which VDOT recommends be collected to take advantage of a cost estimating framework to prepare for inspection, repair, and replacement activities.

Table 2.4 Needs Assessment Parameters and Potential Performance Parameters (Chen et al. 2009)

Needs Assessment Parameters	Symbol	Potential PMs
Preventive maintenance		
Base year PM cost per intersection	P	Share of PM (versus reactive M)
Repair		
Avg. no. of repair trips per year per intersection	#R	Mean time between failures (MTBF)
Avg. minutes spent per repair	RT	
Avg. round trip time in minutes	TT	Mean time to repairs (MTTR)
Avg. no. of signal techs per repair	# Techs	
Avg. tech hourly rate (including benefits)	TechRt	
Avg. no. of bucket trucks per repair	# Trucks	
Avg. truck hourly rate	TruckRt	
Lane closure cost/h	LcC	
Avg. % of repair trips that close lanes	LcR	
Replacement		
#th signal component	*n*	
Replacement cost of component *n*	RPC*n*	
Quantity of component *n*	Q*n*	
Component *n* life expectancy	LE*n*	Component life expectancy (LE*n*)
Remaining service life (LE*n*—years in service)	RLE*n*	Avg. remaining service life (RLE*n*)
Operating needs		
Monthly electric metered cost per intersection	EC	
Avg. monthly phone bill per intersection	PhC	
Private network communications bills	Ntwk	
Annual software licensing fee	SftLcs	
Optimization cost	Opt	
Other cost	Othr	
Additional needs category		
Payment to localities		

VDOT defined operations and maintenance activities in four categories: Preventative Maintenance, Repair, Replacement, and Operating Needs. For each of these areas, the research team determined a set of activities which is regularly carried out by NCDOT districts. These lists of activities can range from containing four items to as many as eighteen. Those items related to inspection can be found in Section 2.2.1. Preventative Maintenance (non-inspection), Repair, and Replacement activities as well as their definitions as defined by VDOT can be found in Table 2.5.

Though not explicitly stated in the report, the implication is that as of 2009, VDOT replaced their signals at the five-year mark. It should be noted that the report does not provide information about the then-used timeline of preventative maintenance, repair, or replacement activities. It also does not provide recommendations for timelines of future activities. Rather, it recommends that these timelines be developed based on analysis of the parameters listed in Table 2.4.

Table 2.5 Repair and Replacement Maintenance Phases Reported for VDOT

Maintenance Phase	Definition	Activities
Preventative Maintenance (PM)	"A set of checks and procedures to be performed at regularly scheduled intervals for the upkeep of traffic signal equipment; it includes inspection *(inspection items shown in section 3.3.1)*, record keeping, cleaning, and replacement based on the function and rated service life of the components."	1. Clean cabinets (interior and exterior) 2. Change control box filters 3. Replace conflict monitors that have up-to-date testing paperwork 4. Replace batteries 5. *fifteen inspection related items
Repair Activities	"Repair, or corrective maintenance, is defined as work required to restore a damaged or deteriorated asset to design, functionality, and capability."	6. Repair equipment malfunction [lamp or lenses burnt out, local controller, master controller, detector sensor, amplifier, conflict monitor, flasher, time switch, load switch and relay, coordination unit, communication (interface, modem), and signal cables] 7. Repair nonswitching signals, repair faulty pedestrian button, replace frayed cables 8. Clean graffiti, fix loose or lost bolts, fix missing covers 9. Repair knockdowns, damage that requires immediate safety-related repair (mast arm, strain pole, span wire or tether, pedestal, cabinet, signal heads)
Replacement Activities	"Replacement maintenance is defined as replacement or complete restoration of assets that cannot be repaired."	1. Replace wiring with mast arms 2. Upgrade detectors 3. Replace lenses 4. Rebuild intersection to bring within life cycle requirements 5. Replace foundations that have met life cycle requirements

Arhin, 2011

A report by Arhin in 2011, the same report providing estimated lifespans in Section 2.1.1, cites two options available to DOTs for the replacement of LEDs – replace individually (spot replacements) as LEDs fall below ITE minimums, or conduct group replacements (blanket replacement) as some signals fall below minimums (resulting in some signals being replaced before their time is up.) The "truly sustainable solution for an agency is to seek to extend the use of an LED past the warranty period as much as possible." However, there are found to be cost benefits to a blanket replacement strategy. Even with the use of blanket replacement, some spot replacement will be required (Arhin et al. 2011).

Long, et. al. Works, 2011 & 2012

In 2011, Missouri S&T's Long developed a replacement plan for LED Modules based on the degradation work conducted at the same time (Long et al. 2011). This plan simply states that MoDOT should replace each of the various modules at the point at which their degradation places them below the ITE threshold. In a 2012 paper, a recommendation is given which takes into consideration the fact that an as-needed individual-module replacement plan is likely not a viable option. That DOTs should conduct a budget analysis to determine what method of replacement will be the most efficient for themselves (Long et al. 2012a). This work fulfills that suggestion, as documented later in the report. Long once again points out that the ITE specifications were developed based on laboratory testing, which ignores the luminosity from the driver's perspective. Their recommended signal database structure is shown at the end of this section in Table 2.6.

NCDOT, 2018

The 2018 NCDOT Maintenance Operations and Performance Analysis Report (MOPAR) provides an update of the maintenance and operations procedures across the state (North Carolina Department of Transportation 2018). Pages relevant to Signal Maintenance show the intended amount of Traffic Signal Maintenance to be 13,406 (unitless) and the accomplished work to be 23,779 (unitless). This indicated a percentage of accomplished work to be 177% for the year 2018. The table provided in the document shows that there is no actual cycle for Traffic Signal Maintenance at the state level, nor at the Division level.

T2 Center, 2019

A brief put out by the University of Connecticut outlines the basic steps required to perform preventative maintenance and record the actions taken (T2 Center 2019). This brief reviews the inspection of all aspects of a traffic signal and provides suggestions as to the types of data to collect throughout the inspection process. These suggestions can be found in Table 2.7 and Table 2.8.

Recommended Database Summary

The development and continued use of a database was recommended throughout the literature. Three of the recommended structures for such a database have been provided as examples in Tables 2.6 to 2.8.

Table 2.6 Recommended Database Structure – Long, 2012

Inter-section	Direction	Signal Head	Indicator (Module)	Manufacturer	Date Manufactured	Date Purchased	Date Installed	Age	Light Intensity Value (cd)

Table 2.7 Recommended Service Request Database Structure – T2 Center, 2019

Caller Name	Caller Contact Information	Date of Complaint	Time of Complaint	Location	Description of Problem	Name of Employee Recording Request

Table 2.8 Recommend Maintenance Database Structure – T2 Center, 2019

Name of Maintainer	Time Dispatched	Time of Arrival on Location	Issues as Identified	Components Replaced	Actions Taken	Time of Issue Resolved

To summarize key topics from the Repair and Replacement literature, Table 2.9 provides the author names, publication year, major topics, and key findings of the most significant repair and replacement resources.

Table 2.9 Repair and Replacement Procedure Literature Summary

Author	Year	Topics	Key Findings
Behura	2007	Maintenance, Record Keeping	Most DOTs are not adequately replacing LED traffic signals – due to a lack of knowledge and a lack of programming.
Urbanik	2008	Control Cabinets, Maintenance, Inspections, Record Keeping, Cost/Funding	Most agencies do not have a systematic method for replacement and maintenance of LED signals.
Chen, et. al.	2009	LED Degradation, Control Cabinet, Cabling, Detectors, Power Source, Maintenance, Inspections, Equipment, Record Keeping, Cost/Funding, DOT Personnel	Highlight the necessity of a dynamic framework for determining needs as priorities and technology changes.
Arhin	2011	LED Degradation, Inspections, Equipment, Record Keeping	LED Lifespan Estimates; also emphasize importance of building accurate database.
Long, et. al.	2011, 2012	Module Type, LED Degradation, Maintenance, Safety, Inspections, Tools, Equipment, Record Keeping, Cost/Funding, DOT Personnel	LED Lifespan Estimates; also emphasize importance of building accurate database.

2.2.3 Budgeting

Although frequently discussed in tandem with replacement processes, the budget for the inspection and replacement of LED Modules and Signal Heads is often determined without reference to the needs of the operating department. This is a trend seen in DOTs across the United States, as indicated by the 2007 ITE Survey mentioned by Behura, Urbanik, and Arhin, "78% of respondents report having inadequate or no funding for monitoring/replacement programs."

Referencing the replacement plan by the Road Commission of Oakland County (ROCO), which Urbanik considers to be a successful practice, it is shown that an option worth evaluating is the slow and steady replacement of modules throughout a system (Urbanik 2008). ROCO planned to establish a 10-year replacement process, in which 10% of the modules are replaced each year. By avoiding a system overhaul and establishing a uniform annual budget, the needs of the ROCO signal department are laid out plainly for decision makers. Using the LED Module's warranty life as the expected life allows the department to establish a worst-case budget. ROCO determined the modules last for 10 years, far beyond the five-year warranty period. If a five-year warranty is used to set the timeline, a replacement of 20% is required – double that of the anticipated 10% expected.

Urbanik recommends, as discussed with ROCO above, that a phased replacement plan is a wise replacement plan from a budgeting perspective as this allows the financial burden to be spread over a long period of time rather than creating the need for an expensive LED replacement project occurring in a year or less across the full area. Also pointed out is that the longer timeline will allow more time in between the cleaning of lenses. Urbanik recommends that there be some monitoring of the state of the LED Modules to ensure that they remain clean throughout their in-place duration.

An NCHRP report from 2009 also concludes that blanket replacement will provide budgetary advantages, so long as certain parameters are met (Bullough et al. 2009). Bullough conducts a Group Replacement Cost

Sensitivity Analysis in which the number of signalized intersections was set to 1,000. For the purposes of this evaluation, group replacement assumes that 10 modules can be replaced during a single trip to an intersection. Basic cost and labor values were set as follows:

- The material cost of an LED signal is assumed to be $75
- During work hours, it is assumed that 15 minutes of travel time to and from the intersection and 5 minutes to set up traffic control is required, per trip to an intersection
- Outside work hours, it is assumed that 30 minutes of travel to and from the intersection and 5 minutes to set up traffic control is required, per trip to an intersection
- Removal and replacement of a single LED Module is assumed to require 9 minutes
- Labor costs for a two-person crew during work hours are $100/hour and outside work hours are $150/hour

The variable in question was the failure rate of the modules. Failure rate was set to be 1) based on an S-curve, 2) 1% of modules, 3) 3% of modules, or 4) 5% of modules. After an analysis to compare spot replacement and blanket replacement of all 1,000 modules based on the cost and labor outlined above, it was found that in 68% of the scenarios, blanket replacement was less expensive than long-term spot-replacement. The remaining 32% of scenarios all involved an expected failure rate of 3% or higher. Note that earlier in the paper Bullough states that based on current (2009) data, an expected failure rate of 2% was considered reasonable. This implies that the likelihood of the 3% and 5% scenarios is smaller than the likelihood of the S-curve and 1% scenarios – indicating that 68% is an underestimate of the portion of instances in which group replacement is more cost effective than long-term spot replacement. This finding reinforces the recommendation of blanket replacement suggested by Urbanik.

2.2.3.1 Virginia Department of Transportation (VDOT)

VDOT has defined their Operations and Maintenance activities into four groups: Preventative Maintenance, Repair, Replacement, and Operating Needs (Chen et al. 2009). VDOT operates on a Needs Based Budgeting System. In order to establish this system, they first needed to establish a method for determining future needs. To do this, a Needs Assessment Process was determined for each of the four groups within Operations and Maintenance. The overall framework for these assessments is shown in Figure 2.2. The chart flows from left to right, indication that the referenced data must be collected prior to any kind of assessment. Note that the data that VDOT indicates here is both quantitative (Inventory, Resource Quantities) and qualitative (Standards, Definitions, etc.). All four Operations and Maintenance groups are represented by four of the five processing blocks shown in the Needs Assessment category on the right.

Highlighted in Figure 2.3 is the specific Needs Assessment Process VDOT developed for Replacement Activities. This process diagrams the logic behind any replacement process, and is similar to the model developed for this project. By utilizing available data, such as the Replacement Rate of a Component, the Replacement Cost, and the overall quantity of components and intersections, the process allows for the estimation of Replacement Needs in the future.

The largest take away from this paper is that for any of these methods to accurately predict budgeting and Traffic Signal replacement needs, there must be a well-maintained database from which to pull data for evaluation. By utilizing the assessment process outlined, the Traffic Systems Operations department can provide accurate estimates of budgetary needs to the larger DOT each year. As further data is collected and these assessments take place year after year, the estimates will become more accurate over time.

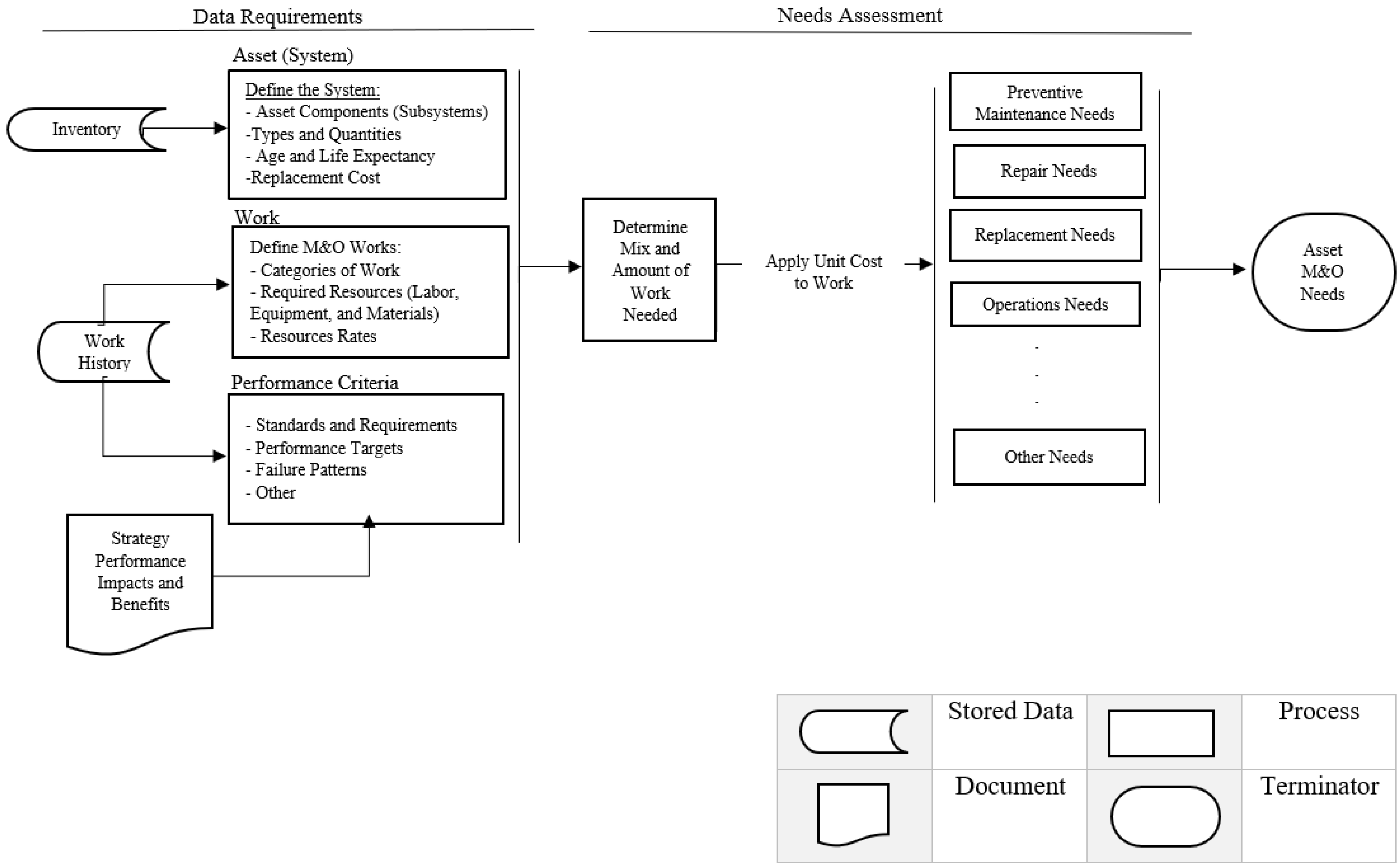
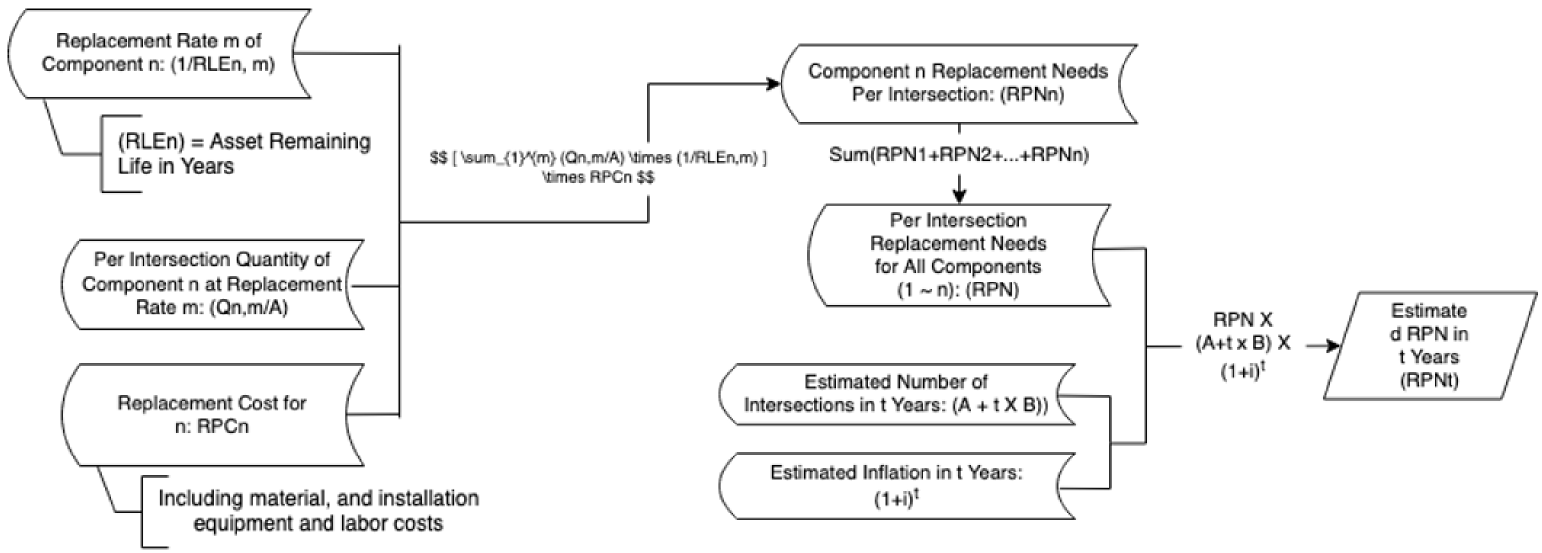


Figure 2.2 VDOT Framework for Signal Operations and Maintenance Needs Assessment (Chen et al. 2009)



Global Parameters	Symbol
# of years in to the needs year	t
# of intersections in the inventory (by system or by country)	A
Annual increase of signalized intersections	B
Annual inflation	i

Replacement Specific Parameters	Symbol
#th signal component	n
Replacement cost of component n	RPCn
Quantity of component n	Qn
Remaining service life of component n	RLEn

Figure 2.3 Replacement Needs Assessment Process (Chen et al. 2009)

2.3 Manufacturer Warranties

As part of the research process, the team was able to meet with two leading LED manufacturers. Leotek and Dialight. Meeting with Leotek reinforced information previously acquired during the literature review. The latest LED modules specifications are the ITE Signal Specifications from 2005 and 2007. However, there have been LED technology improvements since then which allow the module warranty to be extended. The LED module market has recently shifted to providing modules with a fifteen-year warranty. This is triple the warranty of all modules utilized in previous research and is a significant upgrade in LED module quality and performance. Ultimately, the decision to warranty the modules for fifteen years is the result of a combination of business risk evaluation and improvements made to the power supply and wiring of the module. Dialight mentioned in-house testing of the modules as the foundation of their new fifteen-year lifespan.

Though neither manufacturer provided the research team with the raw data they utilized in determining these lifespan estimates, each was willing to share summary information with the research team. Through accelerated testing methods, module manufacturers were able to determine that failure among LED modules follows a Bathtub Curve. Figure 2.4 shows an example of this kind of failure profile. The rate shown at the top is a compilation of the various failure rates found to exist within the body of an LED module. Users should expect that early on there will be a higher rate of failure as those modules which may have subpar wiring or other components will fail quickly. This can be referred to as “Infant Mortality” failure. Towards the other end of the expected life, an increasing quantity of modules will fail. These modules have been in place for some time and such failures can be called “Wear Out” failures. A constant level of random failure also occurs throughout the life of an LED module. Combining these failure rates into one Observed Failure Rate results in the bathtub shaped curve seen at the top of the figure.

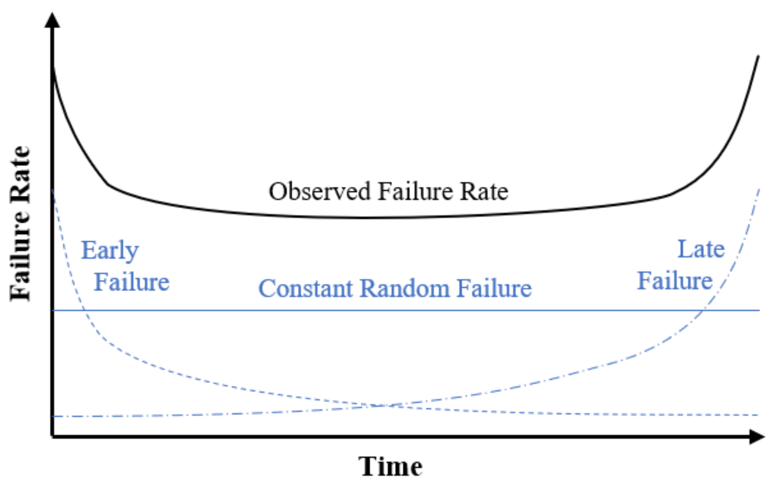


Figure 2.4 Observed Failure Curve

Understanding this failure curve is important for transportation planners. The failure rates provided here can be considered when transportation agencies are allocating labor hours and determining their budget for replacement processes involving LED Modules. Accounting for a reasonable number of spot replacements ensures that agencies will stick enough LED Modules to get them from one blanket replacement period to the next.

2.4 Meta-Analysis of Literature

Additional information on the state of literature on this topic was gathered by performing a meta-analysis of the available, relevant resources. This meta-analysis includes both the time of publication as well as the content published.

2.4.1 <u>Analysis of Publication Timeline</u>

First, analysis of the publication timelines was conducted. Figure 2.5 shows a distribution of all forty of the identified resources according to their year of publication. In any given year, the maximum number of sources published related to Traffic Signal operations was four.

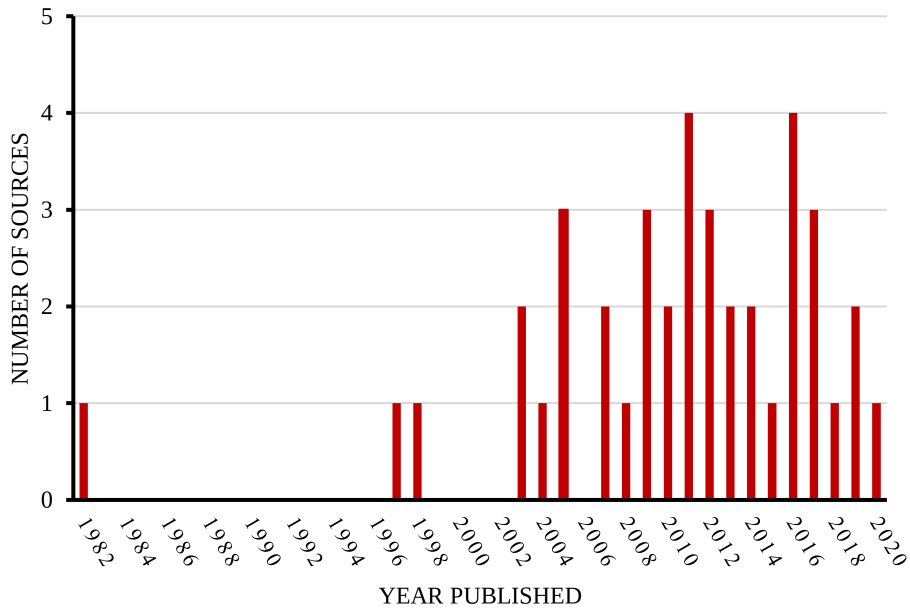


Figure 2.5 Year Published Source Distribution

Figure 2.6 shows all forty of the sources distributed per their relevance to the project. Relevancy scores were assigned by the project team based on the pertinence of the content they contain. A score was given on a scale from 1 to 10, although no resources rated lower than 3 were used for further evaluation. Scores of 8 or higher indicate that the source provides great benefit to the project, 22 of the sources fall into this classification.

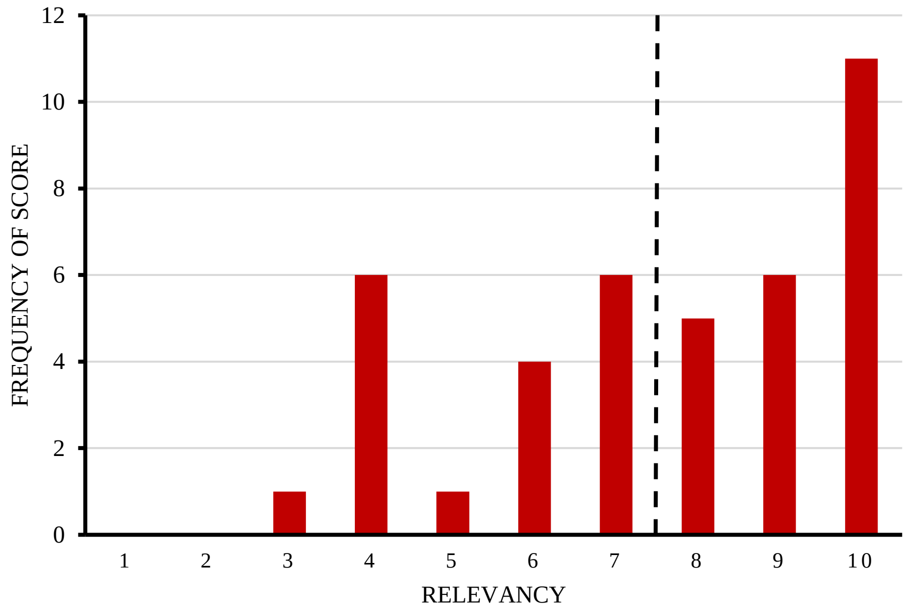


Figure 2.6 Relevancy of Available Literature

Although Figure 2.5 gives the appearance of one peak of publications around 2011 and a second peak around 2016, this is misleading. Further insight is gained by considering Table 2.10, which provides a matrix demonstrating the relevance of literature published in each year. Highlighted portions of the table show that there was a peak in relevant literature between 2009 and 2012. This aligns with an industry response to the supplements released by ITE in 2005 and 2007. The 2016 peak shown in Figure 2.5 is the result of less relevant literature.

The lack of recent literature on these topics was a surprise and led the research team to reach out to other organizations and to the authors of the most relevant documents in search of any publications that may have been overlooked. The research team has made the following contacts in pursuit of further resources.

1. Transportation Research Board Committee on Traffic Control Devices
2. Transportation Research Board Committee on Transportation Asset Management
3. Transportation Research Board Committee on Traffic Signal Systems
4. Dr. Suzanna Long, et. al. (Missouri S&T)
5. Ms. Wenling Chen, et. al. (VDOT)

As of this writing, none of these contacts has been able to direct the NCSU research team towards any previously undiscovered literature on the topic of LED Traffic Signal degradation, lifespan, operations, or replacement.

2.4.2 Analysis of Publication Content

Key topics were determined to aid in the review of literature for this project. Table 2.11 provides the list of key topics and their definitions. These topics were used in the classification and sorting of literature. Note that different names are used to identify the portion of a traffic signal which contains the LED bulbs. This report will use the term *module*. However, other common terms include ‘indicator’ and ‘signal.’ Also note that the term ‘signal’ is frequently used as a blanket term for many signal-system related items: intersections, signal heads, LEDs, individual light poles supporting signal heads, etc.

The top five topics discussed in available literature are:

1. Maintenance (covered in 21 publications)
2. LED Degradation (covered in 17 publications)
3. Record Keeping (covered in 16 publications)
4. Safety (covered in 14 publications)
5. Inspections (covered in 12 publications)

Table 2.10 Relevancy Matrix by Year Published

Year \ Relevance	1	2	3	4	5	6	7	8	9	10	TOTAL
1982								1			1
1997						1					1
1998							1				1
2003				1					1		2
2004							1				1
2005							1		1	1	3
2007									1	1	2
2008										1	1
2009									1	2	3
2010				1						1	2
2011				1		1				2	4
2012						1				2	3
2013				1		1					2
2014			1						1		2
2015										1	1
2016				1			2	1			4
2017				1	1				1		3
2018								1			1
2019								1	1		2
2020								1			1
TOTAL	**0**	**0**	**1**	**6**	**1**	**4**	**6**	**5**	**6**	**11**	**40**

Table 2.11 Key Topics and Definitions

Topic	Definition
Manufacturer	Involves research relating to one specific manufacturer or to a comparison of the performance and systems of various manufacturers.
Future Ideas	Contains ideas and information regarding ongoing research for topics indirectly related to signal maintenance, but that could impact future planning, maintenance, and scheduling.
Materials	Specifically identifies the materials used or will be an examination of said materials.
Timing of Signals	Mentions or includes an analysis of the timing of signals.
LED Degradation	Addresses the degradation causes or rates of LEDs and/or LED signals.
Module Type	Develops conclusions based on the different types of modules available for LED Traffic Signals: Circular Red, Circular Green, Circular Yellow, Red Arrow, Green Arrow, Yellow Arrow.
Control Cabinet	Refers to the electrical components for each signal that control the timing for the illumination of each module within the signal.
Cabling	Refers to the cables connecting the signal hardware to the control cabinet.
Detectors	Discusses the impact that the detectors (used to detect vehicles in various lanes) will have on traffic signal timing or function.
Power Source	Discusses the impact that the power source, its intensity, and its reliability have on the functionality and efficiency of a traffic signal.
Maintenance	Encompasses the overall maintenance of signals - this can include scheduling, required personnel, and training. (There will be some overlap with other key terms.)
Safety	Involves safety in the processes of installing, inspecting, repairing, and maintaining the signals. This can include training, tools, and personnel (There will be some overlap with other key terms.)
Inspections	References inspections. This can be inspections of the signals themselves, inspections of the systems running the signals, and training around inspections (There will be some overlap with other key terms.)
Tools	References required tools for installation, inspection, and maintenance of the physical signals.
Equipment	References required equipment for installation, inspection, maintenance, and replacement of the physical signals.
Training	Includes information about the training of personnel related to maintenance, usage, safety, and signal systems.
Record Keeping	Includes information about the records that are being kept by local governments and transportation professionals.
Cost/Funding	References funding (or lack thereof) for the installation, inspection, maintenance, and replacement of LED Traffic Signals within various DOT or other organizational structures as well as any mention of a cost-benefit analysis for scheduling.
DOT Personnel	Include information about DOT personnel, their numbers, training, abilities, qualifications, etc.

2.5 Conclusions

Below are the conclusions drawn from the literature about the lifespan of modules, the current state of the art practices for LED Modules and Signal Heads, and inspection, repair, and replacement practices. The last subsection addresses potential next steps for this industry based on the literature reviewed.

2.5.1 Module Lifespan

Most of the literature on lifespan is out of date. The papers which do discuss lifespan here are based on analysis of 5-year warrantied modules. As previously mentioned, the market has shifted, manufacturers are now producing modules with 15-year warranties. Thus, regarding the question of lifespan, the literature does not provide the data required to assess the lifespan of current and future modules.

2.5.2 Current State of the Art

Literature indicates the methods used by DOTs for all aspects of signal operations are sound. The next step will be to restructure these methods for the drastically increased lifespan of modern LED modules.

There is clear emphasis on the need for accurate modules databases. These operational databases enable DOTs to fully document their inventory, determine its condition, and evaluate performance. Continued development of such a database will be an ongoing process due to the recent availability of 15-year modules (and the limited field-data currently available from them).

2.5.3 Inspection, Repair, and Replacement

A limited number of papers in the literature review address inspection, repair, and replacement processes for overall signal systems, especially for processes specifically related to LED Modules and Signal Heads. These papers clearly define what the process is and define all components necessary for inspection, repair, and replacement. Thus, inspection, repair, and replacement procedures have been well documented, particularly by VDOT.

It is clear from a budgeting perspective that systematic blanket-replacement is superior to long-term replacement plans only utilizing spot replacement. Blanket replacement was defined as the replacement of multiple modules within an area defined by the DOT on one maintenance trip. Of course, there will still be spot replacement occasionally due to unforeseen events and outages.

A Needs Based Budgeting approach to signal operations is critical. Several sources have indicated that departments are currently working with insufficient funds for this critical transportation asset. By assessing the needs of the traffic departments, DOTs will be better able to ensure that traffic signals are managed in a safe and efficient manner.

2.5.4 Next Steps

Transportation agencies must develop a guideline for future replacement strategies based on the new 15-year warrantied LED Modules. The literature review provides an overview of what has been done to date. However, significant changes will occur in LED Module and Signal Head operations due to the extended performance of new modules. Additional research, such as that presented in this report, is necessary to optimally move forward. LED Module and Signal Head databases will aid in tracking various replacement strategies.

3.0 Data Sources

This section of the report will describe available quantitative data sources that were used throughout the project. These include several sections from the Division Traffic Systems (DTS) database and the NCDOT Geographic Information Systems (GIS) database, as well as evaluation of available LED Module warranty data and Financial Records.

3.1 DTS Database

As interviews were conducted with NCDOT Divisions early in the project, a database, DTS, was mentioned as the source for storing information related to inspection and maintenance of LED modules. Through contact with NCDOT and the North Carolina Department of Information Technology (NCDIT), DTS data was provided to the research team. From the complete database, the team identified the following datasets as being most relevant to the project. These datasets were further analyzed and details related to each set are provided.

1. Events (Table 3.1)
2. LED (Table 3.2)
3. Location (Table 3.3)
4. Signal Head (Table 3.4)

An outline of the data provided in each of the datasets listed is shown in the series of Schema tables below. Each Schema table follows the same formula: Column 1 identifies the variables available in the dataset, Column 2 shows the associated data format, Column 3 shows units associated with the variable (if applicable), and Column 4 shows the definition that the NCSU research team developed based on industry norms and the definitions provided by NCDOT and NCDIT.

Table 3.1 Data Schema – DTS: Events

Variable	Data Format	Units	Working Definition
ID	Numeric	n/a	Action Event identification number.
Signal	Numeric ## - ####	n/a	Intersection identification number. First 2 numbers show the division
Type	Text	n/a	Type of event: emergency, scheduled, preventative, installation, revision
Reported	Date and Time	n/a	Date of event reported.
Arrived	Date and Time	n/a	Date of technician arrival for event.
Completed Date	Date and Time	n/a	Date when event occurred.
Hours Worked	Numeric	Hours	Approximate number of hours worked. (not used as a serious metric).
Comments	Text	n/a	Any additional comments regarding the repair
Action Code	Numeric	n/a	Action number code
Action	Text	n/a	Code Name, as stated in the list of Action Codes provided below.

The Action Codes provided in the Event dataset have been listed below [Action Code: Action]. This list has been shortened to only include those codes relevant to LED Module and Signal Head installation, inspection, repair, and replacement.

Action Codes

1212: Repair/Replace: All Red LED Modules*
1213: Repair/Replace: All Green LED Modules*
1214: Repair/Replace: All Yellow LED Modules*
1215: Repair/Replace: LED Signal Module – Completely Dark*
1216: Repair/Replace: LED Signal Module – Partially Illuminated*
1217: Repair/Replace: LED Signal Module – Normal End-of Life*
1240: Completed: 6-month Operational Performance Review*
1241: Completed: Scheduled Maintenance Checklist*
1242: 12-month Operational Performance Review*
1243: 24-month OPR (heads only)*
1247: Repair/Replace All LEDs*

Table 3.2 Data Schema – DTS: LED

Variable	Data Format	Units	Working Definition
Signal	Numeric ## - ####	n/a	Intersection identification number. First 2 numbers show the division
Quantity	Numeric	n/a	Number of LED Modules at location
Color	Text	n/a	Color of LED Module
Type	Text (#" Shape)	Inches	Size and shape of the LED Modules
Name	Text (intersection Description)	n/a	Name of the cross streets at the location
City	Text	n/a	City where signal is located
County	Text	n/a	County where signal is located
Division	Numeric	n/a	Division number
Latitude	Numeric (-/+ XX.XXXXXX)	n/a	Latitude of the location
Longitude	Numeric (-/+ XX.XXXXXX)	n/a	Longitude of the location
Signal Type	Text	n/a	Type of signal

Table 3.3 Data Schema – DTS: Location

Variable	Data Format	Units	Working Definition
Signal Number	Numeric ## - ####	n/a	Intersection identification number. First 2 numbers show the division
Name	Text (intersection Description)	n/a	Name of the cross streets at the location
City	Text	n/a	City name
County	Text	n/a	County name
Division	Numeric	n/a	Gives division number
Latitude	Numeric (-/+ XX.XXXXXX)	n/a	Latitude of the location
Longitude	Numeric (-/+ XX.XXXXXX)	n/a	Longitude of the location
Signal Type	Text (Signal, Flasher)	n/a	Type of Signal
Sign Mounted	Text	n/a	Tells if mounted on sign
Actuation	Text	n/a	Whether or not timings are determined by timer or sensor
Phases	Numeric	n/a	The number of phases assigned to this signal (timing of traffic flow)
State Owned	Text	n/a	Tells if signal is owned by the state
Rail Preempt	Text	n/a	-
Emergency Preempt	Text	n/a	-
Bridge Preempt	Text	n/a	-
Bus Preempt	Text	n/a	-
Low Priority Preempt	Text	n/a	-
LVOD Preempt	Text	n/a	-
Maintenance Level	Text	n/a	Describes the maintenance agreement (if any) between NCDOT and a municipality.
Comments	Text	n/a	Any additional comments
Signal System	Text	n/a	Which system signal belongs to (seemingly given by Municipality name)
Municipality	Text	n/a	Name of municipality where signal is located
Google Maps URL	Link	n/a	Link to signal on google maps

Table 3.4 Data Schema – DTS: Signal Heads

Variable	Data Format	Units	Working Definition
Signal	Numeric ## - ####	n/a	Intersection identification number. First 2 numbers show the division
Head_A	Numeric #	n/a	The number of heads of this type at the indicated intersection.
Head_G	Numeric #	n/a	The number of heads of this type at the indicated intersection.
Head_H	Numeric #	n/a	The number of heads of this type at the indicated intersection.
Head_I	Numeric #	n/a	The number of heads of this type at the indicated intersection.
Head_J	Numeric #	n/a	The number of heads of this type at the indicated intersection.
Head_K	Numeric #	n/a	The number of heads of this type at the indicated intersection.
Head_L	Numeric #	n/a	The number of heads of this type at the indicated intersection.
Head_M	Numeric #	n/a	The number of heads of this type at the indicated intersection.
Head_N	Numeric #	n/a	The number of heads of this type at the indicated intersection.
Head_O	Numeric #	n/a	The number of heads of this type at the indicated intersection.
Head_P	Numeric #	n/a	The number of heads of this type at the indicated intersection.
Head_Q	Numeric #	n/a	The number of heads of this type at the indicated intersection.
Head_R	Numeric #	n/a	The number of heads of this type at the indicated intersection.
Head_S	Numeric #	n/a	The number of heads of this type at the indicated intersection.
Head_T	Numeric #	n/a	The number of heads of this type at the indicated intersection.
Head_Z	Numeric #	n/a	The number of heads of this type at the indicated intersection.

Figure 3.1 below provides a diagram of each of the Signal Head Types, their size, and configuration, as utilized by NCDOT.

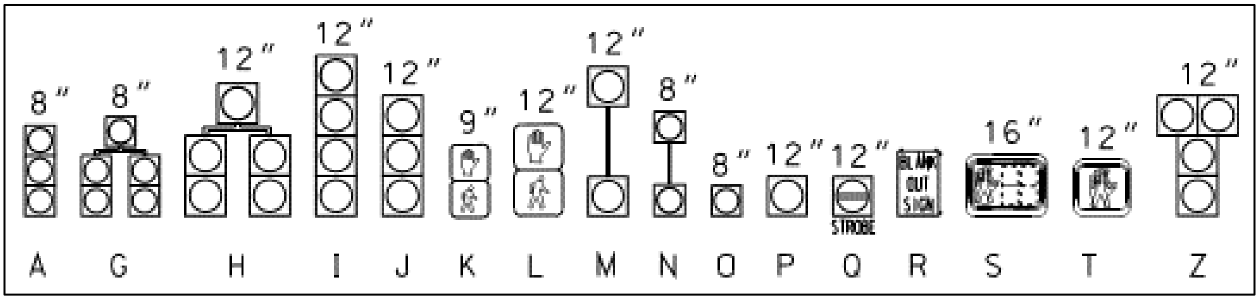


Figure 3.1 Signal Head Diagram

3.2 GIS Database

After a review of the NCDOT GIS database, it was ultimately decided that the DTS database would be the main source of information for this project. There were instances where intersections identified in the DTS database could not be located within the GIS database and vice versa. The GIS database also does not contain the depth of data found in the DTS database. Specifically, it does not track Events (inspection and replacement activities) or quantities of LED Modules or Signal Heads at each intersection. However, all of the information present in the GIS database was also present in the DTS database (intersection locations, state vs municipally owned, signal system, etc.).

3.3 LED Module Product Data

This section has been split between data collection and data evaluation. Together, they inform the available product specifications and resulting data related to LED Modules.

3.3.1 Product Data Collection Process

The research team conducted a search for available product data related to LED Modules, Signal Heads, and other signal components for all brands which were mentioned in the literature or have been established in industry as well-known providers of this technology. These manufacturers include: Dialight, Econolite, GE, Leotek, Oriux, Peek, Philips, Siemens, and Trafficware. Table 3.5 indicates which signal related product or products each company provides.

Table 3.5 LED Module Technology Provided by Signal-Related Companies

Company	Supplied Technology
Dialight	LED Modules
Econolite	Signal Heads
GE	LED Modules
Leotek	LED Modules
Oriux	Signal Heads, Backplates
Peek	Signal Controllers
Philips	Non-Module Light Bulbs
Siemens	Modules (Intelligent Systems)
Trafficware	Signal Heads, Controllers, Software, Control Cabinets

Based on results of the initial search, further effort was put into collecting all available product data from Dialight, GE, and Leotek. Dialight's website contained 12 publicly available product specifications, GE's site contained 7, and Leotek provided 14. Each of these sheets provided information about a product series rather than an individual product. Further evaluation of these specifications can be found in Section 3.2.2.

3.3.2 Evaluation of Available Product Data

From each product specification procured, the Product Identification #, Size, Style, Color, Dominant Wavelength, Wattage, Luminosity/Maintained Intensity, Warranty, and Certifications were recorded. Table 3.6 provides an example of this information for each product available to the research team. The complete table can be found in Appendix B: LED Module Product Specifications Summary. It should be noted that the evaluation of these specifications only included red, green, and yellow LED Modules. LEDs utilized in Pedestrian signals, such as crosswalk directives, were excluded from this evaluation.

Table 3.6 Product Data Specification Summary Table

Manufacturer	Product #/ID	Size	Style	Color	Dominate Wavelength	Wattage	Lumosity/maintained intensity	Warranty (yrs)	Certifications
Dialight	433-1110-003XL15	8"	Circular	Red	625	7	165	15	ITE Compliant
Dialight	433-1210-003XL15	12"	Circular	Red	625	7	365	15	ITE Compliant
GE	DR4-RTFB-71C	200mm	Circular	Red	n/a	8.9	400 - 800	n/a	interek ETL Verified compliant
GE	DR6-GTAAN-VLA	12"	Arrow	Green	500	6.5	76	n/a	interek ETL Verified compliant
Leotek	TSL-EV12R-HPE-A1	12"	Circular	Red	626	7	365	5	*ITE VTCSH Compliance
Leotek	TSL-12Y-LX-IL6-B1-P3	12"	Circular	Yellow	589	10	910	5	*ITE VTCSH Compliance

This project is focused on the expected lifespan of these modules for the purposes of installation, inspection, repair, and replacement. Therefore, the warranty information provided in these specifications has been summarized in Table 3.7. Column one of Table 3.7 identifies the manufacturer. Columns two through four show the associated warranty information – this is shown as the percentage of warranties with the indicated lifespan offered by each manufacturer. For example, 81% of Leotek's listed products are warrantied for five years, while the other 19% are warrantied for fifteen years.

Table 3.7 Percentage of Warranty Length Among Products per Manufacturer

Manufacturer	5 yr Warranty	15 yr Warranty	No Information	TOTALS
Dialight	0%	100%	0%	100%
GE	6%	0%	94%	100%
Leotek	81%	19%	0%	100%

An initial interpretation of the product specifications and their warranty information indicates that all Dialight modules have a 15-year warranty no matter the color, size, or style. Second to Dialight is Leotek with 19% of their modules having a fifteen-year warranty. The Leotek module series that includes the DT-A1 product ID have the fifteen-year warranty period. *These are the products that NCDOT has purchased and plans to use for upcoming installations as the switch from 5-year to 15-year modules is made.* GE only provided warranty information for three types of modules, the 40-U products. These three modules are warrantied for five years.

3.4 Signal Head Product Data

Collecting specifications for Signal Heads did not prove to be as fruitful. The following companies were identified as manufacturing or selling Signal Heads (both aluminum and polycarbonate):

- Eagle Traffic Control Systems
- Econolite
- General Traffic Equipment Corporation
- McCain
- Oriux
- Siemens
- Trafficware

The specifications available from these companies do not state a warranty period or conditions. Therefore, to determine the warranty for Signal Heads, additional inquiries were made to NCDOT. The information that NCDOT provided the research team for Signal Heads currently contains the following text related to warranties.

> "Unless otherwise required herein, provide manufacturer's warranties on Contract-furnished equipment for material and workmanship that are customarily issued by the equipment manufacturer and that are at least 2 years in length from successful completion of the 30-day observation period. Include unconditional coverage for all parts and labor necessary or incidental to repair of defective equipment or workmanship and malfunctions that arise during warranty period.
>
> Ensure all contractor-furnished equipment, including pieces and components of equipment, hardware, firmware, software, middleware, internal components, and subroutines, which perform any date or time data recognition function, calculation, or sequencing will support a four-digit year format for at least 50 years.
>
> Upon successful completion of the 30-day observation period, transfer manufacturer's warranties with proper validation by the manufacturer to the Department or its designated maintaining agency."

From this text one can assume that the warranty period for a Signal Head used by NCDOT to be 2 years. This is not aligned with the reported lifespan of the Signal Heads (neither aluminum nor polycarbonate) which will be discussed in Section 4.1.3.2.

3.5 Financial Records

Financial records were provided by NCDOT for this project. These records include both Purchasing and Distribution records from the Central Warehouse (the Depot) and Annual Expenditure reported from Divisions.

3.5.1 Purchasing and Distribution Records

Purchasing and distribution records were provided by the Central Warehouse from the years 2010 to 2022. These records contained information related to the types of LED Modules and Signals being ordered by the Depot. Table 3.8 contains an example of the data that was received showing the orders placed by the Depot. Column 1 identifies the type of LED Module being purchased, column 2 shows the date of the purchase order, and columns 3 through 6 provide additional information about the quantity and cost of the order. Over 700 LED Module orders and over 200 Signal Head orders were placed by NCDOT between 2010 and 2022. That data was used to understand current practices occurring within NCDOT.

Table 3.8 Example of NCDOT Depot Purchasing Data

Short Text	Document Date	Order Quantity	Order Unit	Net Price	Net Order Value
LED ARROW, 12”, RED	1/20/2010	40	EA	29.76	1,190.40
LED ARROW, 12”, RED, 15-YR WARRANTY	4/27/2021	330	EA	35.24	11,629.20
LED BALL, YELLOW, 12”, EXPANDED VIEWING	6/21/2021	110	EA	18.25	2,007.50

Distribution of LED Modules and Signal Heads to the Divisions was also tracked by the Depot. Table 3.9 provides an example of data provided showing distribution patterns. Column 1 identifies the Division requesting materials from the Depot. Column 2 tracks the Material # of the order, column 3 provides a written description of the items, and columns 4 and 5 provide the order date and quantity. Over 5,000 records of LED Module requests and over 1,500 requests of Signal Heads were provided for our use on this project. This data was used to understand current practices within NCDOT.

Table 3.9 Example of NCDOT Depot Distribution Data

Division	Material #	Description	Document Date	Order Quantity
1	624045110	LED ARROW, 12”, RED	8/30/2010	2
2	624045330	LED BALL, YELLOW, 12”, EXPANDED VIEWING	5/27/2014	72
6	624045210	LED ARROW, 12”, GREEN	6/13/2017	250

3.5.2 Annual Expenditure Reports

Each year, each of the divisions within NCDOT submits an expenditure report to the Traffic Systems Operations Program reporting their related spending for the financial year. These reports cover charges by NCDOT, charges by Contractors, and charges by Municipalities. Those charges represent the money that the Division was able to put towards work by each entity. Charges assigned to NCDOT indicate that NCDOT performed the work. Charges assigned to contractors indicate the amount paid to any and all contractors for their work in the Division throughout the year. Charges assigned to municipalities show the total value for which NCDOT will reimburse the municipality for their work within the Division.

NCDOT charges are divided into Labor, Materials, and Equipment. Activities related to these charges by include:

- Inspection of Intersections, Signals, and Modules
- Purchasing of LED Modules and other Signal Components

- Replacement of Signals and Modules
- Maintenance activities for intersections
    - Removing or installing equipment

Contractor charges are reported as a lump sum. Activities related to these charges typically include signal maintenance activities that are performed by an on-call signal maintenance contractor.

Municipality charges are reported as a lump sum. Activities related to these charges may include the reimbursable maintenance and operations costs related to traffic systems, performed by the municipality on behalf of NCDOT.

These reports provided the research team with additional financial data related to the expenditures within each division: inspection, maintenance, replacement, and operations costs for the traffic signal systems. It should be noted that the funds tracked with these reports are focused on maintenance. Funding for construction and re-construction of signals and systems comes from other sources. It should also be noted that records of funds spent is not necessarily a sign of the level of need within each Division. The Divisions are provided an annual budget and do their best to operate within it, whether it meets their needs or not.

3.6 Possible Future Resources

Towards the end of this project, the research team was informed of a new database being rolled out by NCDOT. An Intersection Inventory for Traffic Safety Analysis was recently developed. The research team attended a webinar on the topic and noted that much of the anticipated data may be useful in future projects related to intersection components. Additional study would be required to determine its true usefulness.

4.0 Current Practices

Understanding the practices in place is the first step to determining any effective strategy moving forward. This section includes both quantitative and qualitative examinations of current NCDOT practices related to LED Module and Signal Head inspection, repair, and replacement.

NCDOT is made up of 14 divisions, all operating with a degree of autonomy. This allows the divisions to have the freedom to adopt strategies that best fit their local needs. The Central Office assists the Divisions by providing operating standards, conducting research, and providing support to the Divisions as it is needed or requested. This section first discusses the overarching expectations of NCDOT, then moves on to show current strategies in use by the divisions, both generally, and with two case studies.

4.1 Statewide Requirements

NCDOT Divisions function, for the most part, independently. State-wide expectations put in place by the central office are outlined below with regards to LED Module and Signal Head inspection, replacement, purchasing, and budgeting.

4.1.1 Inspection Frequency

NCDOT expects each division to conduct biannual inspections of each intersection, along with an annual inspection, and a two-year inspection. These inspections are conducted by Division technicians, and were historically found to be conducted regularly per DTS Events data. Recent years have seen some change to regularity of inspections due to a shortage of personnel.

4.1.2 Repair & Replacement Frequency

Repair of LED Modules is uncommon. Due to the low cost of the item, LED Modules are typically removed from service and replaced when they are no longer functioning at acceptable levels.

While NCDOT does not have explicit language surrounding expected frequency of LED Signal replacement, it was determined through informational interviews that personnel at the main office understood replacements to occur at the five-year mark (the end of the warranty period for older modules).

4.1.3 LED Module and Signal Head Types

Currently, NCDOT has set up their supply chain of LED Modules and Signal Heads to funnel through the NCDOT Central Warehouse (also known as the Depot). Each of the divisions maintains their own smaller warehouse within the division, however most purchasing is done by the Central Warehouse. This means that the majority of LED Module and Signal Heads are purchased at the state level rather than the Division level. The purchases are based on NCDOT specifications and established contracts with manufacturers. Modules and Signal Heads are distributed to the Divisions as needed.

4.1.3.1 Modules

To identify any patterns in purchasing, the quantity and type of modules purchased were analyzed from 2010 to 2022. Table 4.1 provides the total quantity of modules purchased each year during that time. It should be noted that for Figure 4.1, as well as Table 4.1, the quantities provided capture only the red, yellow, and green LED Modules that are found in traffic signals. LEDs which are utilized in pedestrian signals, such as crosswalk directives, were excluded from this analysis. One reason for this exclusion is the scope of the project – LED Modules at an intersection require different maintenance and replacement activities than pedestrian signals. It was also found that NCDOT-maintained pedestrian signals make up only 2% of the total quantity of signals maintained by NCDOT.

Table 4.1 Total Quantities of LED Modules Purchased per Year

Year	Quantity of LED Modules Ordered (w/o PED)
2010	56,406
2011	35,902
2012	19,590
2013	31,821
2014	22,236
2015	24,644
2016	10,594
2017	12,076
2018	17,071
2019	1,009
2020	104
2021	7,572
2022	5,988
TOTAL	250,921

An initial interpretation of the purchased quantities shown in Table 4.1 and Figure 4.1 indicates that there was a bulk buy in 2010, following the ITE recommendation that signals be switched from incandescent to LEDs. The following five years (2011-2015) there continued to be an average purchase of approximately 26,800 modules each year. This implies that the initial state-wide replacement of incandescent modules with LEDs took approximately five years.

From 2016 to 2019 the average quantity of modules purchased was 10,200 – less than half of the previous average. This indicates that during those years, few replacement modules were needed. A budget shortfall starting in 2018 led to NCDOT operating under restricted purchasing allowances, resulting in an abnormally low quantity of signals (AECOM 2015; Coletti 2019; Stradling 2020). Purchasing quantities rise again starting in 2021, however they do not reach previous levels, peaking at around 7,500 and decreasing again for 2022. Figure 4.1 shows a graphical representation of LED Module purchasing over time. As mentioned above, there was a hold on spending for NCDOT during 2019 and 2020, which is reflected here.

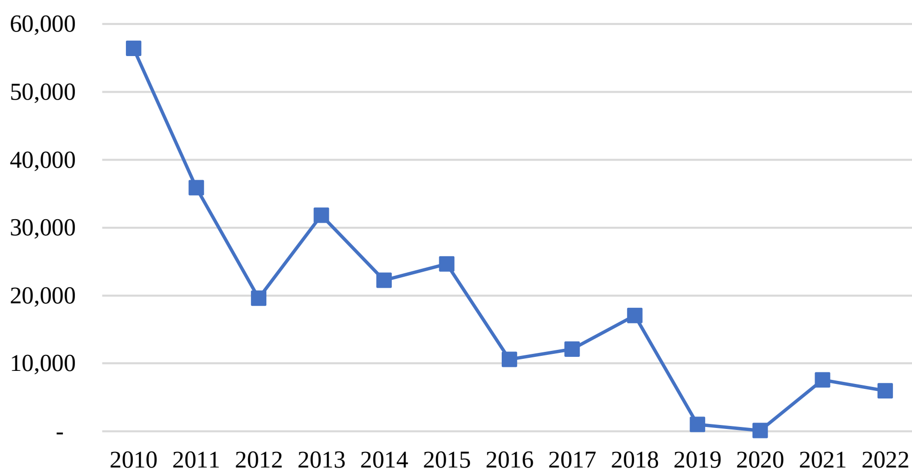


Figure 4.1 Total Quantity of LED Modules Purchased (without pedestrian) [2010-2022]

Based on the assumption that replacements should be occurring when modules reach the end of their 5-year warrantied life, an additional bulk purchase of modules would have been expected around the year 2015. This is not reflected in the data. Another option for consideration is that a uniform quantity of modules would be replaced each year, eliminating the bulk purchase but potentially increasing the annual purchasing. Assuming one fifth of the 155,000 LED Modules in the state were replaced each year, an order of 31,000 modules would be anticipated. Thus, it is strongly suggested that the combination of a purchasing freeze and COVID 19 were largely responsible for the and a serious recovery had not occurred through 2022. That does not appear to be present in the data either. Additional analysis of LED Module age will be discussed in Section 4.2.2 to determine the replacement practices currently in place within NCDOT.

Table 4.2 provides the portion of LEDs that were either red, yellow, or green as a percentage of the total quantity purchased from 2010 to 2022, including the relative portion of pedestrian LEDs. The split between red, yellow, and green modules is nearly even, each of them making up a little over 30% of the modules purchased. There are slightly more yellow and green modules purchased than red, which makes sense when various signal head configurations are considered. Many of the 4- and 5-module signal heads utilize two green modules, or two green and two yellow.

Table 4.2 Percentage of Each Module Ordered from 2010 to 2022

Module Color	**Red**	**Green**	**Yellow**	**PED**
Quantity Ordered (2010-2020)	31%	33%	34%	2%

Analysis so far has shown the quantity of modules purchased by the Central Warehouse. Were all those modules making their way to the Divisions? That was the next question. NCDOT was able to provide division disaggregated data for analysis. Figure 4.2 illustrates that, yes, it appears the purchased quantity of modules was reflective of the quantity of modules requested by the Divisions. Blue circular points ● and the blue regression line are the same as those shown in Figure 4.2. The additional orange square points ■ and regression line represent the total quantity of modules requested by the fourteen divisions each year. Both the data points and the lines are similar, meaning that the Central Warehouse was responding to the needs of the divisions. The points shown in grey triangles ▲ represent the quantity of modules that were ordered by the Divisions from outside vendors. This occurs primarily with new intersection construction.

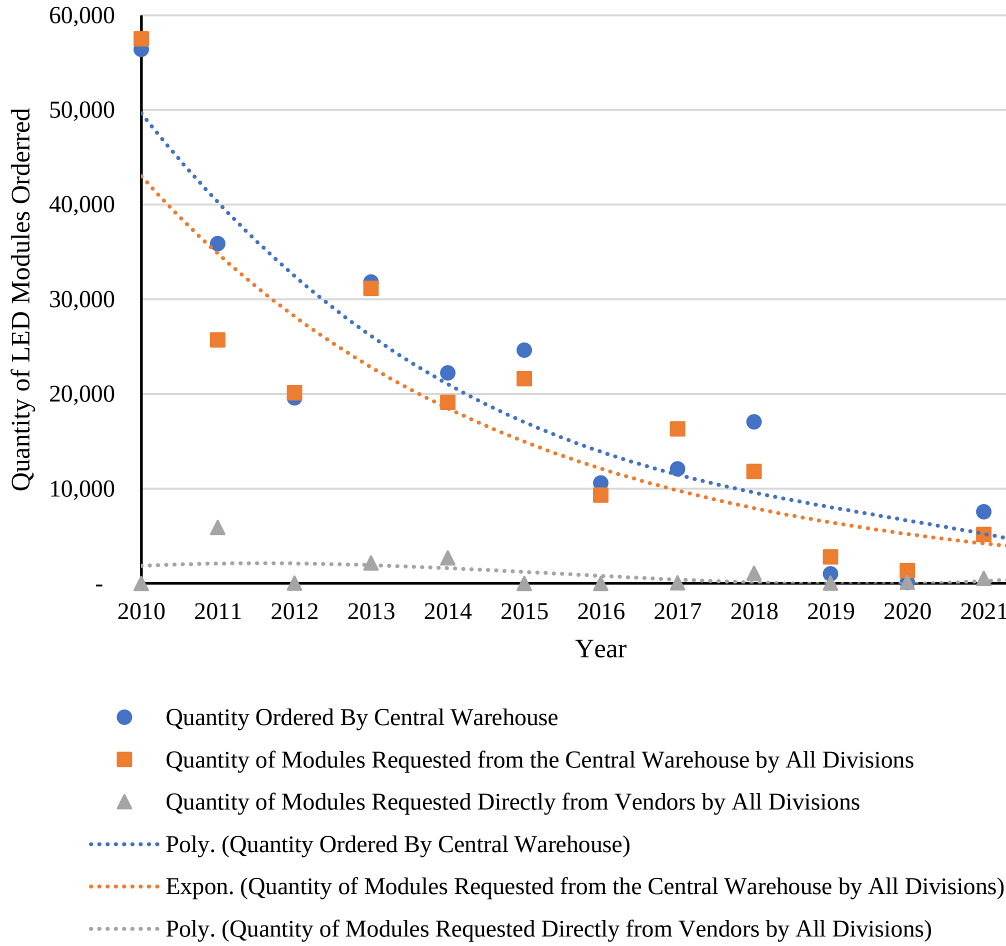


Figure 4.2 Module Request and Purchasing Quantities Over Time (without pedestrian) [2010-2022]

4.1.3.2 Signal Heads

Purchasing data related to Signal Heads was made available. This data goes back to 2010. It was brought to our attention that there may be an opportunity to pre-package the LED Modules into the Signal Heads prior to installation. Before any further emphasis could be placed on this idea, it was important to understand the current state of Signal Heads for NCDOT.

As it stands currently, the Central Warehouse provides the Divisions with mostly aluminum signal heads, which have a special warranty of two years. In some cases polycarbonate signal heads are provided. Based on informational interviews with Division employees, it is our understanding that the true lifespan of these aluminum assets is somewhere between 15 and 20 years, depending on the level of aesthetic degradation deemed acceptable by the Division. There have been more extreme anecdotal cases provided, broadening the expected lifespan to include outliers of 3 and 30 years. Table 4.3 provides the total quantity of Signal Heads (both aluminum and polycarbonate) purchased each year from 2010 to 2022.

Table 4.3 Total Quantities of Signal Heads Purchased per Year

Year	Signal Heads Purchased
2010	2,905
2011	1,650
2012	2,730
2013	1,384
2014	1,357
2015	980
2016	634
2017	439
2018	1,700
2019	480
2020	85
2021	480
2022	410
TOTAL	15,234
Annual Average	1,172

Figure 4.3 breaks out these quantities based on who is submitting the purchasing request. The blue circular data points ● indicate how many Signal Heads were ordered by the Central Warehouse for that year. Orange square data points ■ represent the quantity of Signal Heads requested by the divisions from the Central Warehouse. The grey triangular data points ▲ represent the quantity of Signal Heads ordered directly from outside vendors. As would be expected, the division requests for Signal Heads and the Central Warehouse supply of Signal Heads have some variation, but follow the same trend.

Given that there are 43,000 (excluding one division due to data gaps) Signal Heads recorded as in place in North Carolina, it would be expected that, with a regular replacement cycle (anywhere from 15 to 20 years), somewhere between 5 and 7% of the total number of Signal Heads in the state would be replaced each year. This implies that a similar number should be purchased on a regular basis. If the signal heads were being replaced at 20 years, the expected annual order would contain a minimum of 2,150 heads. If they were replaced at 15 years, the order would be 3,010 heads. As shown in Table 4.3 and Figure 4.3, however, there are only two years for which this is true. The average number of signal heads ordered each year is only 1,814. The average being lower than the expected order quantities. This average being lower than the estimated order quantities indicates that there are likely many signal heads in place across the state which are at an advanced age and could be in a state of disrepair.

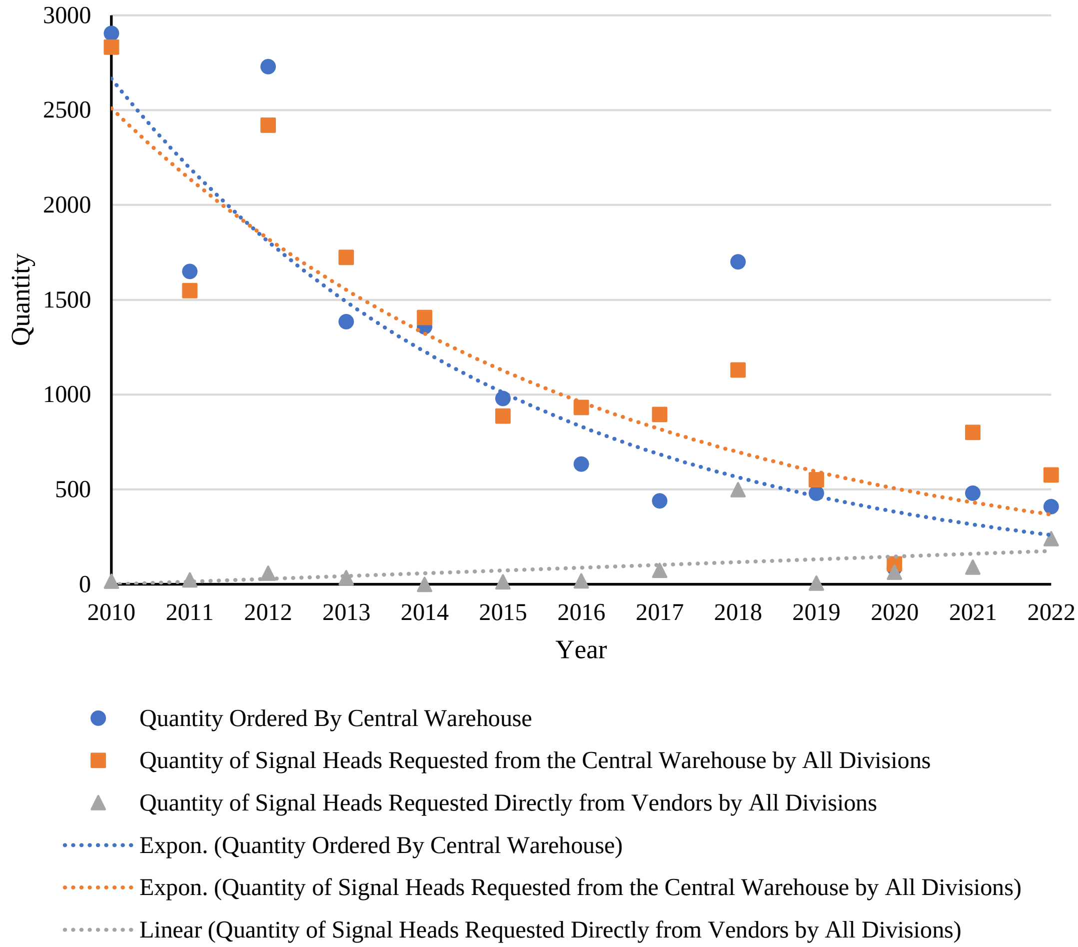


Figure 4.3 Signal Head Request and Purchasing Quantities Over Time (without pedestrian) [2010-2022]

4.1.4 Financial Considerations

This section will discuss financial considerations related to LED Module and Signal Head replacement from both an in-house (NCDOT) budgeting and expense perspective, and a contracting perspective.

4.1.4.1 Budgeting and Expenses

The budgeting process for NCDOT is such that next year's budget is based on the previous year's expenditures. However, there is not a specific "LED Module and Signal Head Maintenance" item that the state includes in the General Maintenance Reserve budget. Each division receives a larger sum for their overall Traffic Maintenance needs. Based on the needs and priorities of the division, some portion of the allotted funds is allocated specifically to LED Signal Maintenance. Note that there are currently no highway assets (including LED Modules and Signal Heads) which are proactively replaced on a scheduled basis. Once an asset fails (for LED Modules this means going dark, for Signal Heads it means breaking or falling), funding may be supplied by the division to repair or replace the asset.

Every year, each of the divisions within NCDOT submits a spending report to the Traffic Systems Operations Program, reporting their traffic signal maintenance expenditures for the fiscal year. These reports show the charges by NCDOT, charges by contractors, and charges by municipalities.

These reports provide the research team with additional financial data related to the inspection, repair, replacement, and operation of traffic signal systems within the NCDOT divisions. It should be noted that other funds exist to support construction and reconstruction of intersections and signal systems. The total Traffic Systems Operations needs of a division are not fully represented by the Traffic Signal Maintenance Expenditures Annual Reports. Additional operations needs include: freeway operations, Traffic Maintenance Centers, ITS device maintenance and operations, IMAP, and signal retiming. The data for this analysis are largely based on the Traffic Signal Maintenance Expenditures Annual Reports.

As an example of the content found in the expenditure reports, Table 4.4 provides an expenditure summary. Across the divisions, NCDOT reported spending almost $11 M on Traffic Signal Maintenance for fiscal year 2021. NCDOT Divisions conducted 46% of the spending ($4.97 M), contractors 28% ($3.0 M), and municipalities 26% ($2.92 M).

Table 4.4 Traffic Signal Maintenance Expenditures Annual Reports [2021]

Division	NCDOT ($)	Contractor ($)	Municipal ($)	Total ($)
1	966,374.90	157,201.91	-	1,123,576.81
2	1,813,097.38	496,424.47	217,693.24	2,527,215.09
3	1,194,903.02	398,258.59	713,783.50	2,306,945.11
4	1,205,451.00	310,000.00	437,601.00	1,953,052.00
5	1,711,611.94	1,524,034.16	2,699,616.87	5,935,262.97
6	790,899.23	140,889.69	446,327.05	1,378,115.97
7	1,667,249.85	156,357.57	1,835,550.36	3,659,157.78
8	775,424.04	202,654.58	-	978,078.62
9	672,682.46	186,509.75	634,558.00	1,493,750.21
10	515,057.73	161,750.27	443,138.06	1,119,946.06
11	615,714.38	26,233.94	-	641,948.32
12	736,368.04	224,231.15	668,072.59	1,628,671.78
13	1,178,692.96	205,290.51	-	1,383,983.47
14	685,763.25	95,818.72	-	781,581.97
NCDOT	14,529,290.18	4,285,655.31	8,096,340.67	26,911,286.16

Additional analysis of the expenditure reports consisted of determining the total amount attributed to each entity (NCDOT, contractor, and municipality) by NCDOT each year from 2016 to 2021. Table 4.5 shows these total expenditures. Note that reports for the year 2020 did not identify any expenditures, thus zero values have been included. It may be that this data is missing, but it is also more likely that the COVID-19 pandemic greatly impacted available spending on Signal Maintenance. Inquiries to NCDOT personnel have not been able to resolve the question of why the 2020 documents contained no reported spending.

Table 4.5 Reported Traffic Maintenance Expenditures by All NCDOT Divisions [2016-2021]

Charges	2016	2017	2018	2019	2020	2021
NCDOT ($)	11,926,623.93	10,403,212.79	12,097,819.81	11,096,691.20	0	14,529,290.18
Contractor ($)	4,857,329.27	3,166,613.86	4,440,112.28	5,465,804.60	0	4,285,655.31
Municipal ($)	8,882,714.66	6,651,164.67	6,554,790.04	5,025,991.22	0	8,096,340.67
TOTAL ($)	25,666,667.86	20,220,991.32	23,092,722.13	21,588,487.02	0	26,911,286.16

Figure 4.4 provides a graphical representation of these expenditures over the last five years. With only five years of data the significance of any noticeable trends is low. However, there does appear to be an overall decreasing in expenditures from 2016 to 2019. Charges to NCDOT remain somewhat steady, while charges to contractors are increasing and charges to municipalities are decreasing during that time. The solid trend lines in Figure 4.4 include an interpolated value estimate for 2020, while the dashed lines show the reported values (all being $0). The lack of reporting for the year 2020 makes it difficult to speak to any long-term trends. However, a similar dip in purchasing was noted during the discussion of purchasing data from the Depot. While the reason why expenditures were not reported for fiscal year 2020 are not certain, it is in line with the effects that the purchasing freeze and COVID-19 had on purchasing.

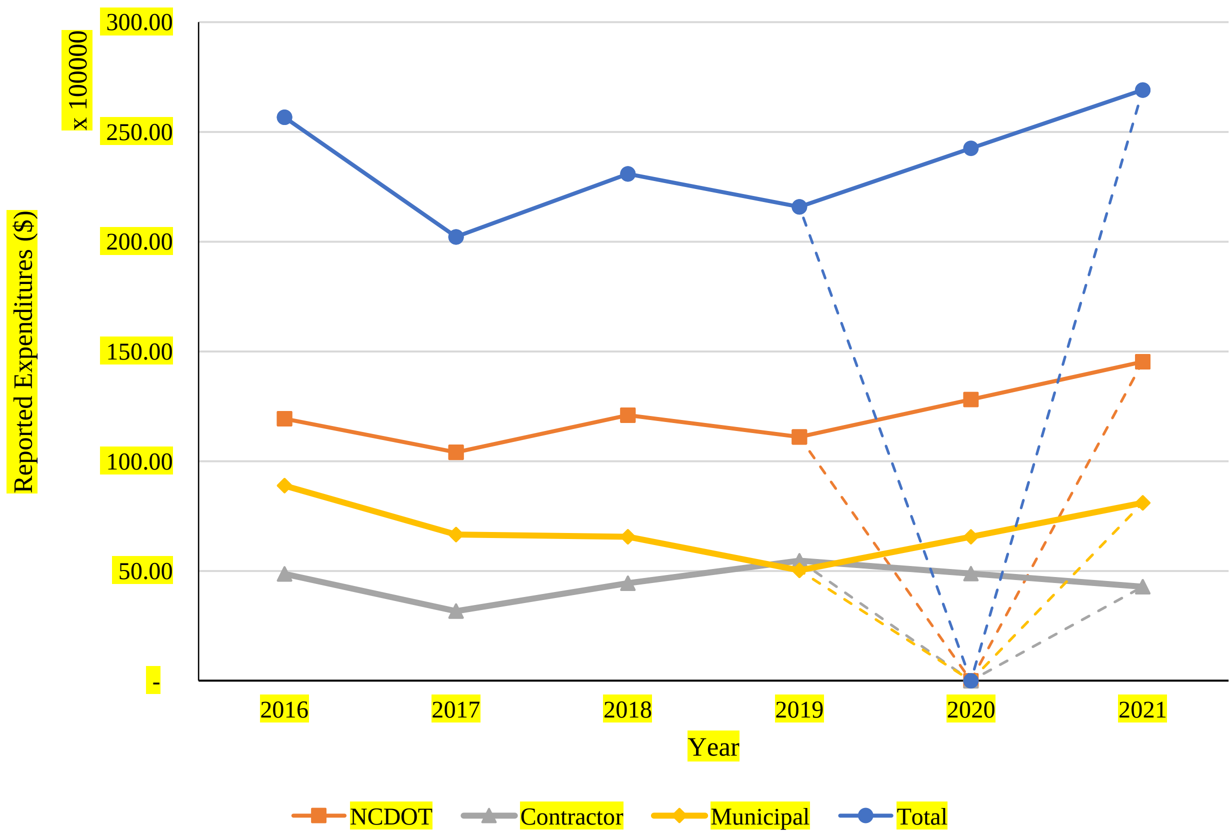


Figure 4.4 All NCDOT Reported Maintenance Expenditures Over Time

4.1.4.2 Contracts

Each Division acts independently to secure contracts related to LED Module and Signal Head repair and replacement. By comparing the seven contracts from 2022 that were made available, it is possible to gain an understanding of the pros and con that varying contract language may provide to the divisions. That language then has the potential to be used in a future boiler plate document across the state, bringing additional savings to the Divisions. Appendix C contains information from each of the contracts, including language surrounding material procurement and related line items from each contract.

Table 4.6 compiles the line items from the On-Call Maintenance contracts into one location for comparison. The included line items are related to the installation, repair, or replacement of LED Modules and Signal Heads. Column 1 provides the description of the contracted line item – note that the language was copied verbatim and varies from contract to contract. Column 2 shows the contracted price for performing the work related to that line item. Those contracts which provide NCDOT materials are shown to have an additional Material Cost, in Column 3. The contracts which pass material procurement to the contractor do not show an additional material cost as it is incorporated into the Contracted Price in Column 2. The total costs shown here assume that a replacement activity includes both the Signal Head and the appropriate quantity of LED Modules. Column 4 provides the Total Price, which is the sum of Columns 2 and 3. Finally, Column 5 identifies the Division associated with each line item and price.

Table 4.6 Contract Comparison Across Divisions

Description	Contracted Price	Material Cost	Total Price	Division
VEHICLE SIGNAL HEAD (12", 3 SECTION)	750.00	n/a	750.00	5
VEHICLE SIGNAL HEAD (12", 3 SECTION)	850.00	n/a	850.00	5
VEHICLE SIGNAL HEAD (12", 4 SECTION)	950.00	n/a	950.00	5
VEHICLE SIGNAL HEAD (12", 4 SECTION)	1,175.00	n/a	1,175.00	5
VEHICLE SIGNAL HEAD (12", 5 SECTION)	1,100.00	n/a	1,100.00	5
VEHICLE SIGNAL HEAD (12", 5 SECTION)	1,299.00	n/a	1,299.00	5
Mobilization for Emergency Response	1,500.00	n/a	1,500.00	6
Vehicle Signal Head (12", 3 Section)	625.00	n/a	625.00	6
Vehicle Signal Head (12", 4 Section)	748.00	n/a	748.00	6
Vehicle Signal Head (12", 5 Section)	1,025.00	n/a	1,025.00	6
8" or 12" LED Single Bulb Replacements (Burn-out replacements)	105.00	n/a	105.00	6
VEHICLE SIGNAL HEAD (12", 3 SECTION)	875.00	n/a		7
VEHICLE SIGNAL HEAD (12", 4 SECTION)	990.00	n/a		7
VEHICLE SIGNAL HEAD (12", 5 SECTION)	1,500.00	n/a		7
Department Furnished Signal Heads	400.00	*		7
Department Furnished Replacement Vehicle Signal LED Module	30.00	*		7
Removal of Existing Vehicular Traffic Signal Head	10.00	n/a		7
Assemble & Ints. Of Signal, Ped. Signal (Head) and LED Blankout Sign *(3-section)*	250.00	324.39	574.39	9
Assemble & Ints. Of Signal, Ped. Signal (Head) and LED Blankout Sign *(4-section)*	250.00	437.52	687.52	9
Assemble & Ints. Of Signal, Ped. Signal (Head) and LED Blankout Sign *(5-section)*	250.00	765.65	1015.65	9
Removal of Signal, Ped. Signal (Head) and LED Blankout Sign	100.00	n/a	100.00	9
Install State-Furnished Traffic Signal Head (3-Section)	250.00	324.39	574.39	11
Install State-Furnished Traffic Signal Head (4-Section)	250.00	437.52	687.52	11
Install State-Furnished Traffic Signal Head (5-Section)	250.00	765.65	1015.65	11
Relocate Existing Traffic Signal Head	115.00	n/a	115.00	11
Install State-Furnished LED in Existing Traffic Signal Head	30.00	n/a	30.00	11
Vehicle Signal Head (12" – 3 Section)	750.00	*		12
Vehicle Signal Head (12" – 4 Section)	900.00	*		12
Vehicle Signal Head (12" – 5 Section)	1,150.00	*		12
Modify Exst. Signal Head	50.00	n/a		12
Removal of Vehicle Signal Head	50.00	n/a		12
Remove & Replace Vehicle Signal LED L	85.00	*		12

Divisions 7 and 12 have asterisks in the Material Cost column because it is not clear from the document alone how the material cost are incorporated into the Total Price.

The initial prediction for this analysis was that Divisions supplying material would be paying less overall for LED Module and Signal Head replacement. While that does appear to be the case at first glance, with Divisions 9 and 11 having a lower total cost, Division 6 does not supply materials and has contract prices that are not too far off from Divisions 9 and 11 ($575 in Divs. 9 and 11 vs $625 in Div. 6 for a 3-section Signal Head Replacement). Divisions 7 and 12 break this trend. Both divisions seem to provide material to the contractors based on the language in the contract. However, the prices are more like other divisions who are not providing material, leading to much higher costs overall.

An additional point of difference are the product specifications and warranty requirements provided in the contracts. Some contracts reference NCDOT's Qualified Products List (QPL), other contracts list specific requirements, still other contracts require that all LED Modules and Signal Heads be acquired directly from NCDOT's Depot. While these differences may not themselves be a problem, it is an area of the contracts that may be improved with some degree of uniformity across the Divisions.

If NCDOT is able to perform future research into the finer points of these contracts, the agency may be able to standardize prices of contracted work across the state. That examination is beyond the scope of this research, but is recommended in order to ensure that LED Module and Signal Head maintenance is occurring with optimal financial efficiency for NCDOT.

4.2 Divisions' Strategies for LED Signal Inspection, Repair, and Replacement

To understand LED Module and Signal Head Inspection and Replacement strategies at a division level, informational interviews were conducted with four divisions as well as with main office personnel. A set of over fifty questions was used to guide the interviews. Based on these informational interviews, we determined that each of the Divisions was following the same inspection and replacement process, with some adaptations for their respective quantities of personnel and budgetary restrictions. The general process for *spot replacement triggered by inspections* can be found in Figure 4.5. Each division also conducts spot replacements based on other triggers, such as individuals calling in that a module is out, or an emergency event. Informational interviews revealed that while divisions knew of the 5-year blanket-replacement expectation, often only spot-replacement of dark LED Modules was occurring due to budget and personnel constraints.

One example of a blanket replacement process was provided in detail by Division 13. This is discussed in section 4.2.1.

NCDOT does not currently utilize their DTS database to track the in-place service life of LED modules, therefore additional investigation into available data was necessary to determine true replacement periods and strategies. This analysis will be discussed in section 4.2.2.

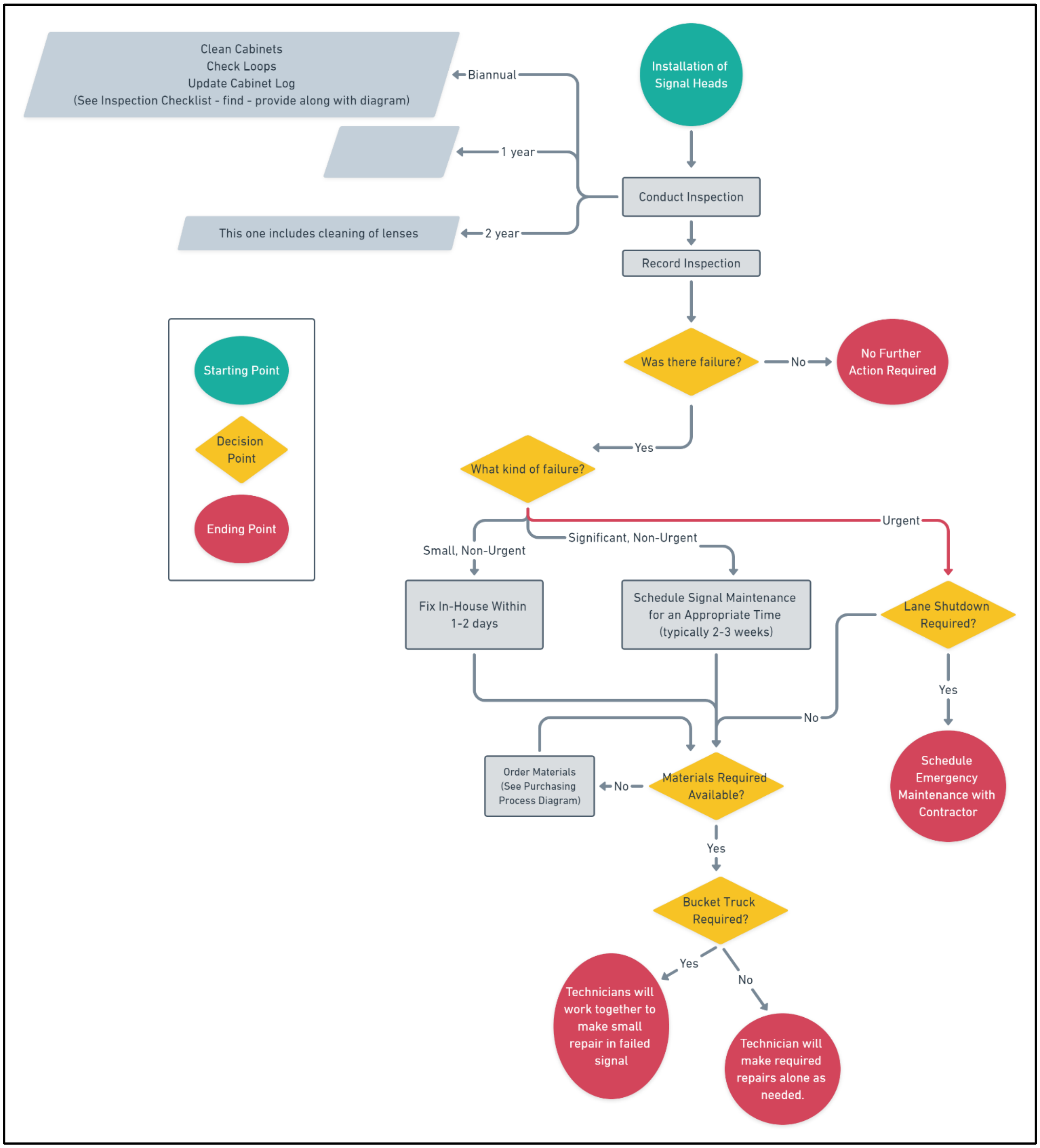


Figure 4.5 Inspection and Maintenance Process Diagram

4.2.1 Case Study: Division 13 LED Blanket Replacement Strategy

Division 13 was able to provide records of the blanket replacement which occurred in the division starting in 2011 and continuing through 2015. The division was able to conduct a full replacement of LED Modules over the course of five years (the warranty period at the time). Due to budgeting constraints and staffing shortages, the following replacement cycle (planned to start in 2016) was unable to be initiated. A detailed account of the blanket replacement process is provided in this section. Based on the data available (maps provided by the division and the informational interviews conducted) it was determined that the qualitative accounts align with the records available describing this replacement process.

4.2.1.1 LED Module Replacement

Division 13 provided data related to their 2011 LED Module replacement plan. This data consisted of a set of hand-marked maps of the division, as well as tables providing the County, Signal ID, Major Route, Minor Route, and information as to whether the location contained a Signal or a Flasher. Division 13 provided all the data that was available for use. Because DTS is an elective software (Divisions are not required to use it), comparable data for Division 13 was not available in the DTS data for this blanket replacement examination.

Utilizing the data provided in the tables, it was determined that LED Modules at 581 intersections were replaced from 2011 to 2015 within the Division. Table 4.7 shows that the work was divided, approximately evenly, between the years to accomplish all the replacements.

Table 4.7 Total Quantities and Relative Portions of Division 13 Intersections Replaced Annually

Year	Total Intersections Replaced	Portion of Replacement (%)
2011	129	22.2 %
2012	114	19.6 %
2013	128	22.0 %
2014	111	19.1 %
2015	99	17.1 %
TOTAL	581	100%

4.2.1.2 Discussion of Replacement Plan per Informational Interview

Based on our communication with Division 13, it is understood that the division technicians were split into two groups to complete the blanket replacement process. Each group, typically made up of two trucks and three technicians, completed half of their replacements in remote locations and half in their home counties. Approximately three intersections could be serviced in one day.

Although the division was divided into five areas for replacements (one for each year), we were told that there was no deliberate logic developed for the day-to-day replacement at each intersection. Rather, a day's planned replacements would be based on the other duties and requirements of the technicians.

Assuming that three intersections worth of LED Modules were replaced each day that the technicians were focused on replacement, the whole replacement process took 194 days over the course of five years. That works out to be approximately 8 dedicated work weeks or 930 dedicated technician hours each year of the process.

4.2.1.3 Cross Referencing Data

<u>Purchasing – Modules</u>
Purchasing data shows that Division 13 requested an average of 3,022 modules from the Central Warehouse each year from 2010 to 2015. The total quantity of modules ordered was 18,136. Based on rough estimations (581 intersections serviced, with an assumed 24 modules per intersection – data not being available in DTS for Division 13), 13,944 modules would have been required. The quantity requested by

the division exceeds this estimation, indicating that they did indeed replace all the modules within the division during this time.

Purchasing – Signal Heads

Based on purchasing data regarding Division-requested Signal Heads, Division 13 only ordered 10 signal heads in 2010 and 36 in 2011. This implies that many signal heads in the division were left in place and only the modules were replaced.

DTS – Quantity Data

The DTS database does not contain historical quantity data for Division 13, therefore no comparisons can be made.

DTS – Events Data

Examining events data from DTS, it is indicated by report codes that from 2011 to 2015 that 91% of all intersections had ‘all red modules replaced’, 88% had ‘all green modules replaced’, and 28% had ‘all yellow modules replaced.’ However, frequently in the comments for these codes, technicians write that they “Replaced all LED’s,” indicating that the percentage of intersections with new modules is higher than those listed above.

Overall, the events recorded in DTS are substantially aligned with the maps and other data provided to the research team by Division 13.

4.2.2 Case Study: Division 3 LED Signal Replacement Practices

Division 3 was chosen for an in-depth case study because (upon preliminary viewing) the data appeared to be relatively complete. Additionally, Division 3 has also been helpful by participating in interviews and answering questions related to the Inspection and Replacement process.

The following subset of Action Codes are those from the DTS database which the research team determined to be directly related to module inspection (performance review), maintenance, and replacement. Table 4.8 identifies whether each code is an inspection code or replacement code, it then provides the numerical Action Code, the Action Code name, and the understood definition of the code.

Table 4.9 provides a partial timeline wherein every “X” in the table denotes that the respective action took place during the month and year indicated. For example, in Table 4.9, the third line of data (highlighted) shows all recorded occurrences of Action Code 1240 for the signal with ID 03-0100. Action Code 1240 is used to record the occurrence of 6-month Operational Performance Reviews. As shown below, from the years 2010 to 2014 these 6-month reviews were completed consistently.

Table 4.8 Inspection and Replacement Action Code Definitions

Code Type	Action Code	Code Name	Code Meaning
Inspection	1240	Completed: 6-month Operational Performance Review	A regular 6-month inspection was performed at this intersection.
	1241	Completed: Scheduled Maintenance Checklist	*Under review*
	1242	12-month Operational Performance Review	A regular 12-month inspection was performed at this intersection.
	1243	24-month OPR (heads only)	A regular 24-month inspection was performed at this intersection.
Replacement	1212	Repair/Replace: All Red LED Modules	All red LED modules were replaced at this intersection.
	1213	Repair/Replace: All Green LED Modules	All green LED modules were replaced at this intersection.
	1214	Repair/Replace: All Yellow LED Modules	All yellow LED modules were replaced at this intersection.
	1215	Repair/Replace: LED Signal Module – Completely Dark	Some number of LED modules (unknown quantity or color) were replaced at this intersection due to being completely dark.
	1216	Repair/Replace: LED Signal Module – Partially Illuminated	Some number of LED modules (unknown quantity or color) were replaced at this intersection due to being partially illuminated.
	1217	Repair/Replace: LED Signal Module – Normal End-of Life	Some number of LED modules (unknown quantity or color) were replaced at this intersection due to end-of-life.
	1247	Repair/Replace All LEDs	All LED modules (of every color) were replaced at this intersection.

Table 4.9 Example of Division 3 Event Timeline

ID	Action Code	2009					2010											
		NO DATA					J	F	M	A	M	J	J	A	S	O	N	D
03-0100	1205																	
03-0100	1229																	
03-0100	1240									X						X		
03-0100	1241																	
03-0100	1242															X		
03-0100	1243															X		
03-0100	1246																	
03-0101	1240										X					X		
03-0101	1241																	
03-0101	1242										X					X		
03-0101	1243										X					X		
03-0101	1246																	

ID	Action Code	2011											
		J	F	M	A	M	J	J	A	S	O	N	D
03-0100	1205			X									
03-0100	1229												
03-0100	1240					X						X	
03-0100	1241												
03-0100	1242											X	
03-0100	1243												
03-0100	1246											X	
03-0101	1240					X						X	
03-0101	1241												
03-0101	1242											X	
03-0101	1243												
03-0101	1246											X	

ID	Action Code	2012											
		J	F	M	A	M	J	J	A	S	O	N	D
03-0100	1205												
03-0100	1229												
03-0100	1240				X							X	
03-0100	1241				X							X	
03-0100	1242											X	
03-0100	1243											X	
03-0100	1246				X							X	
03-0101	1240				X						X		
03-0101	1241				X						X		
03-0101	1242										X		
03-0101	1243										X		
03-0101	1246										X		

ID	Action Code	2013											
		J	F	M	A	M	J	J	A	S	O	N	D
03-0100	1205												
03-0100	1229			X									
03-0100	1240				X						X		
03-0100	1241				X						X		
03-0100	1242										X		
03-0100	1243										X		
03-0100	1246				X						X		
03-0101	1240				X						X		
03-0101	1241				X						X		
03-0101	1242										X		
03-0101	1243										X		
03-0101	1246				X						X		

ID	Action Code	2014											
		J	F	M	A	M	J	J	A	S	O	N	D
03-0100	1205												
03-0100	1229												
03-0100	1240				X								
03-0100	1241				X								
03-0100	1242												
03-0100	1243												
03-0100	1246				X								
03-0101	1240				X								
03-0101	1241				X								
03-0101	1242												
03-0101	1243												
03-0101	1246				X								

Table 4.9 includes only two intersection (03-0100 and 03-0101). However, it also shows one complication that the research team has found – there are many intersections for which data points are not recorded for

the whole period from 2010 to 2020. Data for these two intersections stops after the year 2014. Continued analysis will make the most of the data, however it should be noted that there are some sizeable gaps in the available data. It should also be noted that the available data is at the intersection level rather than the module level. As a reminder, within Division 3 there are a recorded 372 intersections containing 3,914 modules. This is in comparison to the 8,200 intersections and 155,000 modules recorded for all of NCDOT.

4.2.2.1 Timeline Analysis

Initial analysis of the developed timeline resulted in the determination of average frequencies for the occurrence of each of the above Action Codes for each intersection (372 in Division 3). For example, in Table 4.9, Action Code 1240 occurred at intersection 03-0100 with a mean frequency of 5.78 months. The standard deviation of the same data is 0.97 months. These values provide sample statistics for each action code utilized at each intersection within Division 3 and can be extrapolated statewide.

In order to determine a division-wide frequency of events, it is necessary to take these sample statistics and use them to determine overall means and standard deviations of frequency for each action code. The next sections present and discuss the distribution of average frequency for each Action Code from Table 4.8.

Inspection Codes

Use of inspection codes is further analyzed in this section. This analysis had provided a set of sample statistics showing how frequently each action code is utilized at each intersection within Division 3.

Action Code 1240: Completed – 6 month Operational Performance Review

Statistics related to the frequency distribution of action code 1240 can be found in Table 4.10. The unit for all the values in this table is months. To determine these statistics, the average frequency with which the code was used at each intersection was calculated. This theoretically provides 372 data points for analysis. Intersection averages were then analyzed to determine distribution statistics for usage of the action code across the Division.

Table 4.10 first identifies the minimum frequency of code usage at an intersection. This means that there is at least one intersection in Division 3 for which code 1240 was reported, on average, every 3 months. Rows 2 through 5 report the rest of the data spread via the 1st quartile, the median, the mean, the 3rd quartile, and the maximum. It is important to note here that the mean shown in Table 4.10 is the Division 3 Mean Frequency of use of the code 1240. It is an average of averages. It is the mean of each of the intersection averages, which gives an overall mean for the whole Division. Row 6 shows the standard deviation of the intersection average frequencies. Row 7 indicates the quantity of intersections in the division to which the action code was not applied (NA). Division 3 did not apply action code 1240 to three intersections. This pattern of data is used for each of the distribution statistics tables that follow in this section.

Table 4.10 "6-month Inspection" Frequency Distribution Statistics [Action Code 1240]

Statistic	Value (months)
Minimum	3.00
1st Quartile	8.33
Median	10.73
Mean	10.73
3rd Quartile	12.60
Maximum	32.60
Standard Deviation	3.32
NA's	3

Figure 4.6 contains a histogram describing Action Code 1240 data for Division 3. The distribution is a graphic representation of the frequency distribution described in Table 4.10. Remember that the data for this distribution is made up of the available intersection average frequencies of the use of code 1240. It is possible to identify the intersection with the minimum average frequency at 3 months as well as the intersection with the maximum average frequency at 32.6 months. The remainder of the statistics from Table 4.10 identify the size, shape, and location of the distribution curve. The x-axis of this histogram identifies the average frequency of code usage at an intersection in months. The minimum frequency of 3 months can be seen farthest to the left, the maximum of 32.6 months can be seen farthest to the right. The y-axis of the histogram identifies the quantity of intersections with that average code use frequency. For example, there were approximately 30 intersections identified as having a 5-month Code 1240 use frequency.

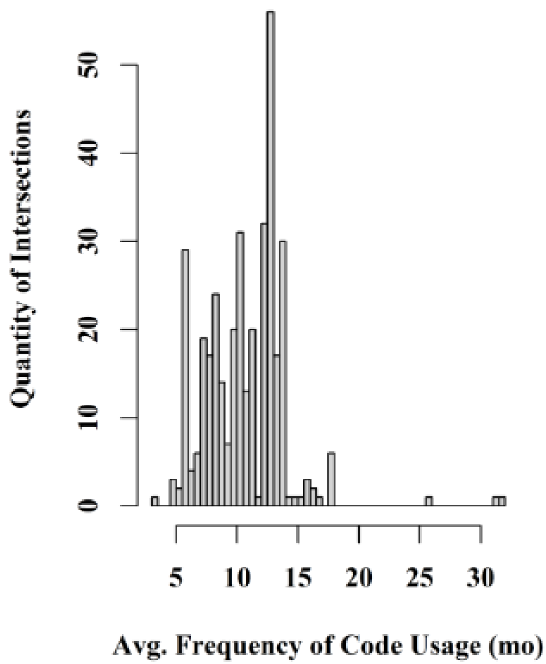


Figure 4.6 Use of Action Code 1240

It should be noted that Action Code 1240 was not applied to three intersections of the 367 for which there were recorded events in DTS. Therefore, it was recorded for 364 (99%) of the intersection in Division 3 with any recorded events. Code 1240 has been utilized consistently from 2010 to 2020. However, there are some intersections with data that only extend to 2014.

Action Code 1241: Completed – Scheduled Maintenance Checklist

Statistics related to the frequency distribution of Action Code 1241 can be found in Table 4.11. Division 3 did not apply Action Code 1241 to 13 intersections. Figure 4.7 provides a graphic representation of the events data, mirroring the statistics found in Table 4.11, showing the overall collection of data rather than the descriptive characteristics. Code 1241 has been utilized consistently from 2010 to 2020. However, there are some intersections with data that only extends to 2014.

Table 4.11 "Completed Scheduled Maintenance Checklist" Frequency Distribution Statistics [Action Code 1241]

Statistic	Value (months)
Minimum	1.00
1st Quartile	8.70
Median	11.73
Mean	14.05
3rd Quartile	16.50
Maximum	54.0
Standard Deviation	8.21
NA's	13

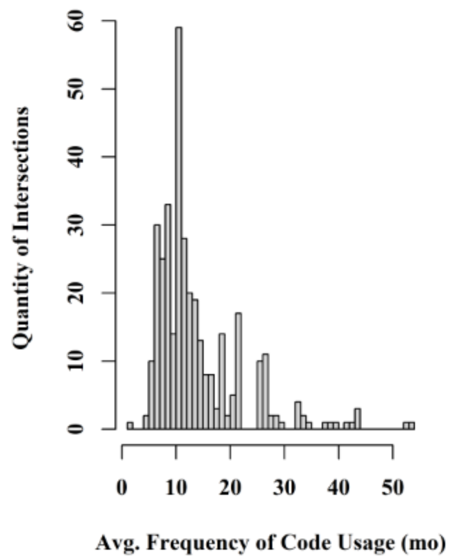


Figure 4.7 Use of Action Code 1241

Action Code 1242: 12-month Operational Performance Review

Statistics related to the frequency distribution of Action Code 1242 can be found in Table 4.12. Division 3 did not apply Action Code 1242 to 5 intersections. Figure 4.8 provides a graphic representation of the events data, mirroring the statistics found in Table 4.12, showing the overall collection of data rather than the descriptive characteristics. Code 1242 has been utilized consistently from 2010 to 2020. However, there are some intersections with data that only extends to 2014.

Table 4.12 "12-month Inspection" Frequency Distribution Statistics [Action Code 1242]

Statistic	Value (months)
Minimum	4.50
1st Quartile	8.60
Median	9.80
Mean	9.64
3rd Quartile	10.83
Maximum	33.00
Standard Deviation	2.11
NA's	5

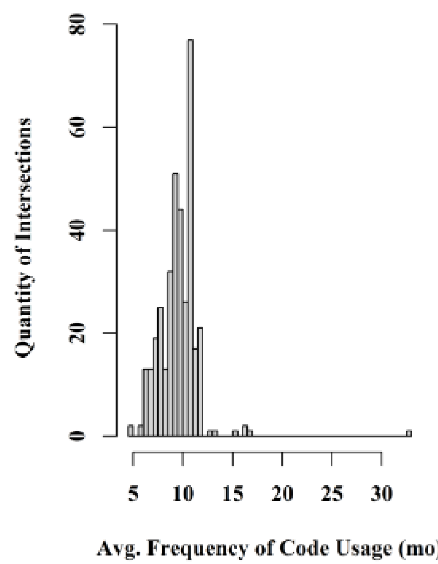


Figure 4.8 Use of Action Code 1242

Action Code 1243: 24-month Operational Performance Review (heads only)
Statistics related to the frequency distribution of Action Code 1243 can be found in Table 4.13. Division 3 did not apply Action Code 1243 to 17 intersections. Figure 4.9 provides a graphic representation of the events data, mirroring the statistics found in Table 4.13, showing the overall collection of data rather than the descriptive characteristics. Code 1243 has been utilized consistently from 2010 to 2020. However, there are some intersections with data that only extends to 2014.

Table 4.13 "24-month Inspection" Frequency Distribution Statistics [Action Code 1243]

Statistic	**Value (months)**
Minimum	1.00
1st Quartile	9.80
Median	11.75
Mean	14.46
3rd Quartile	17.00
Maximum	102.00
Standard Deviation	8.55
NA's	17

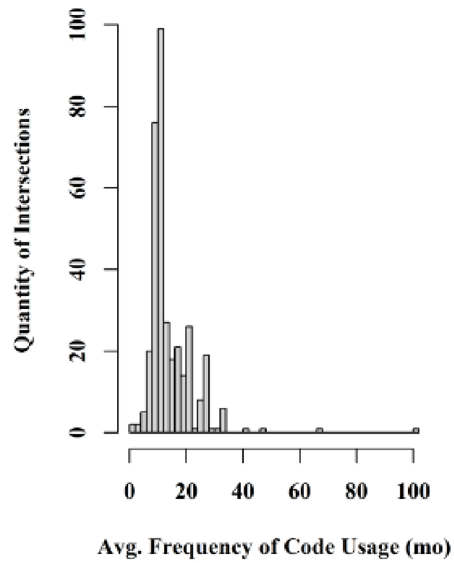


Figure 4.9 Use of Action Code 1243

Replacement Codes
Use of replacement codes is further analyzed in this section. Analysis provided a set of sample statistics showing how frequently each of the action codes is utilized at each intersection within Division 3.

Action Code 1212: Repair/Replace all Red LED Modules
Statistics related to the frequency distribution of Action Code 1212 can be found in Table 4.14. Division 3 did not apply Action Code 1212 to 285 intersections. Figure 4.10 provides a graphic representation of the events data, mirroring the statistics found in Table 4.14, showing the overall collection of data rather than the descriptive characteristics. Of note is the fact that Code 1212 has only been used two times since the year 2013. Once in 2014 and once in 2019. At first glance this implies that few red LED Modules have been replaced since 2013. However, codes 1215, 1216, 1217, and 1247 can also indicate that red modules have been replaced. Therefore, it is inaccurate to claim that most red LED Modules have been in place since 2013 (seven years from the end of the data: 2020) based on action code 1212.

Table 4.14 "Repair/Replace: All Red LED Modules" Frequency Distribution Statistics [Action Code 1212]

Statistic	Value (months)
Minimum	6.00
1st Quartile	24.00
Median	26.00
Mean	27.40
3rd Quartile	27.00
Maximum	105.00
Standard Deviation	11.24
NA's	285

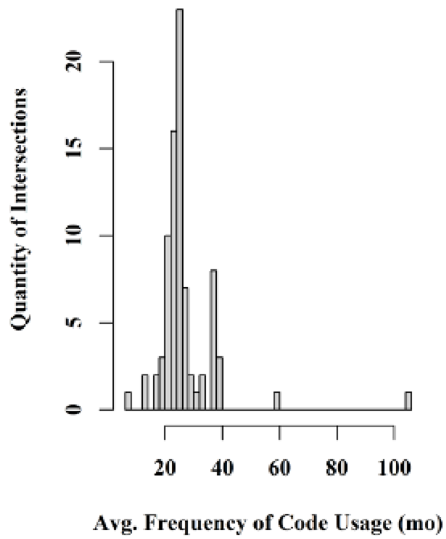


Figure 4.10 Use of Action Code 1212

Action Code 1213: Repair/Replace all Green LED Modules

Statistics related to the frequency distribution of Action Code 1213 can be found in Table 4.15. Division 3 did not apply Action Code 1213 to 287 intersections. Figure 4.11 provides a graphic representation of the events data, mirroring the statistics found in Table 4.15, showing the overall collection of data rather than the descriptive characteristics. Of note is the fact that Code 1213 has only been used one time since the year 2013, in 2019. At first glance this implies that few green LED Modules have been replaced since 2013. However, codes 1215, 1216, 1217, and 1247 can also indicate that green modules have been replaced. Therefore, it is inaccurate to claim that most green LED Modules have been in place since 2013 (seven years from the end of the data: 2020) based on action code 1213.

Table 4.15 "Repair/Replace: All Green LED Modules" Frequency Distribution Statistics [Action Code 1213]

Statistic	Value (months)
Minimum	6.00
1st Quartile	22.75
Median	25.00
Mean	26.04
3rd Quartile	27.00
Maximum	105.00
Standard Deviation	11.51
NA's	287

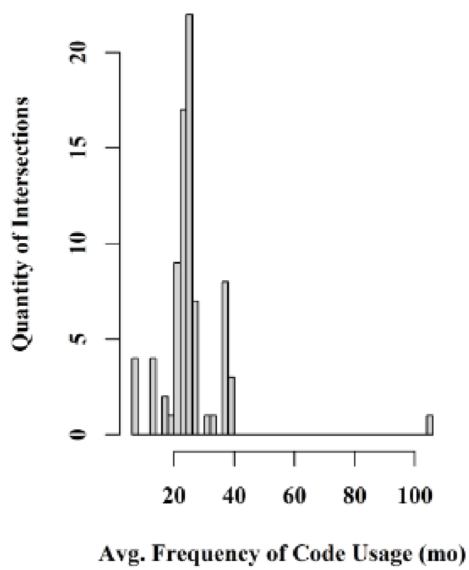


Figure 4.11 Use of Action Code 1213

Action Code 1214: Repair/Replace all Yellow LED Modules

Statistics related to the frequency distribution of Action Code 1214 can be found in Table 4.16. Division 3 did not apply Action Code 1214 to 287 intersections. Figure 4.12 provides a graphic representation of the events data, mirroring the statistics found in Table 4.16, showing the overall collection of data rather than the descriptive characteristics. Of note is the fact that Code 1214 has only been used one time since the year 2013, in 2019. At first glance this implies that few yellow LED Modules have been replaced since 2013. However, codes 1215, 1216, 1217, and 1247 can also indicate that yellow modules have been replaced. Therefore, it is inaccurate to claim that most yellow LED Modules have been in place since 2013 (seven years from the end of the data: 2020) based on action code 1213.

Table 4.16 "Repair/Replace: All Yellow LED Modules" Frequency Distribution Statistics [Action Code 1214]

Statistic	Value (months)
Minimum	6.00
1st Quartile	23.00
Median	25.00
Mean	26.81
3rd Quartile	27.00
Maximum	105.00
Standard Deviation	10.90
NA's	287

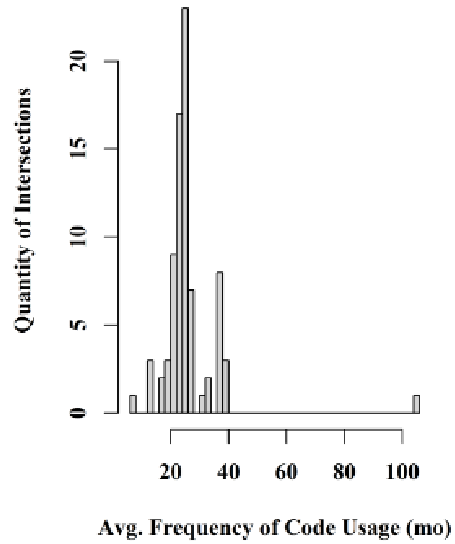


Figure 4.12 Use of Action Code 1214

Action Code 1215: Repair/Replace LED Signal Module – Completely Dark

Statistics related to the frequency distribution of Action Code 1215 can be found in Table 4.17. Division 3 did not apply Action Code 1215 to 282 intersections. Figure 4.13 provides a graphic representation of the events data, mirroring the statistics found in Table 4.17, showing the overall collection of data rather than the descriptive characteristics. Code 1215 has been used regularly from 2010 to 2020, as would be expected of a spot replacement code like this one.

Table 4.17 "Repair/Replace: LED Signal Module – Completely Dark" Frequency Distribution Statistics [Action Code 1215]

Statistic	Value (months)
Minimum	8.00
1st Quartile	20.00
Median	36.00
Mean	47.32
3rd Quartile	66.00
Maximum	132.00
Standard Deviation	34.59
NA's	282

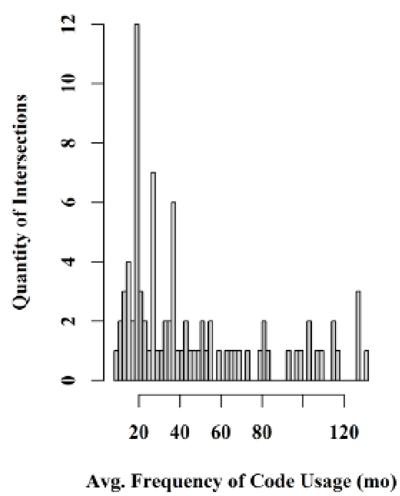


Figure 4.13 Use of Action Code 1215

Action Code 1216: Repair/Replace LED Signal Module – Partially Illuminated
Statistics related to the frequency distribution of Action Code 1216 can be found in Table 4.18. Division 3 did not apply Action Code 1216 to 332 intersections. Figure 4.14 provides a graphic representation of the events data, mirroring the statistics found in Table 4.18, showing the overall collection of data rather than the descriptive characteristics. Code 1216 has been used regularly from 2010 to 2020, as would be expected of a spot replacement code like this one.

Table 4.18 "Repair/Replace: LED Signal Module – Partially Illuminated" Frequency Distribution Statistics [Action Code 1215]

Statistic	Value (months)
Minimum	8.00
1st Quartile	17.00
Median	27.00
Mean	46.83
3rd Quartile	69.50
Maximum	132.00
Standard Deviation	39.29
NA's	332

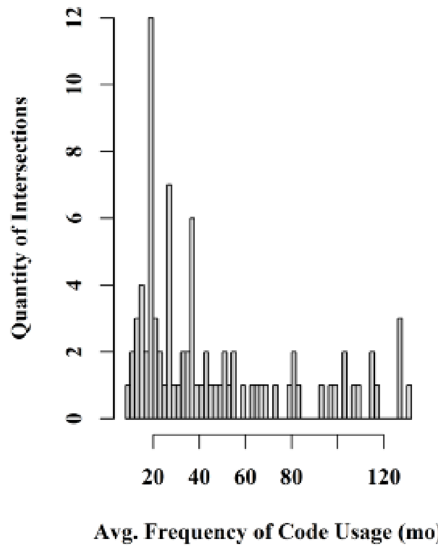


Figure 4.14 Use of Action Code 1216

Action Code 1217: Repair/Replace LED Signal Module – Normal: End of Life
Statistics related to the frequency distribution of Action Code 1217 can be found in Table 4.19. Division 3 did not apply Action Code 1217 to 296 intersections. Figure 4.15 provides a graphic representation of the events data, mirroring the statistics found in Table 4.19, showing the overall collection of data rather than the descriptive characteristics. Note that Code 1217 has only been used two times since the year 2013. Once in 2018 and once in 2020. At first glance, this implies that few LED Modules have been replaced for End-of-Life since 2013. However, codes 1212, 1213, 1214, 1215, 1216, and 1247 can also indicate that modules have been replaced. They may have been used instead of code 1217; therefore, it is inaccurate to claim that most modules have been in place since 2013.

Table 4.19 "Repair/Replace: LED Signal Module – Normal: End of Life" Frequency Distribution Statistics [Action Code 1217]

Statistic	Value (months)
Minimum	8.00
1st Quartile	20.00
Median	36.00
Mean	47.32
3rd Quartile	66.00
Maximum	132.00
Standard Deviation	34.59
NA's	282

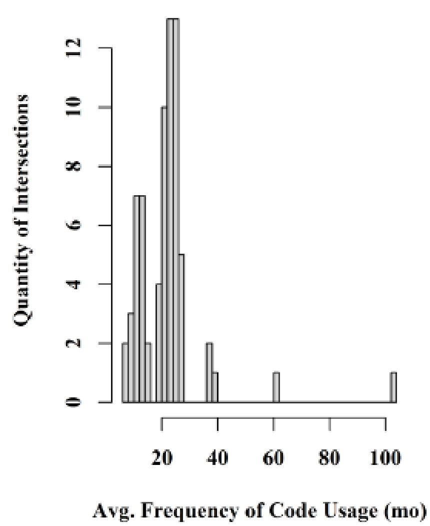


Figure 4.15 Use of Action Code 1217

Action Code 1247: Repair/Replace All LEDs
Statistics related to the frequency distribution of Action Code 1247 can be found in Table 4.20. Division 3 did not apply Action Code 1247 to 354 intersections. Figure 4.16 provides a graphic representation of the events data, mirroring the statistics found in Table 4.20, showing the overall collection of data rather than the descriptive characteristics. Note that Code 1247 has only been recorded for 13 intersections from the year 2014 to 2018.

Table 4.20 "Repair/Replace: All LEDs" Frequency Distribution Statistics [Action Code 1247]

Statistic	Value (months)
Minimum	17.00
1st Quartile	67.00
Median	82.00
Mean	75.77
3rd Quartile	101.00
Maximum	106.00
Standard Deviation	28.83
NA's	354

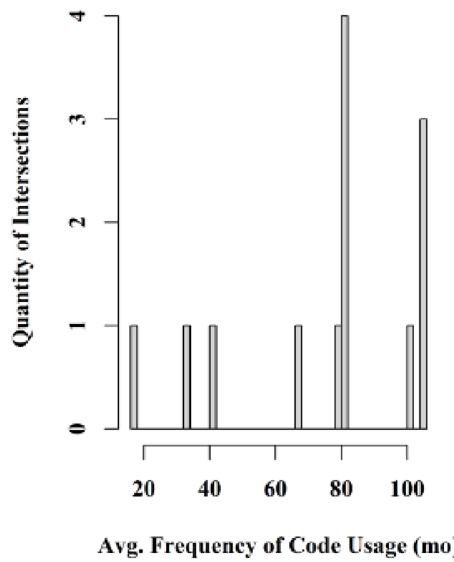


Figure 4.16 Use of Action Code 1247

4.2.2.2 Conclusions from the Division 3 Case Study

Table 4.21 provides a summary of the usage of LED Module related Action Codes in Division 3 from 2010 to 2020. Distribution statistics for each of the Inspection and Replacement codes has been provided. Table 4.21 provides the Action Code, along with the quantity of intersections at which it was applied, the percentage of intersections using that code in Division 3, the mean frequency at which the code was reported, and the standard deviation of the reporting frequency. For example, the first Action Code, 1240, was used at 364 intersections within Division 3 between 2010 and 2020. That makes up 99% of the total quantity of intersections that are maintained by Division 3. This also means that there was 1% of intersection for which the Action Code 1240 was never recorded. Code 1240 was used with an average frequency of 10.73 months, with a standard deviation of 3.32 months. Remember that Action Code 1240 is used to record 6-month inspection activities. Therefore, this analysis found that the annual inspections are occurring at approximately 11 months, give or take around 3 months. That is the expected result of a timeline analysis of annual inspection activities, as the 6-month inspections occur in-between the 12-month inspections.

There are notable differences in the quantity of intersections to which inspection codes were applied versus the quantity of intersections to which replacement codes were applied. Column 2 shows this quantity as a numeric value, while Column 3 shows the same quantity as a percentage of the intersections found in Division 3 (percent coverage). The *lowest* percentage of intersections using an inspection code for Division 3 Inspections was 95%. However, the *highest* amount of coverage for Division 3 Replacements was only 23%. This implies that, in the field, there may be more emphasis placed on recording inspection activities than there is on recording replacement activities. This could be attributed, in part, to inspection logs. Inspection logs are physically kept in the cabinet for the intersection and must be filled out manually, requiring technicians to immediately note work performed. Replacement codes may be input when timesheet hours are recorded rather than immediately after performed work, which means they are likely done later. This could mean that the recording of some of these activities is being overlooked.

Remember it was mentioned that for codes 1212 (Replacement of Red LED Modules), 1213 (Replacement of Green LED Modules), and 1214 (Replacement of Yellow LED Modules), there were only a handful of datapoints after the year 2013. The assumption initially was that the remainder of the Replacement codes would make up for the lack of data found. However, looking at Table 4.21, if one assumes that (1) all replacement activities occurred at unique intersections, and (2) all these activities occurred after 2013, that would mean that 56% of intersections (sum of Col 3. For 1215, 1216, 1217, and 1247) had their modules replaced since 2013. Leaving a conservative estimate of 44% of modules being in place for at least seven years. This is at least two years longer than the warranty period and the expected replacement timeline of NCDOT.

Table 4.21 Action Code Frequency Distribution Statistical Summary

Action Code	Intersections with Code (Quantity)	Intersections with Code (% of Division)	Mean Frequency (months)	Standard Deviation of Frequency (months)
Inspection				
1240	364	99 %	10.73	3.32
1241	354	96 %	14.05	8.21
1242	362	99 %	9.64	2.11
1243	350	95 %	14.46	8.55
Replacement				
1212	82	22 %	27.40	11.24
1213	80	22 %	26.04	11.51
1214	80	22 %	26.81	10.90
1215	85	23 %	47.32	34.59
1216	35	10 %	46.83	39.29
1217	71	19 %	22.59	12.96
1247	13	4 %	75.77	28.83

Conducting this Case Study of Division 3 shows that technicians are completing inspection activities in a timely manner and are replacing LED Modules as needed on a spot replacement basis. This finding is in line with the information provided by Division 3 during their interviews. Many LED Modules are reported as having been in place for at least seven years. This dataset is limited to 2010-2020, meaning that it is possible some LED Modules have been replaced between 2021 and the time of this report. However, based on the replacement patterns shown it is likely that many modules are reaching ten years or older.

Due to time constraints, it is not possible to do such an in-depth analysis for each of the 14 Divisions during the duration of this project. However, with statistical assistance, the average age of modules in the field across NCDOT was found to be 7.41 years (as of 2020) as discussed in Section 4.2.3 LED Module Age Across NCDOT.

4.2.3 LED Module Age Across NCDOT

Due to the volume of data made available from DTS, Sneha Karanjai and Chengyu Zhou provided statistical assistance for its analysis. Ms. Karanjai and Mr. Zhou are both graduate students from the Statistics Department at NCSU. Because DTS does not specifically track the "time in field" for LED Modules, that information had to be gleaned from the available LED and Events data sets. First, these datasets were joined. Once the data was combined, it was filtered for the most recent activities based on the Replacement Action Codes provided in Table 4.8. The "Completed Time" of each activity is recorded, providing a date of replacement. That date of replacement was then used to determine the "time in field," or assumed age, of LED Modules across the state and for each division.

The hypothesis in question for this analysis was: On average, LED modules have been in place for greater than 5 years. This hypothesis was based on the findings of the Division 3 Case Study (estimating approximate ages to be seven years). Due to the large sample size and unknown population variance, a one sample t-test was used to test the hypothesis against the data.

Table 4.22 provides summary statistics for NCDOT along with each of the 14 Divisions. Column 1 indicates which Division the data is from. Column 2 shows the sample size of modules identified by the statistics team. Columns 3 through 8 provide distribution statistics for the sample (Minimum, 1st Quartile, Median, Mean, 3rd Quartile, and Maximum). Column 9 indicates the percentage of LED Modules found to be older than 5 years. Column 10 provides the result of the one-sample t-test performed on the data, indicating whether the result is significant or not. In the case of these data, all the results were significant (indicated by a p-value of less than 0.05), meaning that a large majority of the LED Modules were found to be older than 5 years.

Table 4.22 Analysis of "Time in Field" or Age of LED Modules

Division	Sample Size	Minimum	Q1	Median	Mean	Q3	Max	% > 5 years	t-test (p-value)
1	320	1	9	10	8.66	10	11	83.44	<0.0001
2	3,047	0	7	7	7.35	8	11	88.28	<0.0001
3	2,460	0	8	9	8.38	10	11	87.11	<0.0001
4	8,207	0	3	10	7.51	11	11	65.69	<0.0001
5	2,174	0	9	10	9.37	11	11	93.33	<0.0001
6	6,980	0	4	9	7.51	10	11	66.69	<0.0001
7	555	1	5	7	6.72	10	11	61.26	<0.0001
8	22,916	0	5	6	7.51	10	11	71.33	<0.0001
9	16,249	0	4	6	6.88	11	11	56.73	<0.0001
10	16,227	0	4	7	7.05	9	11	73.97	<0.0001
11	6,132	2	8	9	8.27	10	19	86.51	<0.0001
12	2,235	2	4	7	6.06	8	11	52.13	<0.0001
13	8*								
14	3,156	0	7	7	7.99	10	11	82.41	<0.0001
NCDOT	**90,666**	**0**	**5**	**9**	**7.41**	**10**	**11**	**70.77**	**<0.0001**

The average age of an LED Module recorded in DTS (from 2010-2020) was 7.41 years for the modules owned by NCDOT. Again, there is the possibility that this has been lowered with replacements that occurred between 2021 and the time of this report. However, it is possible that many of the LED Modules in the field are reaching ten years of age or more, which puts them well past the warranty lifespan. It also pushes them past the expected lifespan discussed in the literature (~8 years). Due to the degradation experienced by LED Modules, older modules will still illuminate. However, their brightness is unlikely to reach the acceptable minimum thresholds set forth by the ITE standards of 2005 and 2007. Regularly utilizing dim LED Modules may be cause for some safety concerns.

4.3 Final Words on Current Practices

The current practices of NCDOT related to LED Module and Signal Head replacement are discussed in this section. Statewide, the expectation is for inspections to occur regularly. There has also been an expectation that LED Modules would be replaced at the end of their warrantied life. Until recently that warrantied life was 5-years.

4.3.1 Purchasing, Expenses, and Contracts

Review of purchasing data highlights that the Central Warehouse for NCDOT is responsive to the needs of the Divisions. The quantities of LED Modules and Signal Heads ordered reflect those requested by the Divisions. The purchasing data also shows that a regular, blanket replacement of LED Modules was not occurring for the 5-year modules. Quantities of LED Modules ordered are lower than would be expected if blanket replacement were occurring.

NCDOT's method for tracking LED Module and Signal Head expenses does a good job of separating the costs between NCDOT, municipalities, and contracted work. Due to the funding for this work being a small part of a larger funding allocation and being based on the previous year's expenditures, there appears to be room for improvement with budget planning. Creating a Needs-Based budgeting system for LED Modules and Signal Heads could ensure a smooth transition from the old 5-year modules to the new 15-year modules.

From the contracts available for analysis, it appears that there is also room for improvement in that area. Statewide there was no discernable pattern among the work contracted by the Divisions. Groups supplying materials were getting a better deal in some Division than others. Moving forward there is a possibility of developing a standard method of contract development, ensuring that Divisions across the state are receiving the same standard of work for a similar price.

4.3.2 Replacement Strategies – Spot & Blanket

Case studies prioritizing both spot and blanket replacement were discussed. A major finding from the informational interviews was that many Divisions have had to shift to a replacement strategy solely based on spot replacement due to a lack of personnel and funding. This is shown in the data from Case Study: Division 3. On average, the age of LED Modules in NCDOT was found to be 7 years (using 2010-20 data), indicating that many modules may now be going on 10 years old. Those modules will need to be replaced.

Potential replacement strategies will be discussed in Section 5: Development of Replacement Strategy Alternatives. Moving from products with a 5-year warranty to products with a 15-year warranty opens an opportunity to establish new strategies and systems that will maintain a blanket replacement process in the future.

5.0 Development of Replacement Strategy Alternatives

Both LED Modules and Signal Heads need to be replaced at the end of their service life. How is that to be done, especially considering the recent significant technology improvements and the resulting service life extension? This section suggests a set of strategies that NCDOT could consider for this purpose.

5.1 LED Traffic Signal Inspection Strategies

As discussed in Section 4.1.1, intersection inspections are conducted on a 6-month, 12-month, and 24-month basis, with resulting spot replacements to follow. This strategy of inspection and spot replacement reportedly functions well for NCDOT Divisions provided they have been able to maintain adequate manpower within the Division to execute the work.

5.2 LED Traffic Module and Signal Head Service Life and Replacement Cycles

To address alternative replacement strategies for both LED Modules and Signal Heads it is necessary to understand current warranties and expected service life for the components utilized by NCDOT.

Based on informational interviews with NCDOT personnel, it is understood that the past goal was to replace LED Modules on a 5-year cycle as that is the warranty length of the modules used since around 2006. Signal Heads, on the other hand, have a significantly longer service life, with many reportedly lasting as long as 30 years before there is noticeable wear and tear. NCDOT recently began the process of filling the Central Warehouse with newer 15-year warrantied modules rather than 5-year modules.

These findings allow for the adoption of, at minimum, a 15-year replacement cycle with new modules, and a maximum of a 20-year replacement cycle. Thus, LED Module blanket replacement cycles to be considered for evaluation in replacement strategy alternatives include:

- 5 years – to serve as a baseline for products that are currently in the field
- 15 years – based on recent LED Module upgrades and respective warranty extensions

5.3 Alternative LED Module and Signal Head Replacement Strategies

Table 5.1 shows a summary of the nine LED Module and Signal Head replacement alternatives identified for evaluation and their defining characteristics. These alternatives are discussed in Sections 5.3.1-5.3.8 below.

The inclusion of Signal Heads in the replacement strategy is a concept that was raised during a site visit with an NCDOT Division. There are increased levels of ease and safety which occur when the modules can be installed in the Signal Heads on the ground at the Division Warehouse. Then the whole unit can be installed at the intersection all at the same time. Given that the signal head expected life has been reported to be at least that of the LED Modules, simultaneous replacing both the modules and the heads is a possibility to be considered. Alternative 1 serves as a benchmark strategy, showing the process that NCDOT has been using since LED Modules were first installed starting in 2006. Alternatives 2 through 13 vary based on expected service life, blanket replacement: cycle length, blanket replacement: replacement period length, concurrent replacement of Signal Heads, and inflation. The following rules were applied to develop Alternatives 2 through 9.

- Inspections are occurring on a constant basis throughout the year and the required maintenance and spot replacements they identify are considered to be separate from the blanket replacement cycle.
- Spot replacement of Signal Heads is assumed to follow an as-needed approach to replacement based on observed head condition in the field.
- The Alternative 1 replacement strategy is assumed to be in place currently, allowing other alternatives to build from a common and familiar starting point.

- Replacement Cycle Length is the total amount of time that an LED Module will stay in the field (assuming it is not replaced during spot replacement).
- Replacement Period Length is the total amount of time that technicians are planning to actively participate in a blanket replacement process.

Table 5.1 shows the characteristics that will be assigned to each alternative so a comparative analysis can be conducted. Column 1 contains the list of characteristics to be defined. Columns 2 through 10 each contain a unique set of values attributed to one specific replacement strategy alternative. For example, Alternative 3 will utilize a Blanket Replacement Cycle Length of 15 years, along with a Replacement Period of 15 years. Because this is an alternative to be considered by NCDOT moving forward, the expected lifespan of the LED Modules is 15 years, per the new warranty period. Alternative 3 is only considering the blanket replacement of LED Modules, Signal Heads will be spot replaced as needed. Alternative 3 uses an interest rate of 0%. This means that Alternative 3 can be compared to other alternatives that are also using an interest rate of 0%. There is one special case, that is Alternative 2, in which no blanket replacement occurs, only spot replacement. Replacement cycle and period length have been removed for that alternative as they are not applicable.

Table 5.1 Characteristics of LED Module and Signal Head Replacement Strategy Alternatives

Characteristics	**Alternatives**								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Blanket Replacement ***Full Cycle Length***	5	-	15	15	15	15	15	15	15
Blanket Replacement ***Replacement Period Length***	5	-	15	15	5	5	1	1	1
Module Expected Life (years)	5	15	15	15	15	15	15	15	15
Replacement of Signal Head with Modules				X		X		X	
Inflation	0%	0%	0%	0%	0%	0%	0%	0%	3%

There are many reasons for considering these alternatives. NCDOT is entering a transitionary period resulting from significant technology advances in lighting. Setting up a sufficient strategy for the future will go a long way towards ensuring that traffic signals across North Carolina are well maintained.

An additional factor for consideration is the level of record keeping which is conducted by NCDOT. These replacement alternatives are dependent on a semi-sequential replacement process. For these scenarios to operate most effectively it will be important that those modules and signal heads replaced early in any blanket replacement cycle are also replaced early in the subsequent replacement cycles. No matter which alternative is ultimately chosen, it is important that NCDOT maintain some form of comprehensive inventory and replacement activity database. Recording the dates on which various modules and heads are installed, and their locations, will allow the agency to document and archive how many of their in-place LED Modules are reaching their end of life. Knowing this information will allow technician crews to work at an improved level of efficiency, prioritizing those signals which have been in place the longest. Thus, it is critical to maintain a database of installation dates, blanket replacement sequencing, and dates of work completed.

5.3.1 Alternative 1: Benchmark

Alternative 1 refers to a benchmark LED Module and Signal Head replacement strategy. It assumes a standard inspection and spot replacement strategy based on the criteria outlined in Section 5.2 above. Signal Heads are spot replaced rather than scheduled with the LED Modules. This alternative assumes a 5-year blanket replacement cycle for the modules as this is the process that has reportedly been in operation for over ten years. This alternative serves as a baseline for comparison to the other alternatives. It will provide a cost estimate based on current conditions which can be used to evaluate the remaining alternatives on a comparison basis. It should be noted that Alternative 1 assumes a 3% rate of inflation.

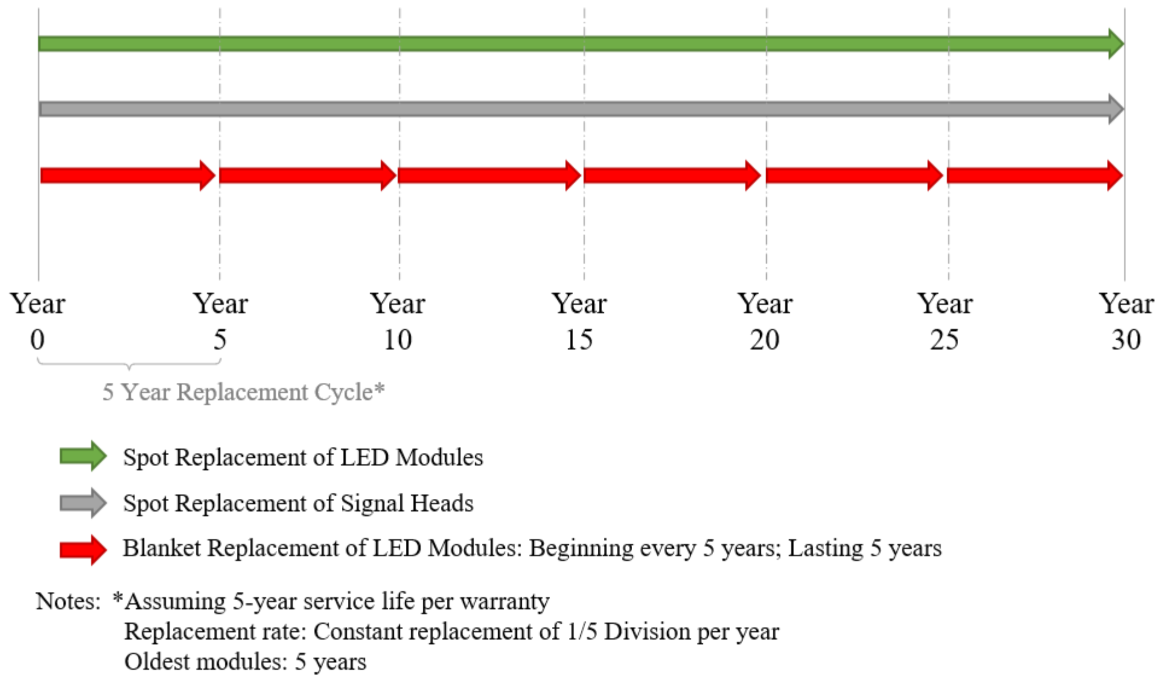


Figure 5.1 Alternative 1 LED Module and Signal Head Replacement Strategy

5.3.2 Alternative 2: Spot Replacement Only

Alternative 2 follows the timeline shown in Figure 5.2. This alternative assumes that blanket replacement will not occur, relying fully on spot replacement to slowly install 15-year modules across the simulated area. Spot replacement of both Modules and Signal Heads will be ongoing. The assumed rate of inflation is 0%.

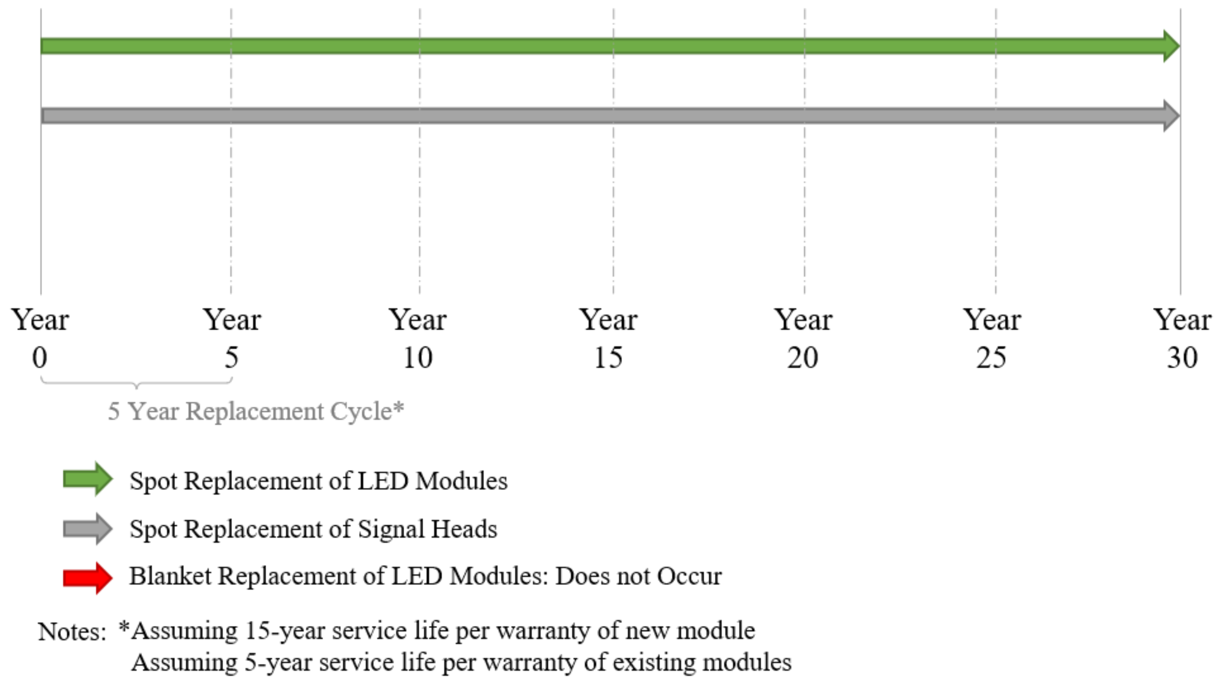


Figure 5.2 Alternative 2 LED Module and Signal Head Replacement Strategy

5.3.3 Alternative 3: 15-year Replacement Period of LED Modules Only

Alternative 3, using the timeline in Figure 5.3, allows a fifteen years period for the agency to conduct a blanket replacement during the 15-year replacement cycle. Spot replacement of LED Modules is assumed to be ongoing. Signal Heads will only be replaced as-needed, on a spot replacement basis. The assumed rate of inflation is 0% for Alternative 3.

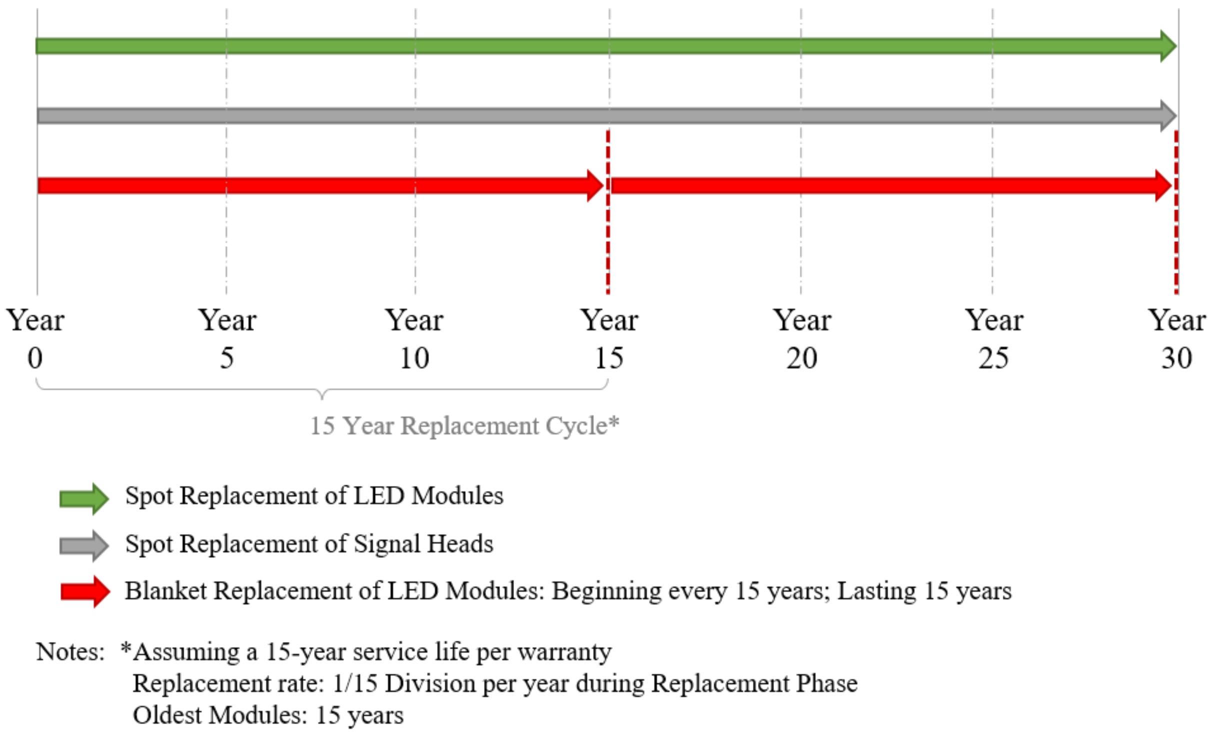


Figure 5.3 Alternative 3 LED Module and Signal Head Replacement Strategy

5.3.4 Alternatives 4: 15-year Replacement Period of LED Modules and Signal Heads

Figure 5.4 depicts Alternative 4. This alternative considers the extended 15-year warranty of the new modules. This alternative allows a fifteen-year period for the agency to conduct a blanket replacement during the 15-year replacement cycle. Spot replacement of LED Modules is assumed to be ongoing. Signal Heads will follow the same blanket replacement process as the LED Modules. The assumed rate of inflation is 0% for Alternative 3.

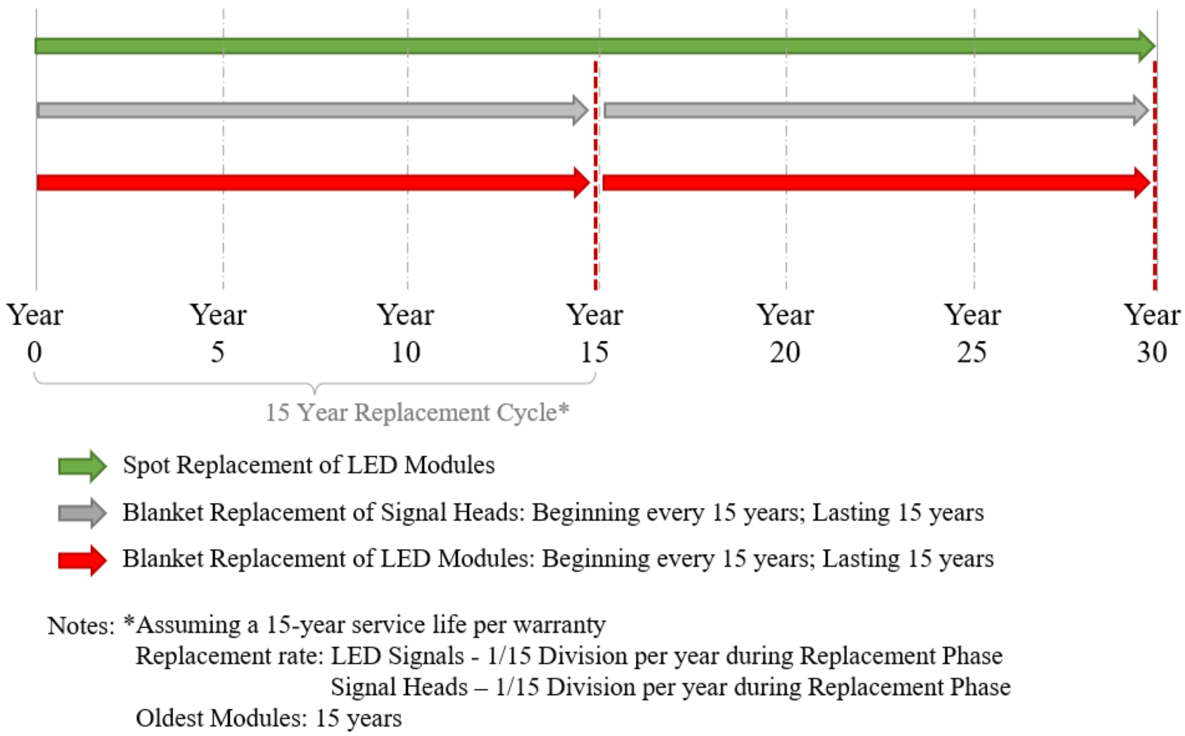


Figure 5.4 Alternative 4 LED Module and Signal Head Replacement Strategy

5.3.5 Alternatives 5: 5-year Replacement Period of LED Modules Only

Alternative 5, using the timeline in Figure 5.5, considers the extended 15-year warranty of the new modules. This alternative allows a five-year period for the agency to conduct a blanket replacement during the 15-year replacement cycle. Spot replacement of LED Modules is assumed to be ongoing. Signal Heads will be replaced on an as-needed, spot replacement basis. The assumed rate of inflation is 0% for Alternative 5.

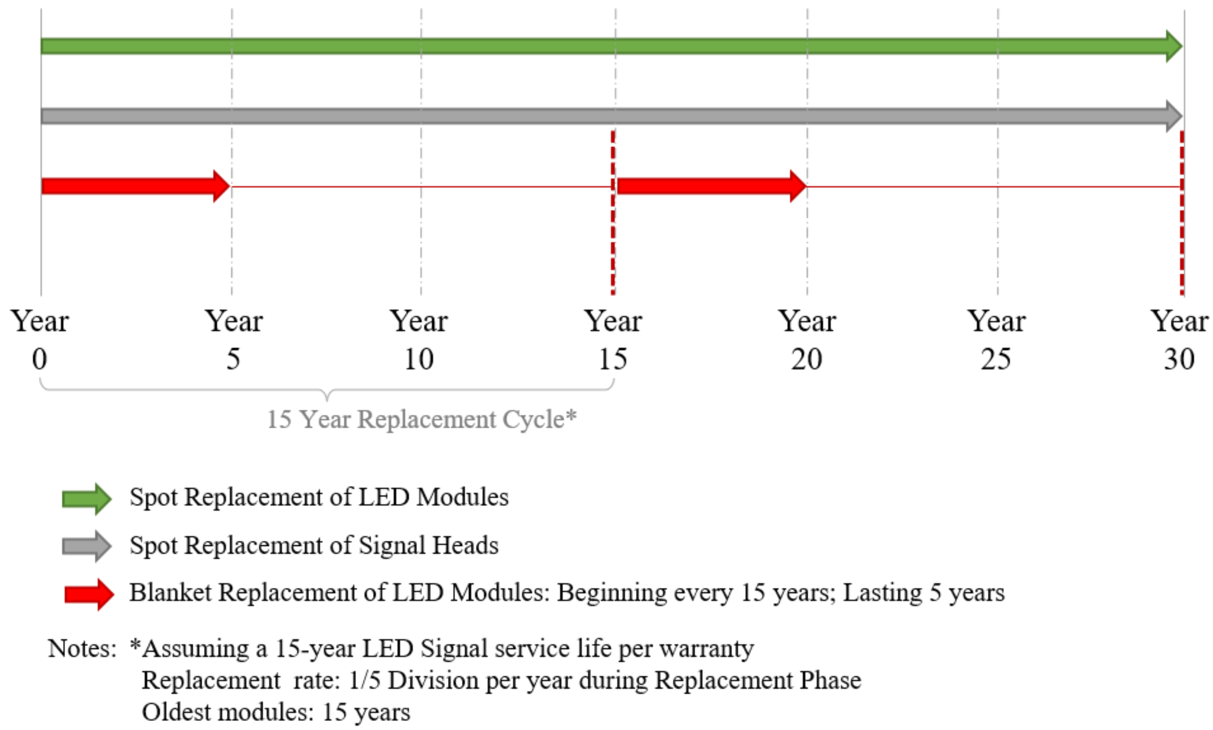


Figure 5.5 Alternative 5 LED Module and Signal Head Replacement Strategy

5.3.6 Alternative 6: 5-year Replacement Period of LED Modules and Signal Heads

Alternative 6, using the timeline in Figure 5.6, consider the extended 15-year warranty of the new modules. This alternative allows a five-year period for the agency to conduct a blanket replacement during the 15-year replacement cycle. Spot replacement of LED Modules is assumed to be ongoing. Signal Heads will follow the same blanket replacement pattern as LED Modules thus reducing field labor time while increasing safety and speed. The assumed rate of inflation is 0% for Alternative 6.

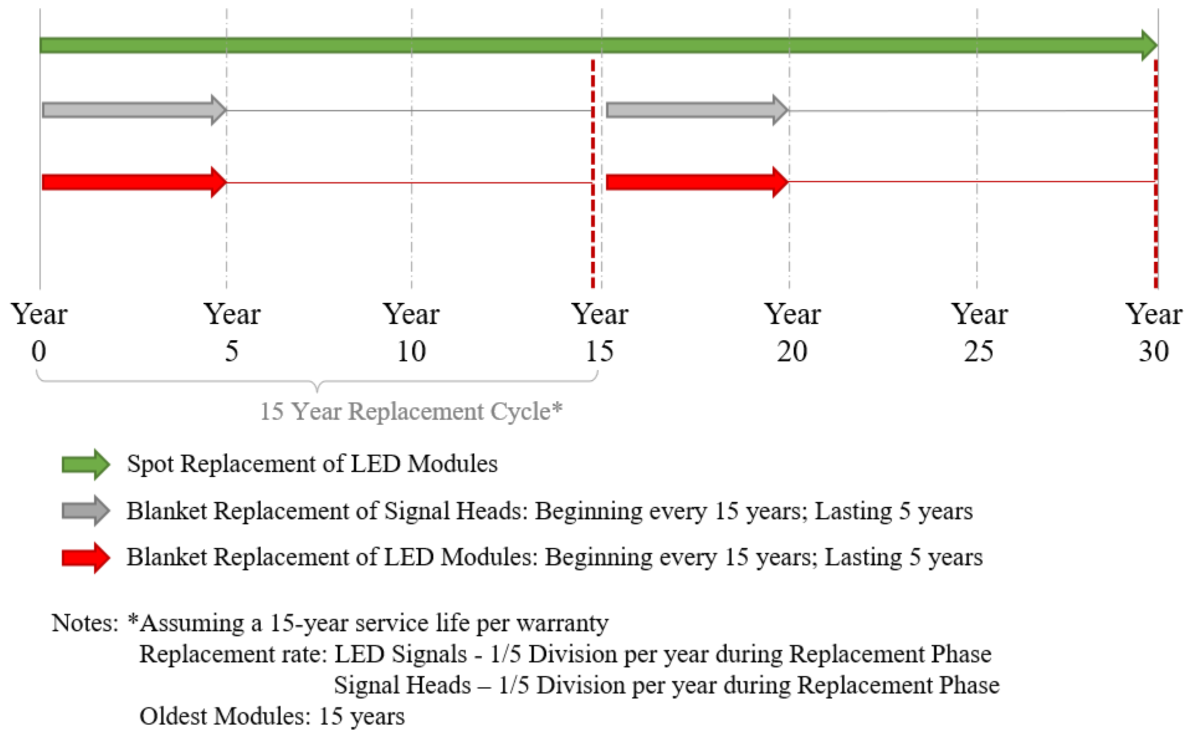


Figure 5.6 Alternative 6 LED Module and Signal Head Replacement Strategy

5.3.7 Alternatives 7 & 9: 1-year Replacement Period of LED Modules Only

Alternatives 7 and 9 use the timeline in Figure 5.7, considering the extended 15-year warranty of the new modules. These alternatives allow a one-year period for the agency to conduct a blanket replacement during the 15-year replacement cycle. Spot replacement of LED Modules is assumed to be ongoing. Signal Heads will be replaced on an as-needed, spot replacement basis. The assumed rate of inflation is 0% for Alternative 7, while the rate of inflation is assumed to be 3% for Alternative 9.

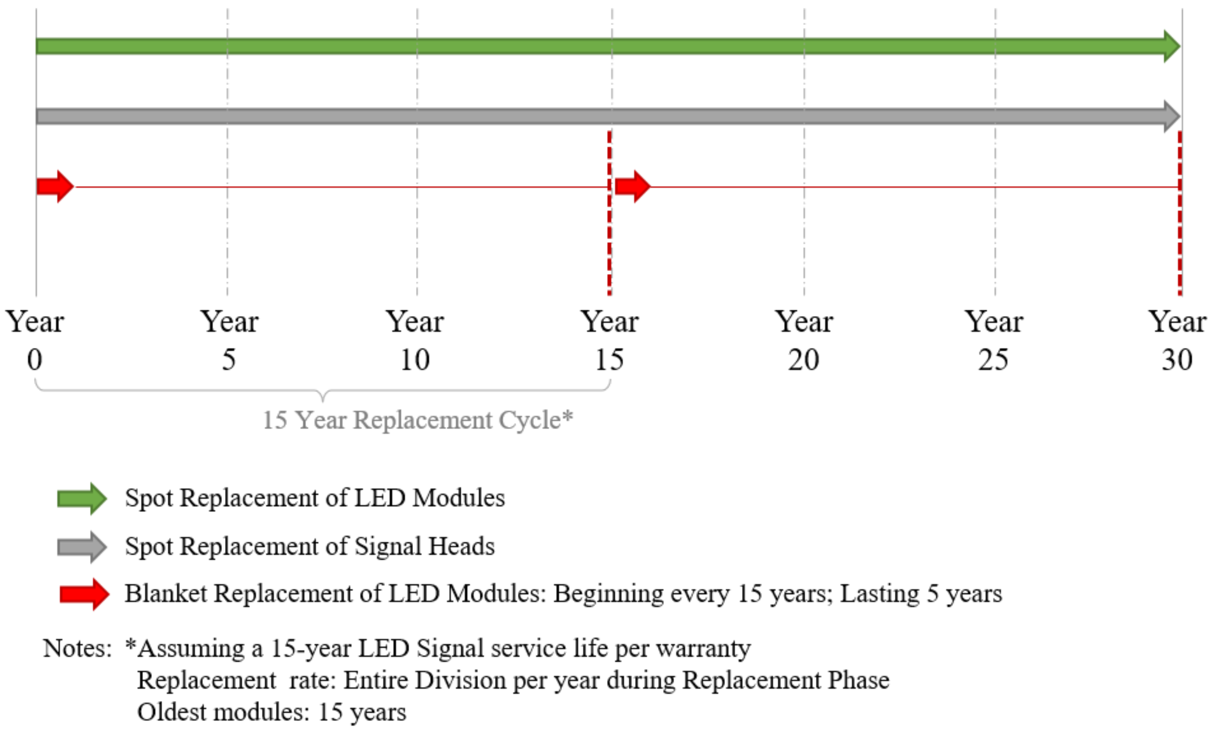


Figure 5.7 Alternatives 7 & 9 LED Module and Signal Head Replacement Strategies

5.3.8 Alternative 8: 1-year Replacement Period of LED Modules and Signal Heads

Alternative 8, using the timeline in Figure 5.8, consider the extended 15-year warranty of the new modules. This alternative allows a one-year period for the agency to conduct a blanket replacement during the 15-year replacement cycle. Spot replacement of LED Modules is assumed to be ongoing. Signal Heads will follow the same blanket replacement pattern as LED Modules thus reducing field labor time while increasing safety and speed. The assumed rate of inflation is 0% for Alternative 8.

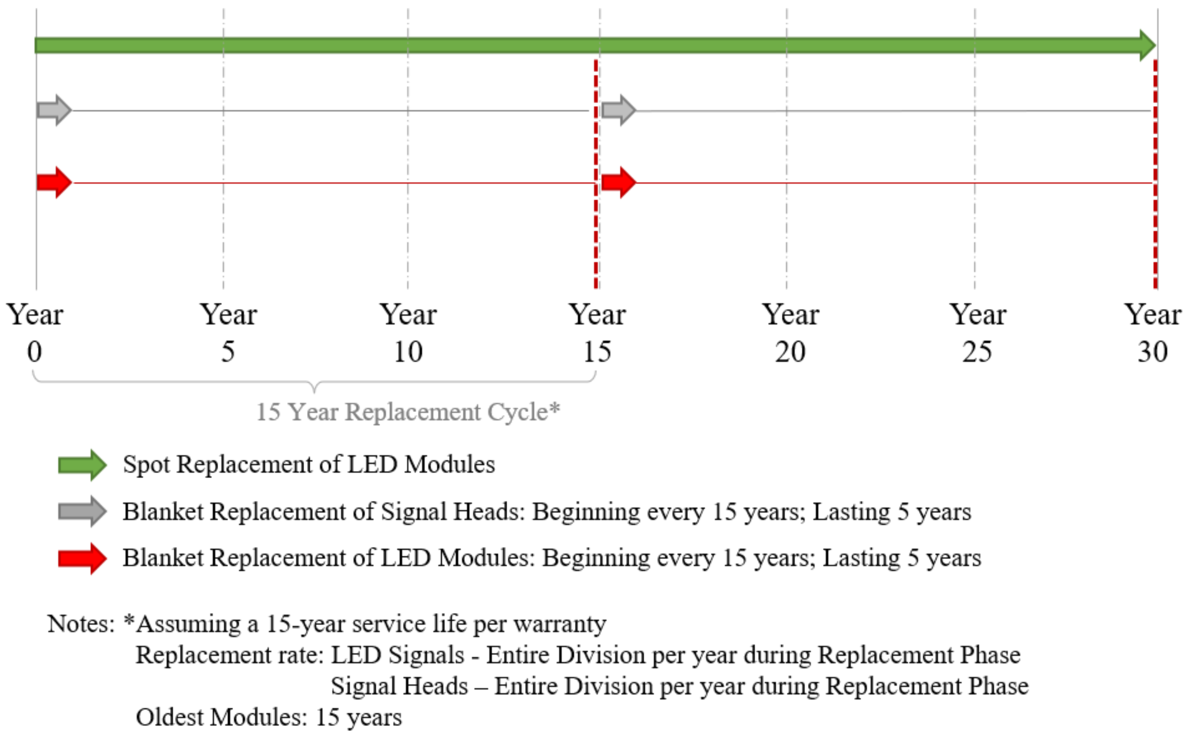


Figure 5.8 Alternative 8 LED Module and Signal Head Replacement Strategy

5.4 Concluding Remarks on Alternate Replacement Strategies

Each of the nine alternatives presented in Section 5.3 is in line with our understanding of current NCDOT practices (See Section 4.0 for details). The set of alternatives has been discussed with the NCDOT research steering committee and refined per their suggestions.

6.0 Development of Simulation

The goal of this project is to determine the cost of replacement strategy alternatives, enabling NCDOT to select a Module and Signal Head replacement plan. The characteristics of this problem include estimating Module lifespan, Module and Signal Head failure rates, and the cost of each replacement activity. Thus, to model the replacement process over time we selected simulation. This chapter evaluates available software, explains why developing a simulation was the most appropriate course of action, and describes the model and the input data.

6.1 Available Software

Searching for possible software to use for this project included identifying currently available options related to transportation asset management and budgeting, and traffic modeling.

Four transportation modeling software programs were identified for evaluation. These include:

- TransCAD,
- PTV VisSim,
- PTV Visum, and
- Synchro Studio v12

TransCAD is specifically for transportation planning, mapping, and analysis from a transportation-user perspective (Caliper n.d.). It is a powerful software for predicting travel demand and highlighting areas of congestion in existing transportation networks. It does not address asset management or system maintenance. Therefore, this software is not suited to the work required for this study. PTV VisSim and PTV Visum are the Micro and Macro programs developed by PTV for modeling transportation network demand (PTV Group n.d., n.d.). They do not appear to address stationary asset management or transportation infrastructure maintenance. Therefore, neither program is suited to the work required for the modeling need addressed herein. Synchro Studio was developed for modeling signal phasing and traffic impacts due to traffic signals (CUBIC Transportation Systems n.d.) and it also is clearly not suited to the modeling needs. All of these programs focus primarily on modeling traffic.

Eight programs were identified related to transportation management. These include:

- Shipwell
- Alvys
- Samsara
- NetSuite
- TAMS
- Hardcat
- DPSI iMaint
- Oracle Enterprise Asset Management

Shipwell, Alvys, and Samsara are all marketed for fleet and trucking operations (alvys n.d.; Samasara n.d.; Shipwell n.d.). These programs do not address stationary asset management or infrastructure maintenance. Therefore, these programs are not suitable to the work required by NCDOT. NetSuite is targeted at freight and other goods-shipping industries (Orcale NetSuite n.d.). It is a powerful software for managing the delivery of manufactured goods. However, it does not relate to stationary asset management or transportation systems. TAMS (Transportation Asset Management Software) provides support of database development related to transportation assets (MS2 n.d.). It appears similar to the DTS database maintained by NCDOT. TAMS does not offer any sort of forecasting capability for asset replacement planning. Hardcat is marketed for the tracking and tagging of assets for review of maintenance, procurement, and depreciation (Hardcat n.d.). It does not have a budgeting component; therefore, it is not suitable for the work required for this project. DPSI's iMaint is similar to the type of program developed for this work – it tracks work orders, preventative maintenance activities, and costs (dspi n.d.). DPSI's budgeting tool is meant for tracking costs, while this research needs predictions of future costs. Finally, Oracle Enterprise Asset Management appears to be a comprehensive asset management software, capable of tracking maintenance and costs (Oracle n.d.). Again, this research requires that cost predictions be made into the future, not simply that costs be tracked as they are incurred.

Other, more generic simulation software is available. For instance, SIMIO, Wolfram Mathematica, and MATLAB are all programs which allow the user to develop simulations of any kind, not specific to transportation or any other field. The research team opted not to utilize these options due to their complexity. It was deemed more practical to explore alternatives solutions better aligned with my workflow requirements. In addition, each of the software programs discussed in this section requires a paid subscription, meaning that any products developed with them could only be distributed to companies or groups already using the software or who were willing to take on the additional cost of the service.

6.2 Key Elements of Developed Software

Due to the limitations described in Section 6.1 Available Software, it was determined that a custom program would be developed specifically for the needs of this project. The custom program was developed to reflect the geography and history of NCDOT. Through informational interviews and the data analysis described in section 4.0 Current Practices, there is sufficient information to create a model of NCDOT's LED Module and Signal Head replacement system.

6.2.1 Modeling Method

To create a custom program for this project, Python 3.10.9 was used to develop an object-oriented program that could simulate specific objects (Intersections, Signal Heads, and Modules) over time. Currently the software is at a basic level, as only the research team has needed to use it. There is a possibility of further development in the future which would add an easy-to-use User Interface, allowing the program to be distributed for use by a wider audience. Due to the program being custom and written in Python for this project, there is currently no cost associated with its use. This is a feature that we would seek to maintain with any future development.

The simulation program was developed using the Monte Carlo (MC) method. "The defining characteristic of MC methods is the random generation of input parameter values from probability distributions (Oberle 2015)." Over increasing iterations, the randomization of an MC simulation provides results with greater and greater accuracy.

6.2.2 Input Basics

The model developed to simulate LED Module and Signal Head replacement utilizes a robust set of input parameters as its base, including a few probability distributions. Table 6.1 provides a list of 21 parameters, a name, assigned value, unit, and short description are provided for each. The following section provides additional sourcing information for each of the parameters in greater detail. Parameters 1 – 15 were assigned values based on information provided by NCDOT. Parameters 16 – 21 were based on the replacement alternative simulated at the time. Note that the input parameters provided here should be reviewed and updated based on current information if this model is used again, with future values that are appropriate to NCDOT.

Table 6.1 Model Input Parameters

#	Parameter	Value	Unit	Model Section	Source
1	Quantity of Intersections	205	Numeric	Setup	Scaling analysis results.
2	Quantity of Signal Heads at an Intersection	Random	Numeric	Setup	Set based on probability density function. [DTS: LEDs; State-Maintained Intersections]
3	Quantity of Modules in a Signal Head	Random	Numeric	Setup	Set based on probability density function. [DTS: Intersections; Signal Heads]
4	Failure Rate: Modules	Variable	%	Spot Replacement	Discrete Failure Curve based on Manufacturer information.
5	Failure Rate: Signal Heads	Variable	%	Spot Replacement	Failure Rate based on expected lifespan of Signal Head
6	Material Cost: Module	33.13	USD	Cost	Purchasing data. (average)
7	Material Cost: Signal Head	Based on Quantity of Modules	USD	Cost	Purchasing data. (average for type)
8	Travel Distance (Long & Short)	58.10 & Random	Miles	Blanket Replacement	Straight Line Analysis [DTS: Locations] and DBSCAN Clustering
9	Travel Speed	45	mph	Blanket Replacement	Assumed
10	Labor & Equipment Cost: Spot Replacement	Variable	USD	Cost; Spot Replacement	Division Data
11	Labor & Equipment Cost: Blanket Replacement	Variable	USD	Cost; Spot Replacement	Division Data
12	Crew Quantity	4	Numeric	Blanket Replacement	Division Data
13	Truck Quantity	4		Blanket Replacement	Division Data
14	Labor Hours: Blanket Replacement	Variable	Hours	Blanket Replacement	Division Data
15	Quantity of Iterations	8	Numeric	n/a	Scaling analysis.
16	Inflation Rate	Variable	%	Setup	Alternate Dependent
17	Replacement Period	Variable	Years	Blanket Replacements	Alternate Dependent
18	Replacement Cycle	Variable	Years	Blanket Replacements	Alternate Dependent
19	Signal Head Lifespan	30	Years	Setup	Assumed
20	New Module Warranty	Variable	Numeric	Spot and Blanket Replacement	Alternate Dependent
21	Joint Replacement	Yes/No	Flag	Blanket Replacement	Alternate Dependent

6.2.3 Output Basics

Ultimately, for each implementation of the simulation, five final files are generated. These include:

- Simulation Lifetime Summary (Table 6.5)
- NCDOT Yearly Summary (Table 6.6)
- NCDOT Yearly Summary (per Intersection) (Table 6.6)
- Contractor Yearly Summary (Table 6.6)
- Contractor Yearly Summary (per Intersection) (Table 6.6)

Each of these files contains average, median, and standard deviation values for:

- LED Module Replacement Counts
- Signal Head Replacement Counts
- Total Cost of Replacement
- Cost of Blanket Replacement
- Cost of Spot Replacement
  - LED Modules and Signal Heads
- Labor Hours

The Simulation Lifetime Summary contains summary information for both NCDOT and Contractor replacement costs, as well as LED Module and Signal Head counts, and labor hours. The values shown in this file contain were calculated across all iterations of the simulation for the entirety of the chosen timeline. Each of the Yearly Summary files, both for NCDOT and a Contractor, provide a summary of replacement costs, LED Module and Signal Head counts, and labor hours, for each of the years observed in the simulation. These files calculate the total costs, counts, and hours for the quantity of intersections utilized during the simulation.

Each of the ‘per Intersection’ Yearly Summary files (NCDOT and a Contractor) provide a summary of replacement costs, LED Module and Signal Head counts, and labor hours, for each of the years observed in the simulation. These files calculate the total costs, counts, and hours as an average per intersection, based on the quantity of intersections utilized in the simulation.

The output measures outlined here will be described in greater detail in section 6.4 Output Measures.

6.2.4 Simulation Logic

Figures 6.1 through 6.6 portray the logic behind the simulation. The overall function of the model is shown in Figure 6.1, which illustrates only the Joint Blanket Replacement process (replacing LED Modules and Signal Heads at the same time). The Independent Blanket Replacement process is shown in Figure 6.2. The simulation starts once the Alternative’s input parameters are specified. Once this has occurred, Year 0 of Iteration 1 begins. A field of intersections is created (see Figure 6.3) containing intersections, Signal Heads, and LED Modules. Once the field is established, each intersection is assigned a replacement phase (see Figure 6.4) correlating to the years in which blanket replacement will occur at that intersection.

Once the intersections are created and the replacement phases are assigned, time starts moving. To start each year, the proper blanket replacement process is followed for either joint or independent replacement (see Figure 6.2 for specifics on independent replacement). Following that determination, the simulation determines whether the current year is one in which blanket replacement will occur. If it is, then the simulation determines which of the intersections are in a replacement phase for that year. Note that spot replacement will occur at all intersections within the simulation each year after blanket replacement has taken place (if it does).

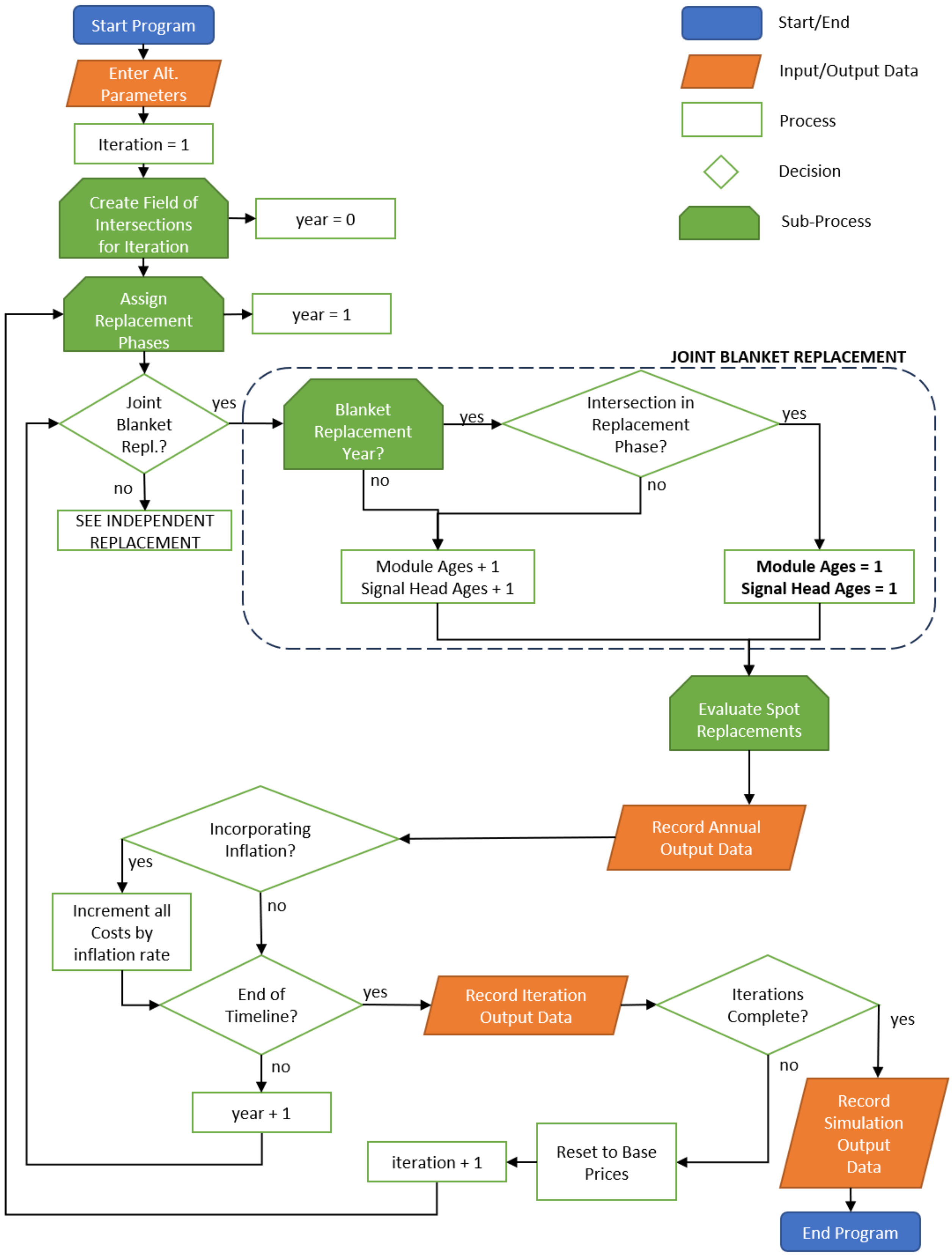


Figure 6.1 Simulation Logic Diagram – Joint Blanket Replacement Settings

Blanket replacement will not occur at all intersections within the simulation in one year unless the user specifies that it should. For the intersections that are in the replacement phase, all LED Modules and Signal Heads are 'replaced' within the model – their ages are reset to one. For all intersections not in a replacement phase, the ages of the LED Modules and Signal Heads are increased by one year. Once blanket replacement has occurred, each Signal Head and Module are evaluated in the spot replacement sub-process (see Figure 6.5). As the intersections are being evaluated, annual output data is recorded for each year. This data includes replacement counts as well as estimated costs and labor hours.

Once annual data is recorded, the simulation incorporates a rate of inflation (if it is being used) with that alternative. If the simulation has not reached the end of the specified timeline (in the case of our alternatives: 30 years) the year is increased by one, and the replacement processes continues. If the simulation has reached the end of the timeline, the output data is recorded for the iteration, based on the annual data previously recorded. If the desired number of iterations has not been reached, then a new field of intersections is created and the replacement processes begin again. If the desired number of iterations has been reached, a set of complete simulation data is recorded based on the iteration data compiled. That data is then processed into the five files mentioned in sections 6.2.3 and 6.4.

Replacement of LED Modules independent of Signal Heads can be modeled using this program. Figure 6.2 provides details on the logic for that process. The outlined steps shown in Figure 6.2 would take the place of the outlined steps shown in Figure 6.1, changing the process from Joint replacement to Independent replacement. In Figure 6.1, when replacement occurs, both the Module age and the Signal Head age are reset. This differs for independent replacement, as only the LED Module age is reset, while the Signal Head age continues to increase.

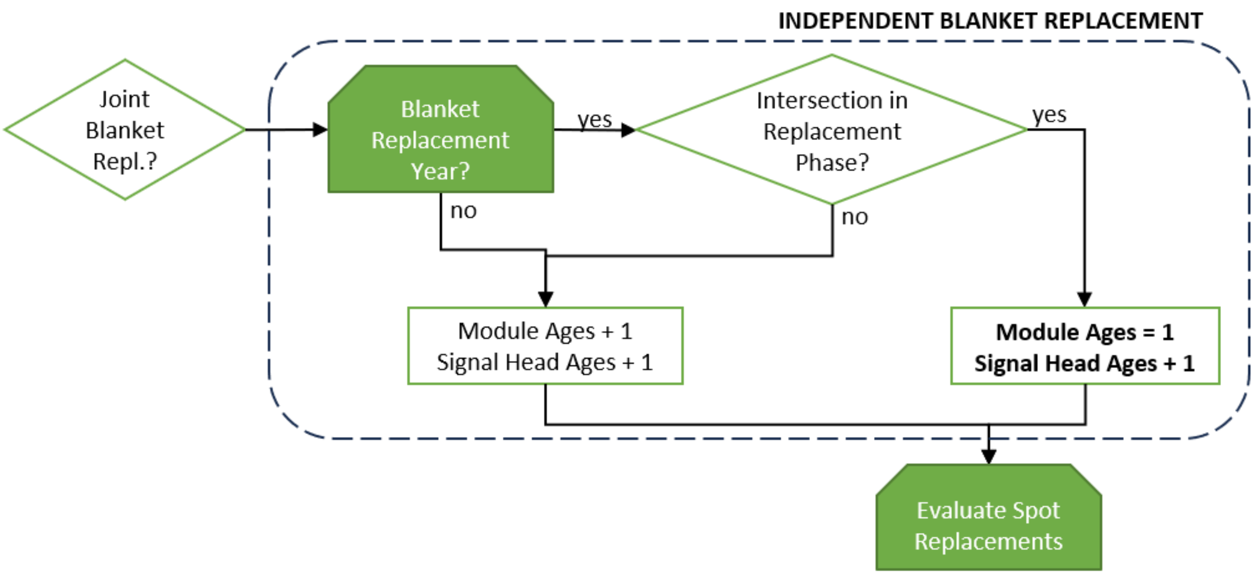


Figure 6.2 Simulation Logic Diagram – Independent Blanket Replacement Settings

The following sections describe each of the subprocesses of the model. These subprocesses were briefly described in the discussion of Figure 6.1, and each is represented in the model by a shaded hexagon.

6.2.4.1 Subprocess: Create Field of Intersections

The purpose of the Create Field of Intersections subprocess is to create a set of Intersection Objects within the model that will be observed for the duration of one iteration of the simulation. This process occurs at the beginning of each iteration of the model. Two probability density functions are utilized in this subprocess, to create a unique field of intersections with each iteration.

Figure 6.3 shows the process by which each intersection is assigned a set of signal heads, then each signal head is assigned a set of LED Modules. The total quantity of intersections is determined by the user and input for the program to use before this subprocess takes place. See section 6.3 for additional details related to determining the total quantity of intersections and signal heads.

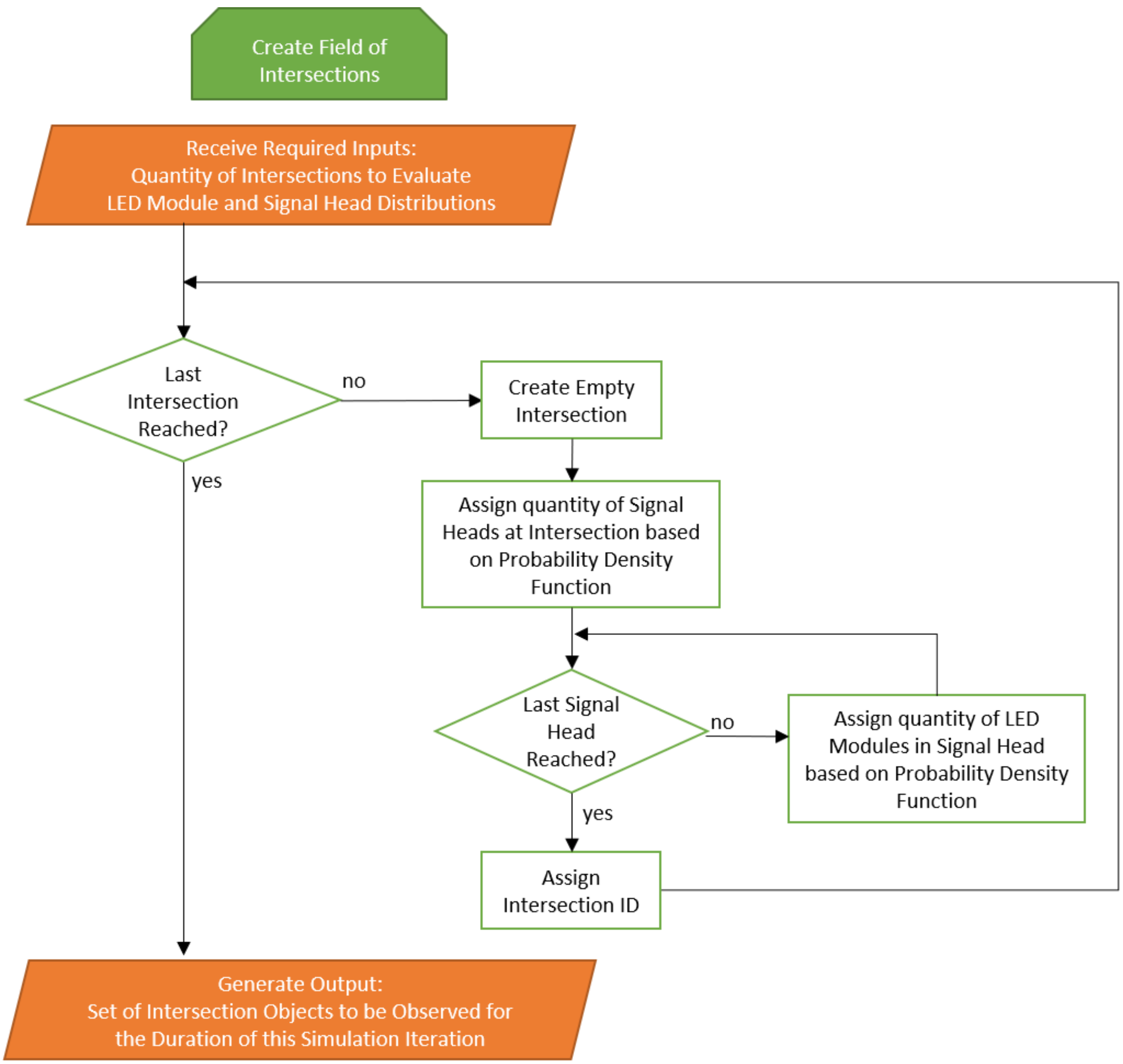


Figure 6.3 Simulation Subprocess – Create Field of Intersections

6.2.4.2 *Subprocess: Assign Blanket Replacement Phase*

The purpose of the Assign Blanket Replacement subprocess, shown in Figure 6.4, is to determine the subset of the field of intersections that is to be replaced each year of the blanket replacement cycle. The program uses the user-input quantities of intersections and replacement period. First, the replacement period is used to determine the quantity of replacement phases. Each year in which blanket replacement will occur is one phase. For a 15-year replacement period, there will be 15 replacement phases, for a 10-year replacement period there will be 10 phases, and so on. It should be noted that the program assigns an equal quantity of intersections to each phase. Using the total quantity of intersections, the number of intersections per phase is calculated. Based on Intersection ID, each intersection is assigned a replacement phase to be used later in the simulation. This ensures that throughout the simulation, the same intersections are replaced during Phase 1, the same intersections are replaced during Phase 2, etc. providing a sequential replacement pattern to the intersections created.

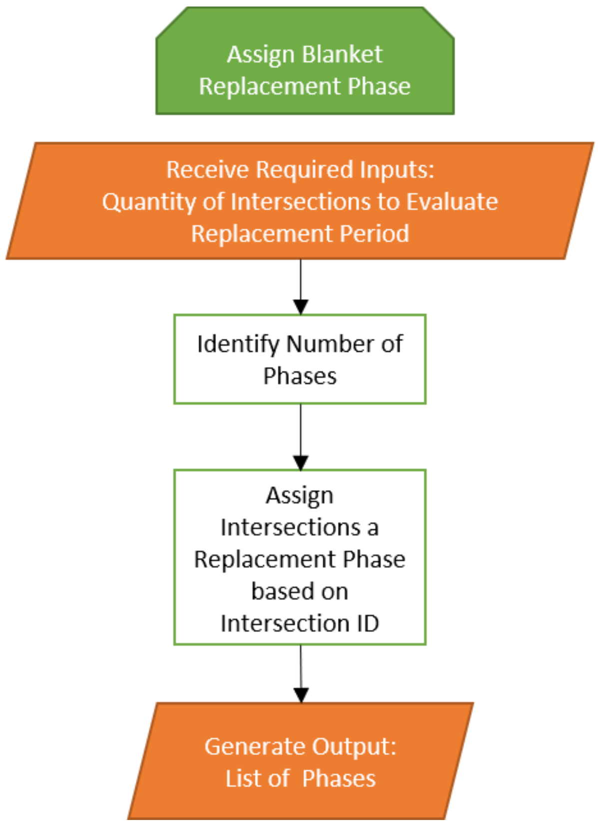


Figure 6.4 Simulation Subprocess – Assign Blanket Replacement Phase

6.2.4.3 Subprocess: Evaluate Spot Replacements

The purpose of the Evaluate Spot Replacement subprocess is to simulate the failure of LED Modules and Signal Heads based on their inherent failure rates. This subprocess evaluates each of the Signal Heads at every intersection to determine whether the Signal Head fails. If the Signal Head fails, then the Signal Head and all of the LED Modules that it contains are replaced. This method of replacing all of the modules within a failed signal head is based on information provided by NCDOT technicians about their work in the field. If the Signal Head does not fail, the program evaluates each of the LED Modules within the Signal Head to determine whether the Modules fail. If a Module within a Signal Head fails it is replaced. Modules that do not fail simply stay in place and will be evaluated again during the blanket replacement process.

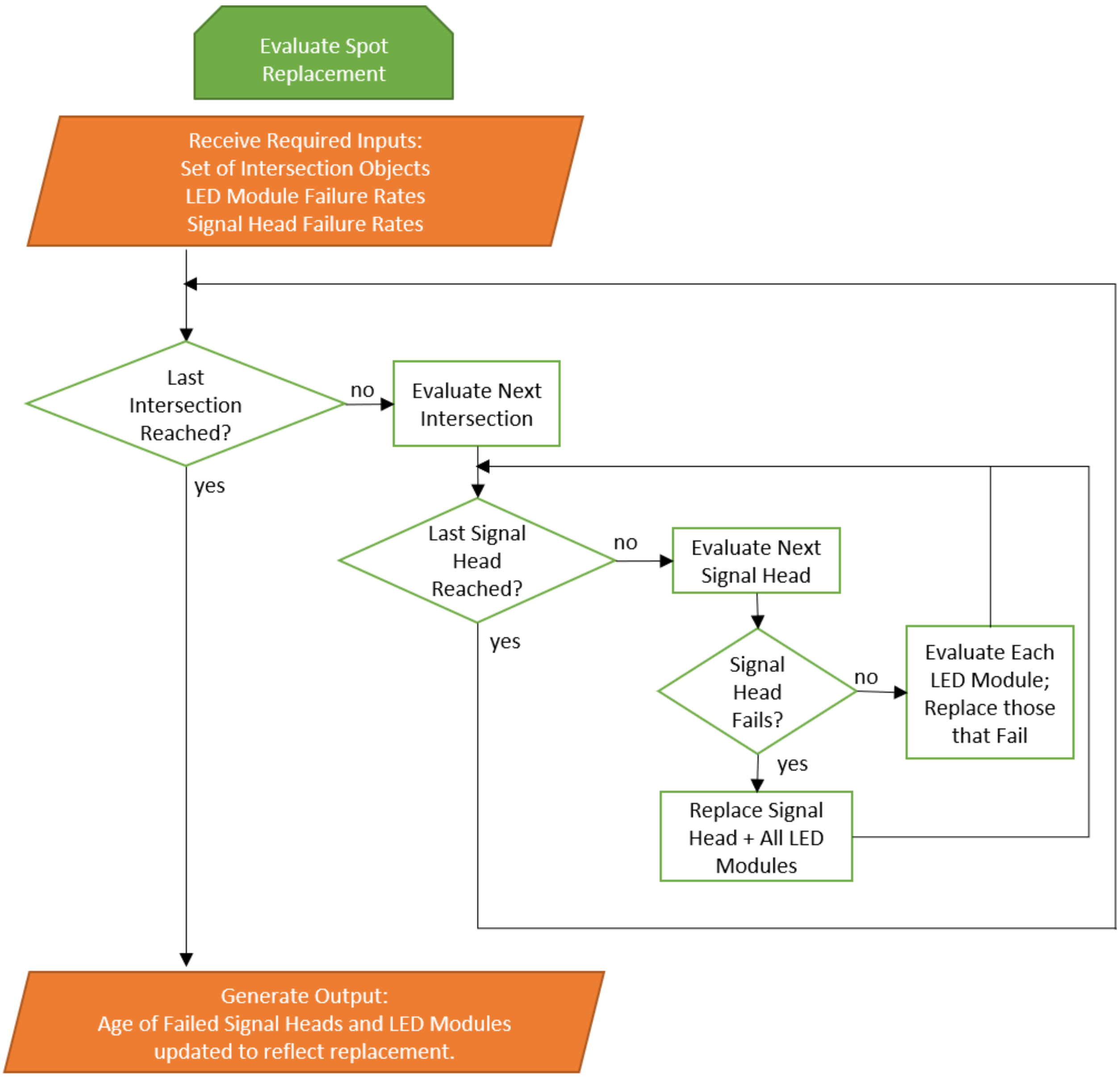


Figure 6.5 Simulation Subprocess – Evaluate Spot Replacement

6.2.4.4 Subprocess: Determine if Blanket Replacement Year

The purpose of the subprocess Determine if Blanket Replacement Year, shown in Figure 6.6, is to determine, based on the current year and the replacement period and cycle, whether any blanket replacement is occurring. This subprocess calls on the list of replacement phases generated during the Assignment of Replacement phases. First, the program calculates the modulus of the Current Year divided by the Replacement Cycle. The modulus is the remainder after the division takes place. The program then compares that modulus to the list of Replacement Phases that were assigned. If the modulus is found in the list of phases, then the Current Year is a replacement year. If the modulus is not found in the list of phases, the Current Year is not a blanket replacement year and all the Signal Heads and LED Modules in the simulation simply age. However, spot replacement is completed for each intersection each year, regardless of replacement phase (see Section 6.2.4.3).

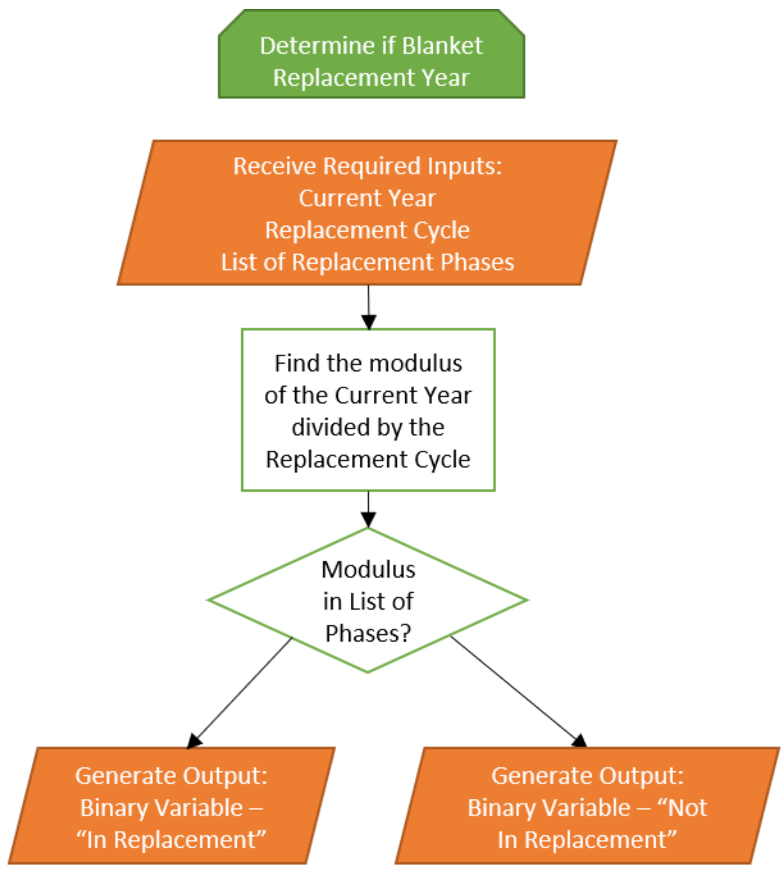


Figure 6.6 Simulation Subprocess – Determine if Blanket Replacement Year

6.3 Input Parameters

This section will go into detail regarding the development of each of the 21 input parameters shown in Table 6.1.

6.3.1 <u>Quantity of Intersections, Signal Heads, and LED Modules (Parameters 1 – 3)</u>

<u>Quantity of Intersections</u>
Since the Monte Carlo simulation outlined here is generative in nature, there is no existing population available to determine an adequate sample size of Intersections required within one iteration of the model.

However, a sufficient sampling of Intersections is needed to ensure that the model's resulting output measures are accurate.

The sample size needed can be determined using the coefficient interval equation, which considers statistical characteristics such as the z-score, sample variance, and the desired half-width (Oberle 2015). Equation 6.1 shows the relationship between these values.

$$n = \frac{z_{\frac{\alpha}{2}}^2 \, s^2}{\Delta^2}$$

$z_{\alpha/2} = the\ z - score\ associated\ with\ the\ Confidence\ Interval$
$s =\ sample\ standard\ deviation$
$\Delta = half - width$
$n = estimated\ sample\ size$

Equation 6.1: Coefficient Interval Equation

The z-score is a measure of how many standard deviations above or below the population mean a sample mean is. Setting the Confidence Interval to 95% means that a z-score of 1.96 will be used for these calculations. The sample standard deviation will be taken from a series of test samples as the required sample size is initially unknown. For this analysis, the standard deviation of the Average Total Cost per Intersection for NCDOT was used. As the quantity of intersections included in the iteration sample changes, the standard deviation among the average cost will change as well. Half-width (Δ) is the margin of error associated with the Confidence Interval (the distance between the estimated average and the upper or lower bound of the interval). The set of half-widths observed will contain five points: $25, $50, $100, $150, and $200 (positive or negative) of the Average Total Cost per Intersection for NCDOT. For each of these half-widths, this procedure will determine what size sample is required so that the simulation's estimated Average Total Cost per Intersection is within $25, $50, $100, $150, or $200.

An iterative process is used to generate sample standard deviations until the estimated sample sizes converge (Oberle 2015). Figure 6.7 shows the convergence of the quantity of intersections based on the set of half-width intervals. For example, the top-most line in the figure indicates the estimated quantity of intersections (on the y-axis) based on the test sample size (on the x-axis). When only 10 intersections were used in the test sample, an estimated 500 intersections were required for a sample that would provide a sample mean within $25 USD of the Average Total Cost per Intersection for NCDOT. Further along, when a test sample of 30 intersections was used, an estimated 237 intersections are required. As shown, to produce an estimate within $25 (positive or negative), a sample of approximately 200 intersections is the convergence point. There was some variation along this convergence line, 205 being at the top of that range. Using 205 intersections in each iteration of the Monte Carlo simulation indicates that, with 95% confidence, the Average Total Cost per Intersection generated by the model will be within $25 USD of the true average. Note that the chart shown in Figure 6.7 uses a logarithmic y-axis to provide additional distinction between the data for half-widths of $100, $150, and $200. On a chart with standard axes, these three data sets are practically indistinguishable from one another.

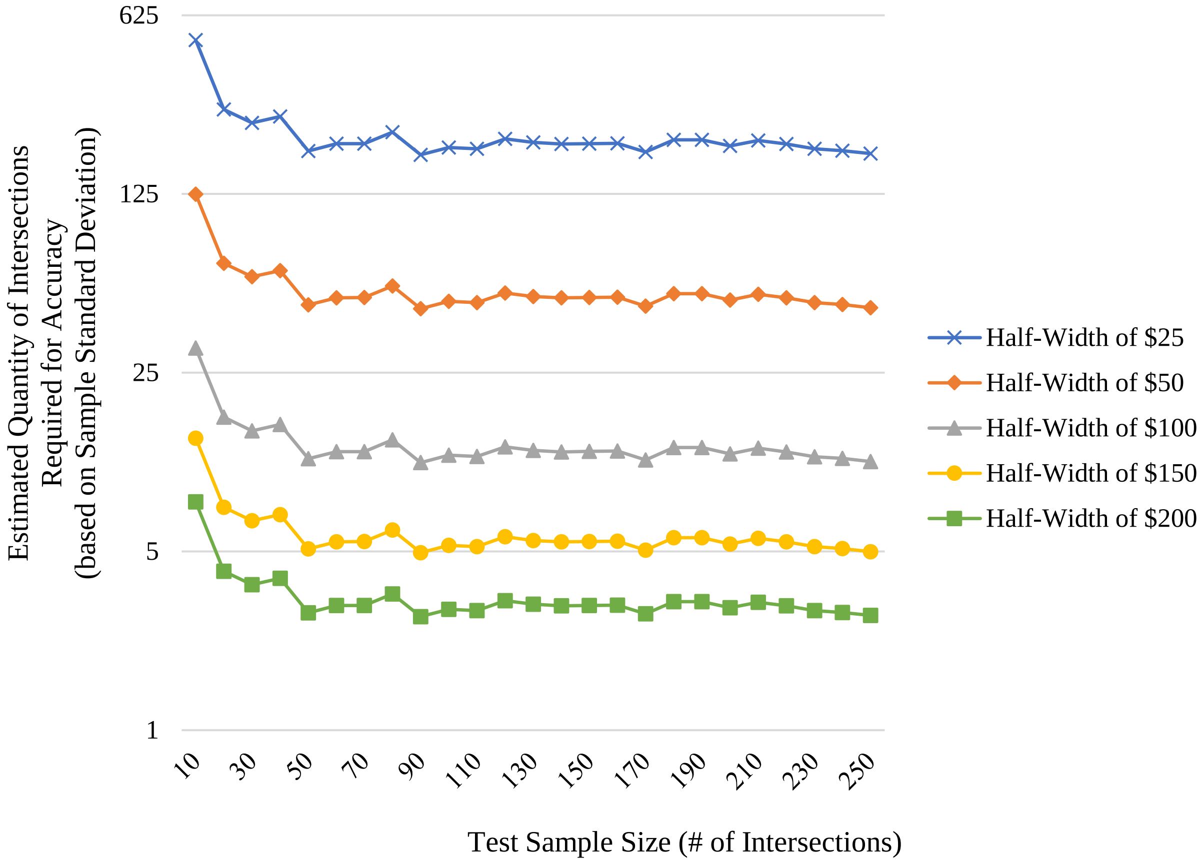


Figure 6.7 Quantity of Intersections Estimated to Reach 95% Confidence in Average Total Cost per Intersection for NCDOT (based on Half-Width)

<u>Signal Heads per Intersections</u>

For each of the 205 intersections in the simulation, some quantity of Signal Heads is assigned. DTS data maintained by NCDOT records the quantity of Signal Heads at each intersection location across North Carolina. Based on this record, a discrete probability density function (PDF) was determined, representing the likelihood that an intersection would be assigned a quantity of Signal Heads, ranging from 1 to 26. Figure 6.8 shows this PDF. It is more likely that an intersection will be assigned eight signal heads (0.347), followed by ten (0.161), then six (0.124). The PDF has been extended to 26 Signal Heads, as there is a miniscule change this assignment may occur, though it is too small to be graphically represented in the figure. This distribution of Signal Heads per intersection has been embedded in the model, providing a random assignment which closely imitates the distribution of Signal Heads across the state.

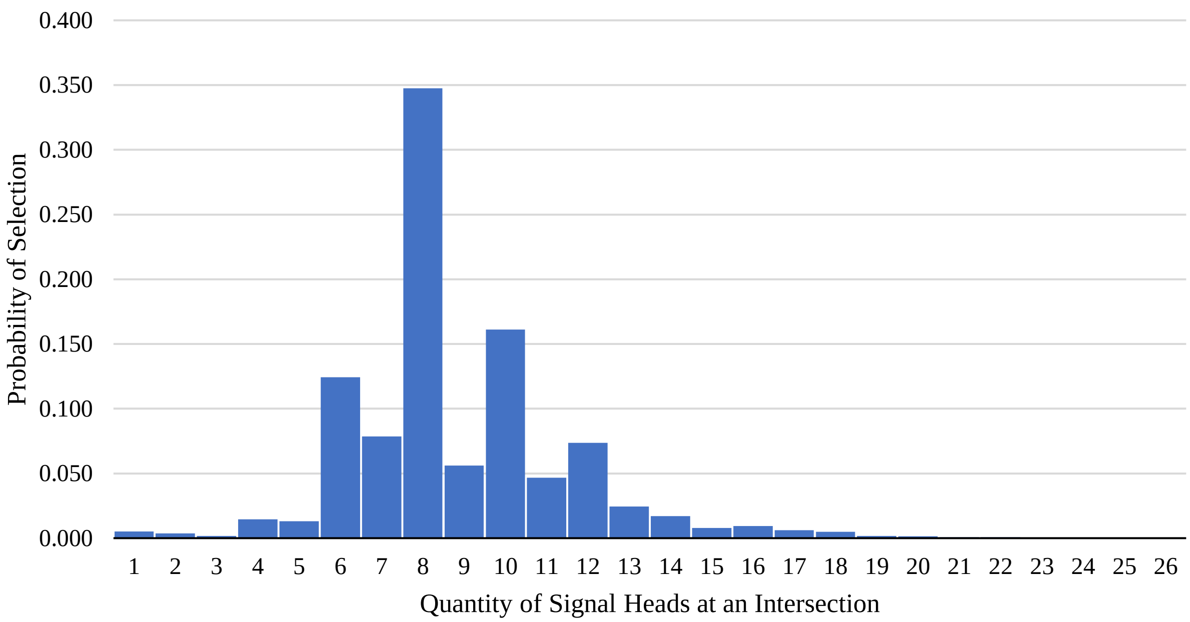


Figure 6.8 Discrete Probability Density Function of Signal Heads per Intersection

<u>Modules per Signal Head</u>

Each of the signal heads assigned to an intersection contains some quantity of LED Modules. The types of signal heads used by NCDOT are shown in Figure 6.9. Sixteen configurations for various LED Modules are shown, however, this work utilizes only 4: Signal Head configurations H, I, J, and Z.

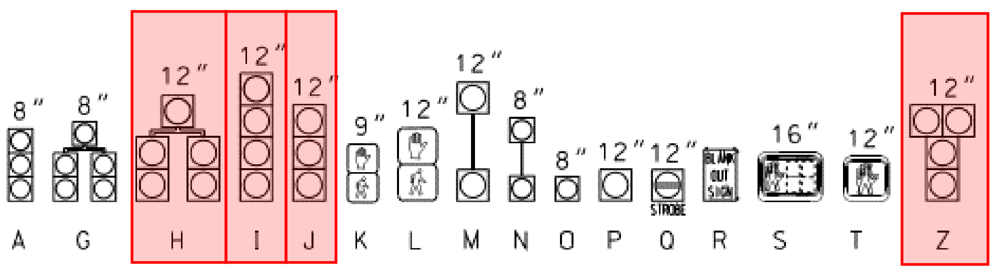


Figure 6.9 Signal Head Configurations Available to NCDOT

Each of these configurations contains a specific quantity of modules, either 3, 4, or 5. Analysis of the DTS Signal Head data produced a discrete probability density function indicating how many Modules each Signal Head will contain. This PDF is shown in Figure 6.10. There is over an 80% probability that a Signal Head will contain 3 Modules with the probabilities for both 4 and 5 being significantly lower. This distribution of LED Modules per Signal Head had been embedded in the model, providing a random assignment which closely imitates the distribution of Modules across the state.

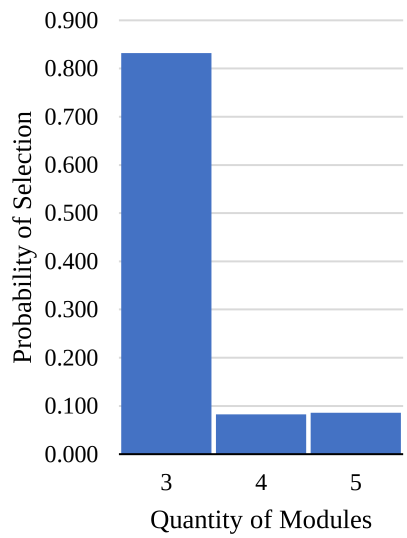


Figure 6.10 Discrete Probability Density Function of Modules per Signal Head

6.3.2 Failure Rates (Parameters 4 – 5)

LED Modules

Discussion with manufacturers revealed that each LED Modules has an inherent failure rate in the shape of a bathtub curve. Shown in Figure 6.11, at the beginning of its life, the LED Module has a higher rate of failure, decreasing over time to reach a steady state, then increasing again towards the end of the module's warranty life.

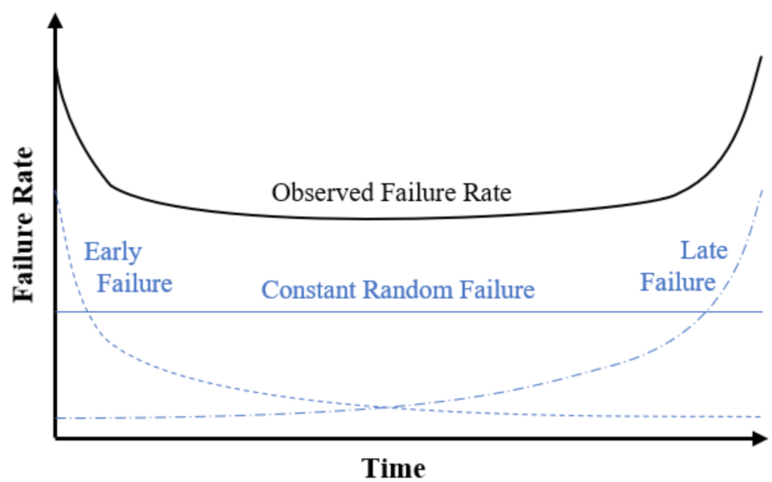
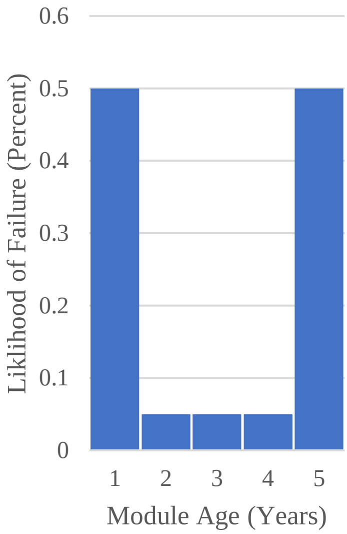


Figure 6.11 Example of Failure Curve

This has been approximated as a discrete failure curve for the model. LED Modules in the baseline simulation (those with a five-year warrantied life) utilize the distribution shown in Figure 6.12, while Modules in all other simulations (those with a 15-year warrantied life) utilize the distribution shown in Figure 6.13. Manufacturer information does not supply specific rates of failure along their curve. The age-based failure rates shown in Figure 6.12 and 6.13 have been assumed. Note that all existing modules (those presently in the field) are assumed to have a flat failure rate of 12.5%. This is due to most of the modules in the field being an average of 10 years old, with a 5-year warranty. An accelerated rate of failure is assumed for these modules. Once the existing modules are replaced, the u-shaped curve failure rates (shown in Figures 6.12 and 6.13) are implemented.



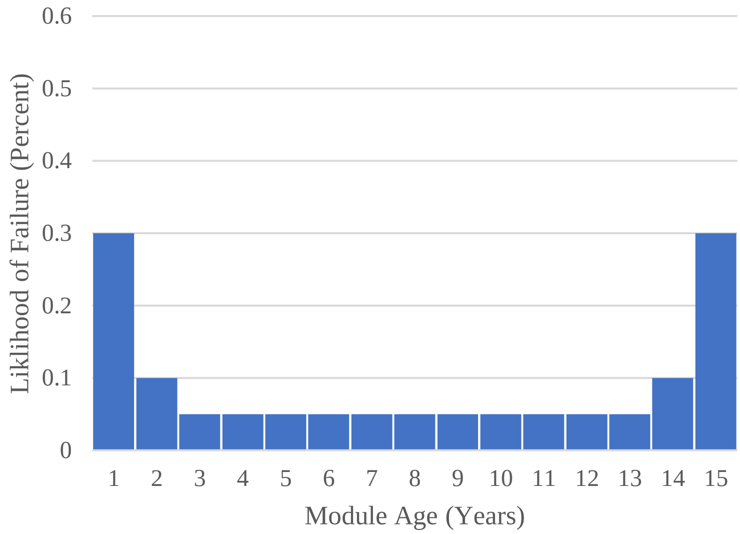


Figure 6.12 Discrete Failure Curve for 5-year Warrantied LED Modules
Figure 6.13 Discrete Failure Curve for 15-year Warrantied LED Modules

There is one scenario using only spot replacement, for which it was necessary to make additional assumptions about the service life of LED Modules. Based on the literature describing service life of 5-year warrantied LED Modules, the service life of 15-year modules was estimated to be 20 years. To consider the service life of the modules during simulation, it was necessary to develop an additional failure curve, extending from 15 years of age to 20. Equation 6.2 provides the curve used to describe failure once the module aged beyond the u-shaped curve described for the warranty period.

$$Failure\ Rate = \left(\frac{Current\ Age - 15}{2.25}\right)^2 + 0.003$$

Equation 6.2: Signal Head Failure Curve

<u>Signal Heads</u>

Signal Heads within the model have an internal failure rate that is triggered by the spot replacement process. Throughout 80% of the anticipated lifespan of the Signal Head, the failure rate is 0.05% each year. After reaching that 80% mark, the failure rate takes on the curve shown in Equation 6.3 and Figure 6.14. Note that in-place Signal Heads are assumed to have a failure rate of 3%. This is due to the unknown age of the Signal Heads that are currently in the field. An accelerated failure rate is assumed. Once the existing Signal Heads are replaced, the failure curve described below is implemented.

$$Failure\ Rate = \left(\frac{Current\ Age - 0.8 * Anticipated\ Life}{2}\right)^2 + 0.05$$

Equation 6.3: Signal Head Failure Curve

Unlike LED Modules, Signal Heads are not likely to spontaneously fail. Instead, Signal Heads will remain in place and slowly degrade with age. Figure 6.14 shows the failure curve for a Signal Head with an anticipated lifespan of 30 years. Failure Rates remain low (at 0.05%) until the Signal Head reaches 25 years of age, then the increase begins. At 30 years of age, indicated with the dashed vertical line, the failure rate has reached 9.05%, and it continues to increase from there.

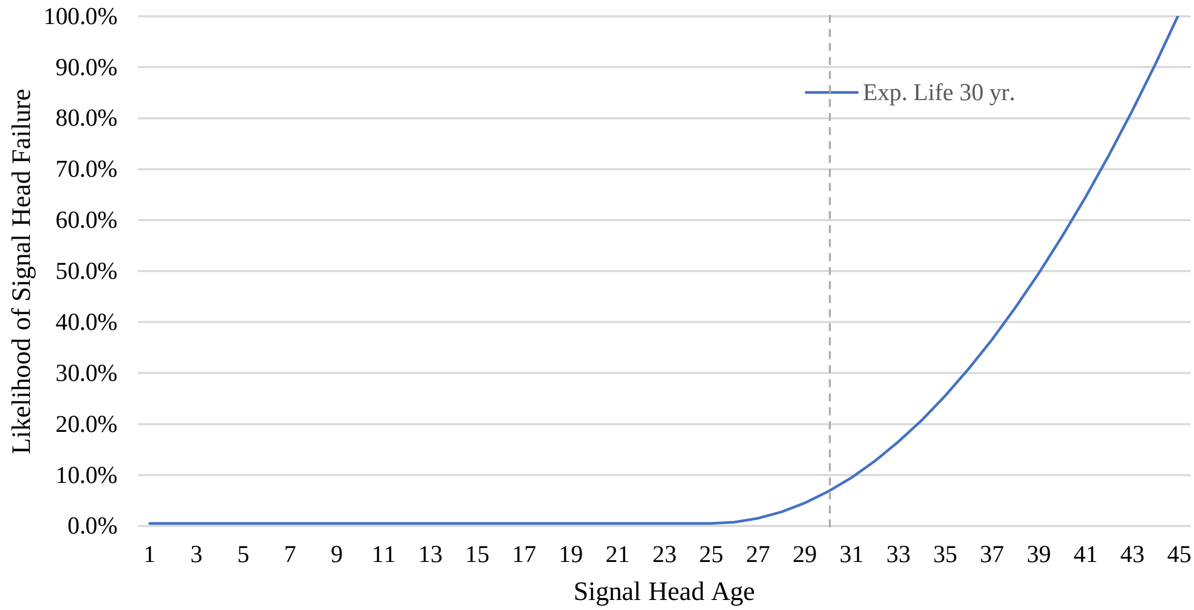


Figure 6.14 Signal Head Failure Rates

6.3.3 <u>Material Costs (Parameters 6 & 7)</u>

Material costs within the model are called upon with each replacement event. This includes both spot replacement events and blanket replacement events. Costs for both LED Modules and Signal Heads are detailed in the following sections.

<u>LED Modules</u>
Material cost of each of the LED Modules has been set to $33.13. This is based on analysis of the purchasing data provided by the NCDOT Depot through the year 2022. The model assumes that all LED Modules are 12” in diameter. Module material cost is held as a static value throughout the duration of the model (except in the case that inflation is being observed). Due to the ultimate use of the model being comparative analysis, rather than attempting to estimate actual costs over time, changes in cost due to technological advancements have not been incorporated.

<u>Signal Heads</u>
Material cost of each of the Signal Heads is determined based on the configuration of the Signal Head in question. Purchasing data reported by the NCDOT Depot for the year 2022 indicates the material costs identified in Table 6.2. Column 1 identifies the configuration of the Signal Head based on those shown in Figure 6.9. Column 2 identifies the quantity of Modules that are included in each Signal Head configuration. Column 3 shows the material cost of that Signal Head configuration per the NCDOT provided purchasing data.

Note that purchasing data does not distinguish between Signal Head configurations with the same quantity of Modules. The model currently assumes that all Signal Heads are aluminum, the material costs shown reflect this assumption. Signal Head material cost is held as a static value throughout the duration of the model (except in the case that inflation is being observed). Due to the ultimate use of the model output being comparative analysis, rather than attempting to estimate actual costs over time, changes due to technological advancement have not been incorporated.

Table 6.2 Material Cost of Signal Head Types

Signal Head Configuration	Quantity of Modules	Material Cost
H	5	$ 600.00
I	4	$ 305.00
Z	4	$ 305.00
J	3	$ 225.00

6.3.4 Travel (Parameters 8 & 9)

Distance

Travel Distance is utilized within the model to determine the travel time (and therefore labor hours) associated with blanket replacement work for each intersection. In a blanket replacement scenario, it is assumed that there will be an initial 'long' travel distance to the first intersection of the day. This is followed by shorter travel distances as the crew of technicians replaces intersections which are all in a nearby area. To determine the initial long travel distance, the average distance between any NCDOT Maintained Intersection and its respective NCDOT Division Headquarters was calculated. NCDOT's DTS database contains the geographical location of each of the intersections under their purview. By conducting a straight-line analysis within each Division, a state-wide average distance between an intersection and its Division Headquarters was determined to be 58.1 miles. A straight-line analysis consists of determining the geographic distance directly between to geographic points.

To determine the following shorter travel distances, a machine learning method called DBSCAN was implemented to identify density-based clusters within each of the counties. Utilizing the location data available from DTS, it was possible to isolate each of the 100 counties within North Carolina and perform a unique density-based clustering for each.

DBSCAN, or Density-Based Spatial Clustering of Applications with Noise, is a non-parametric clustering algorithm that can be used to determine an unknown quantity of arbitrarily-shaped clusters. These parameters suit the geographic location data tied to NCDOT Maintained intersections well. The data is not expected to follow any kind of known distribution, either across the state or within each county, as it is spread across a geographic region. Due to the differences in quantity of intersections per county, there is not a known quantity of clusters to expect from each analysis.

DBSCAN is an algorithm that provides an appropriate quantity of clusters based on the density found among the provided points. For example, Wake, Pender, and Bertie counties are shown in Figures 6.15 to 6.17. Each of these figures shows the intersections found in each county, along with their identified clusters. Note that the counties have vastly different distributions of signalized intersections, and DBSCAN was still able to identify clusters within each. Figure 6.15 shows that Wake County's intersections can be sorted into 4 distinct geographic clusters based on their nearness to one another. Pender County's 3 geographic clusters are shown in Figure 6.16, and Bertie County uses the most – 5 clusters – to sort all of the intersections in Figure 6.17.

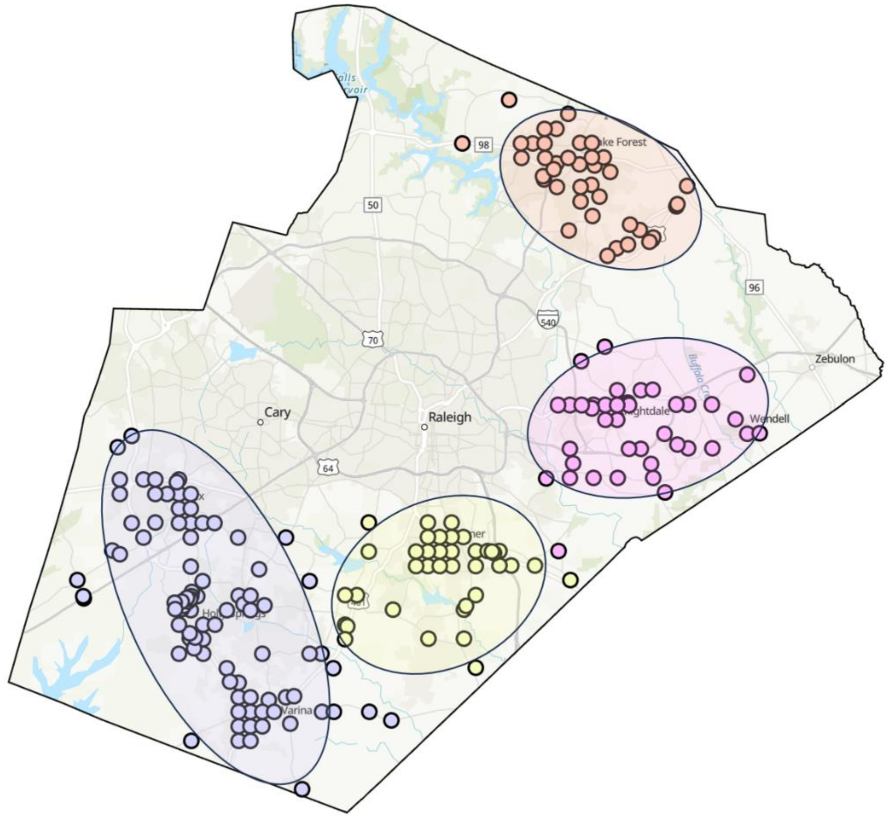


Figure 6.15 Density-Based Clustering of State-Maintained Intersections Within Wake County

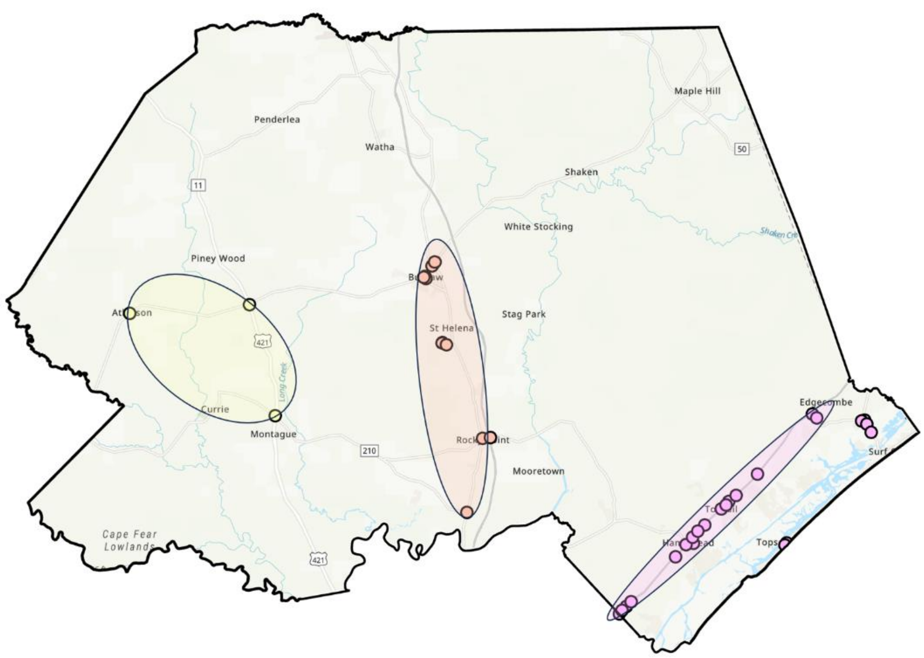


Figure 6.16 Density-Based Clustering of State-Maintained Intersections Within Pender County

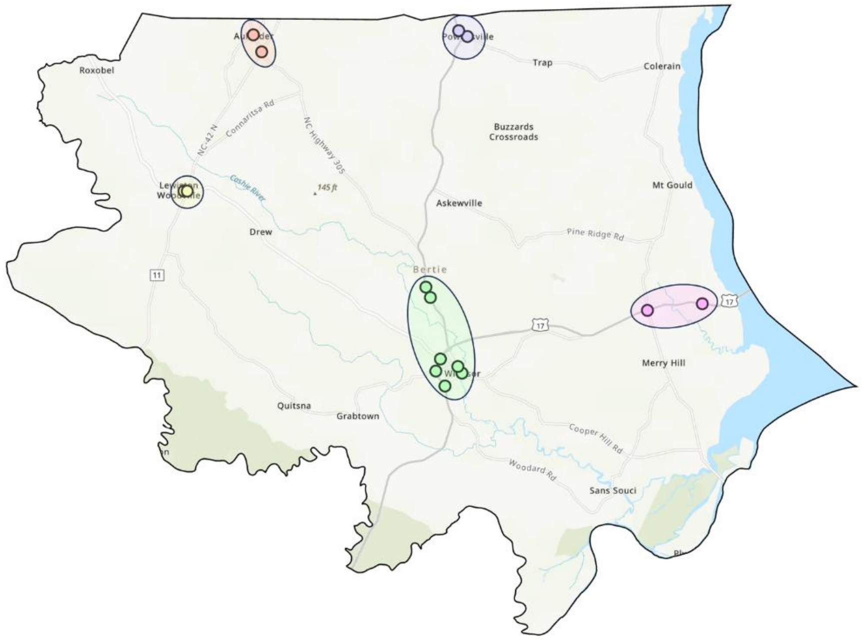


Figure 6.17 Density-Based Clustering of State-Maintained Intersections Within Bertie County

Upon completion of the DBSCAN clustering, a nearest-neighbor calculation was conducted for each cluster within each county. An average nearest-neighbor distance was calculated for 86 counties. Fourteen counties within the state did not contain sufficient intersection data for the DBSCAN analysis to be conducted. This means that in 14 counties, the quantity of intersections, and their locations could not be used by the algorithm to generate clusters based on the minimum point and distance thresholds. Therefore, data from the other 86 counties was used for further analysis. It should be noted that the nearest-neighbor calculations that have been completed were not for additional clustering, such as k-nearest neighbor methods. However, the calculations were to literally identify the distance between nearest neighbor intersections within the identified DBSCAN clusters for each county. The 86 nearest-neighbor distances have been compiled into a discrete probability distribution function, shown in Figure 6.18. This PDF has been embedded in the model to randomly assign the 'Short' travel distance in a distribution that is unique to North Carolina.

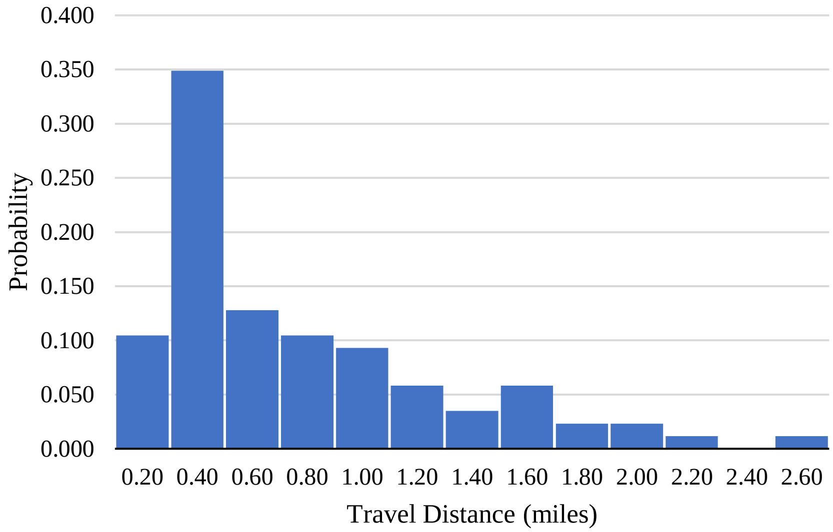


Figure 6.18 Discrete Probability Density Function of 'Short' Travel Distances Between Intersections for Blanket Replacement

<u>Speed</u>
State-wide, the default speed-limit is 55 miles per hour. Often this is the speed posted on small highways and backroads. Due to most signalized intersections being within more populated areas, we have lowered the assumed speed of technician travel to 45 miles per hour.

6.3.5 <u>Labor & Equipment Cost per Spot Replacement (Parameter 10)</u>

Cost of a Spot Replacement activity has been divided into two elements: Labor & Equipment and Materials. This section discusses the determination of the Labor & Equipment costs. Working with NCDOT Divisions, the Labor & Equipment cost for replacing a single LED Module within a Signal Head was determined for both in-house work (utilizing NCDOT personnel) and Contracted work. This is the only cost data that was made available for Spot Replacement, and has been utilized to describe both replacement of LED Modules and of Signal Heads for the purposes of this simulation. Table 6.3 outlines the Labor and Equipment costs for each replacement activity. The first column of Table 6.3 provides a list of the line items considered when calculating the total cost of spot replacement. Costs incurred with in-house work are identified in Column 2. Costs incurred when spot replacement work is contracted out are identified in Column 3. Material costs (discussed in Section 6.3.3) must be added to the Labor and Equipment costs to determine the total cost of a Spot Replacement activity.

Table 6.3 Labor and Equipment Costs per Spot Replacement Activity

Line Item	**NCDOT Cost**	**Contractor Cost**
NCDOT Technician Labor & Equipment	$ 158.40	-
Replace LED – Line Item	-	$ 40.00
NCDOT Tech Inspection Time	-	$ 158.40
Material Cost	Price of Materials	Price of Materials
TOTALS (w/o Materials)	158.40	198.40

At this point, travel costs associated with Spot Replacements are calculated within the provided Labor & Equipment cost. After review of the data with NCDOT employees, it was clear that travel costs were included in the values provided. However, determination of the travel cost values was not provided. The model combines the Labor & Equipment costs shown here with the Material price of a single LED Module to determine the overall total cost of a Spot Replacement.

Calculations for the labor hours related to a spot replacement are not accounted for within the model.

It should be noted that Contractor costs vary from Division to Division within the state of North Carolina. All costs above can be modified in future use of the model to represent specific Divisions as needed. See Section 4.1.4.2: Contracts for additional information on the variation across the state.

6.3.6 Labor & Equipment Costs of Blanket Replacement (Parameter 11)

Cost of blanket replacement activity has been divided into two elements: Labor & Equipment and Materials. This section discusses the determination of the Labor & Equipment costs. Working with NCDOT Divisions, the Labor & Equipment costs for replacing a 'typical' intersection with twelve three-module signal heads were determined for both in-house work (utilizing NCDOT personnel) and Contracted work. This is the only cost data that was made available for Blanket Replacement, and has been utilized to describe both joint replacement of LED Modules and of Signal Heads and independent replacement of LED Modules for the purposes of this simulation. This 'typical' intersection is the unit used by NCDOT to record costs internally. Table 6.4 outlines these costs. The first column of Table 6.4 provides a list of the line items considered when calculating the total cost of blanket replacement. Costs incurred with in-house work are identified in Column 2. Costs incurred when blanket replacement work is contracted out are identified in Column 3. Material costs (discussed in Section 6.3.3) must be added to the Labor and Equipment costs to determine the total cost of a Blanket Replacement activity.

Table 6.4 Labor and Equipment Costs of Blanket Replacement Activities

Line Item	NCDOT Cost	Contractor Cost
NCDOT Technician Labor & Equipment	$ 633.60	-
Assemble & Install Vehicle/Pedestrian Signal Head	-	$ 3,000.00
Removal of Old Signal Heads		$ 600.00
NCDOT Tech Inspection Time	-	$ 396.00
Material Cost	Price of Materials	Price of Materials
TOTALS (w/o Materials)	633.60	3,996.00

Cost of travel associated with blanket replacements is calculated with the Labor & Equipment cost estimates provided. The model assigns each intersection the same Labor & Equipment costs, while utilizing a variable Material cost. Material costs are determined based on the quantity of Signal Heads and Modules at that specific intersection within the model (see Section 6.3.3 for additional details). It should again be noted that Contractor costs vary from Division to Division within the state of North Carolina. The costs above can be modified with additional use of the model to represent specific Divisions as needed.

6.3.7 Crews (Parameters 12-14)

Crew Quantity
Crew quantity has been set to four. Based on discussions with NCDOT Divisions, it is typical for a Division to have four crews available for LED Module and Signal Head replacement work. Divisions have specified that a crew is made up of one technician.

Truck Quantity
Truck quantity has been set to four. Based on discussions with NCDOT Divisions, it is typical for each crew available for LED Module and Signal Head replacement work to have an assigned truck.

Labor Hours
Discussions with NCDOT Divisions led to the method for calculating Labor Hours for blanket replacement. The Divisions indicated that a crew of four technicians and four trucks would be able to complete a full replacement of between 4 and 7 intersections in one day. Based on this information, the model calculated the labor hours needed at each intersection.

Also based on Division discussions, the use of Contractors to conduct blanket replacement still requires that NCDOT technicians follow the Contractors and conduct inspections. An estimate of 2 labor-hours per intersection is used to calculate the NCDOT labor that will still be required if blanket replacement is contracted out.

6.3.8 Quantity of Iterations (Parameter 15)

Conducting multiple iterations of the model provides a level of redundancy. This ensures that the results of the simulation are as accurate as possible – they will be made up of average values across multiple iterations of the model, rather than the values produced after one run of the model. Determination of the quantity of Iterations followed a process like that of determining the quantity of Intersection in a single model run. There is no existing population of iterations that can be used to determine an adequate quantity. However, enough iterations (and therefore a sufficient level of redundancy) are needed to ensure that the simulation's output measures are accurate.

The quantity of Iterations needed can be determined using the confidence interval equation, previously explained in Section 6.3.1. The equation is repeated here. Note that for this analysis, the quantity of iterations is the 'sample size.'

$$n = \frac{z_{\frac{\alpha}{2}}^2 s^2}{\Delta^2}$$

$z\alpha/_2 = the\ z - score\ associated\ with\ the\ Confidence\ Interval$
$s =\ sample\ standard\ deviation$
$\Delta = half - width$
$n = estimated\ sample\ size$

Equation 6.1: Coefficient Interval Equation

Again, a z-score of 1.96 will be used for these calculations, giving a Confidence Interval of 95%. The sample standard deviation will be taken from a series of test-samples as the required sample size is initially unknown. For this analysis the standard deviation of the Average Total Replacement Cost for NCDOT over the full simulation timeline (in this case 30 years) was used. As the quantity of iterations included in the simulation changes, the standard deviation among the resulting Average Cost estimates will change as well. Based on an initial run, the 'expected' average is approximately $6 M – that is the value used to determine the set of half-width values. The set of half-widths observed will contain four points: $30k (or 0.5% of $6M), $90k (1.5%), $150k (2.5%), and $210k (3.5%). It should be noted that this $6 million estimate is based on the 205 intersections identified in section 6.3.1. For each of these half-widths, this procedure will determine how many iterations are required so that the simulation's estimated Average Total Replacement Cost is within $30k, $90k, $180k, or $210k.

The same iterative process is used to generate sample standard deviations until the estimated sample sizes converge. Figure 6.19 shows the convergence of the quantity of iterations based on the set of half-width intervals. For example, the third line from the bottom of the figure indicates the estimated quantity of iteration (on the y-axis) based on the test sample size (on the x-axis). When only 6 iterations were used in the test sample, an estimated 11 iterations were required for a sample that would provide a mean within $90k USD of the Average Total Replacement Cost for NCDOT over the lifetime of the simulation (30 years). Further along, when a test sample of 17 intersections was used, an estimated 8 intersections are required. As shown, to produce an estimate within $90k (positive or negative), a sample of approximately 6 iterations is the convergence point. There was some variation along this convergence life, 8 being the top of that range. Using 8 iterations for each Monte Carlo simulation indicates that, with 95% confidence, the estimated Average Total Replacement Cost for NCDOT over the timeline of the simulation (205 intersections for 30 years) will be within $90k USD of the true average. Note that the chart shown in Figure 6.19 uses a logarithmic y-axis to provide additional distinction between the data for half-widths of $90k, $180k, and $210k. On a chart with standard axes, these three data sets are practically indistinguishable from one another.

While it is possible to get an estimate that may be closer to the true average (see the top-most line in Figure 6.19), the amount of increased accuracy does not outweigh the additional time required to run so many more iterations of the model. Attempting to increase the accuracy to within ±$30k takes the simulation from a run time of less than an hour to several hours. The research team also believes that an estimate within ±1.5% of an anticipated average of $6M provides sufficient accuracy to conduct a comparative analysis.

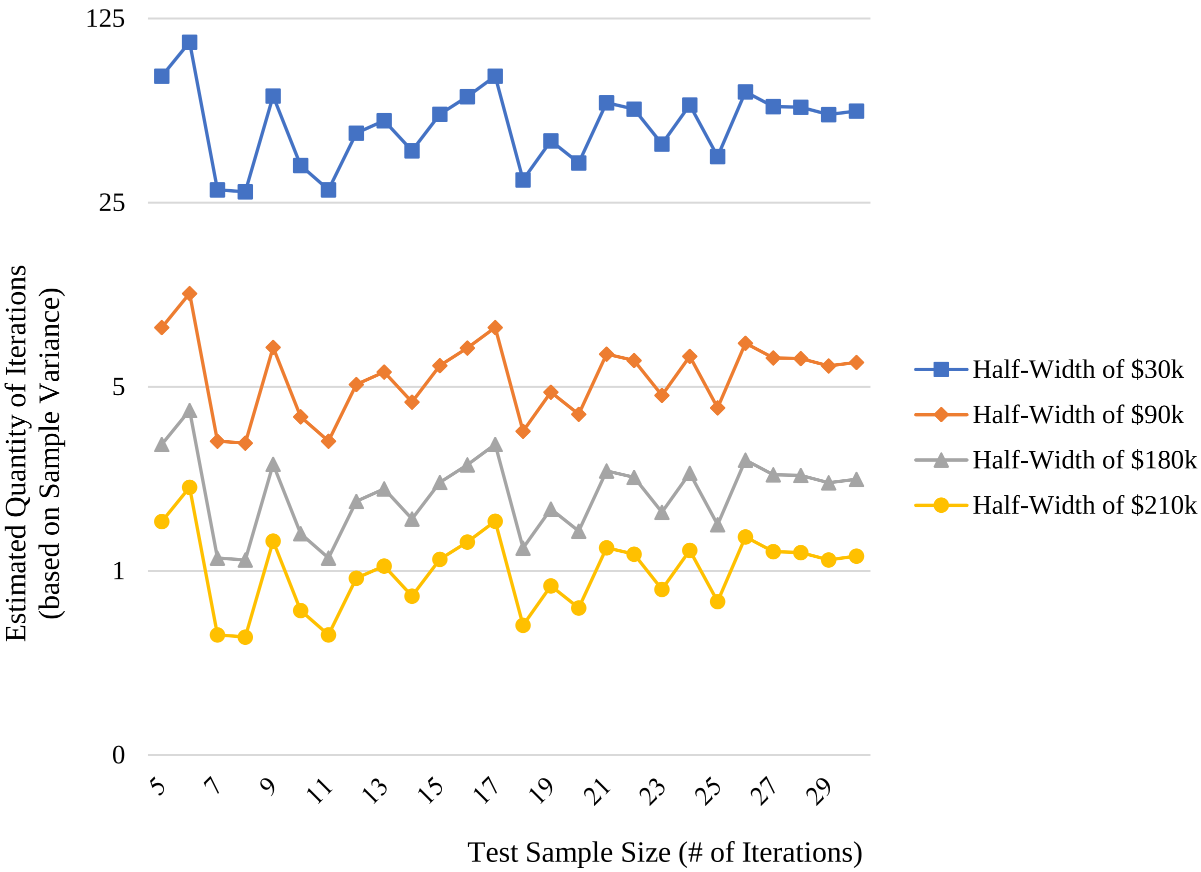


Figure 6.19 Quantity of Iterations Estimated to Reach 95% Confidence in Average Total Cost for NCDOT (based on desired Half-Width)

6.3.9 Inflation Rate (Parameter 16)

Inflation within the simulation is a variable that will be set based on the alternative in question. The alternatives that were developed for this project will utilize inflation rates of 0% and 3%. Using an inflation rate of 0% allows for alternative scenarios to be compared using today's value of money. Using a 3% interest rate, it is possible to predict costs which are more reflective of true future costs.

6.3.10 Replacement Cycle and Period (Parameters 17 & 18)

For each simulation run, a Replacement Cycle and Replacement Period are specified. The Replacement Period is the length of time within the Replacement Cycle during which Blanket Replacement is actively occurring. It does not need to be the same length as the Replacement Cycle, though it can be. If the Replacement Period is shorter than the Replacement Cycle, there will be a length of time after the Replacement Period during which only Spot Replacement will occur. Blanket Replacement will begin again at the start of the next Replacement Cycle.

6.3.11 Signal Head Lifespan (Parameter 19)

Signal Head lifespan is set to 30 years within the simulation. Informational interviews conducted with NCDOT Divisions provide anecdotal evidence that the lifespan of a Signal Head can range from 3 to 30 years depending on the placement and weather conditions.

6.3.12 New Module Warranty (Parameter 20)

The simulation assumes that all modules currently in place have a five-year warranty. By implementing a New Module Warranty input, the user can indicate the warranty period of the modules used for replacement. For example, in the base case (Alternative 1), it is assumed that all LED Modules have a warranty of 5-years. Therefore, the New Module Warranty is also 5 years. In the case of Alternatives 2 through 9, it is assumed that 15-year modules will be incorporated, therefore the New Module Warranty will be 15 years.

6.3.13 Joint Replacement (Parameter 21)

A 'flag' has been built into the simulation allowing the user to indicate whether the Signal Heads are to be replaced concurrently with the LED Modules during a Blanket Replacement Cycle. Informational interviews with NCDOT Divisions tell us that with the 5-year warrantied modules this was not the case. The Signal Heads outlast the 5-year LED Modules by many years. However, there is indication by some Divisions that the ability to pre-fill the Signal Heads with Modules and install all of the items at the same time during replacement may speed the process or provide an additional level of safety by eliminating the need to handle as much wiring while in a bucket truck. Thus, it makes sense to incorporate joint replacement of Signal Heads and Modules in a subset of the alternative replacement scenarios tested.

6.4 Output Measures

As mentioned above, for each implementation of the simulation, five final files are generated. These include:

- Simulation Lifetime Summary (Table 6.5)
- NCDOT Yearly Summary (Table 6.6)
- NCDOT Yearly Summary (per Intersection) (Table 6.6)
- Contractor Yearly Summary (Table 6.6)
- Contractor Yearly Summary (per Intersection) (Table 6.6)

These files are created based on data generated during the running of the simulation. For example, with each blanket replacement activity that is conducted, the cost of material, cost of labor and equipment, quantity of modules, quantity of signal heads, and labor hours required are all recorded for every intersection over time. Once multiple iterations of the simulation have completed, this data is compiled into the summary files listed above.

An example of the Simulation Lifetime Summary file is shown in Table 6.5. This example data shows the Summary for Replacement Alternative Scenario 2 (Replacement Period of 15 years, 0% Inflation, Independent Replacement). The summary provides values calculated over all 8 iterations, for the 30-year timespan of the simulation. It contains average, median, and standard deviation data for 28 different metrics. Column 1 of Table 6.5 identifies the metric, Column 2 identifies whether the values will be for the total quantity of intersections used, or whether they will be on a per-intersection basis. Columns 3 through 5 contain the associated values. For example, Modules at start is the first metric shown in Table 6.5. Both the total number of modules in all 205 intersections and an average quantity of modules found per intersection are provided. The average value is determined using the quantities counted in each of the 8 iterations conducted, as are the median and standard deviation. When observing the 205 intersections used in the simulation, a total of around 5,900 modules are counted within the field of intersections, however only around 29 are found at each intersection. This average value is in line with the average quantity of modules found at an intersection in NCDOT (28 modules per intersection per available DTS data).

Table 6.5 Example of Simulation Lifetime Summary Output Data

Metric	Scope	Average	Median	Standard Deviation
Modules in Place	Total	5896.38	5859.50	123.38
	Per Intersection	28.76	28.59	0.60
Signal Heads at Start	Total	1815.13	1803.00	39.10
	Per Intersection	8.85	8.80	0.19
Modules Replaced	Total	24611.50	24482.00	538.89
	Per Intersection	120.06	119.43	2.63
Signal Heads Replaced	Total	4528.25	4499.50	104.99
	Per Intersection	22.09	21.94	0.52
NCDOT Total Replacement Costs	Total	$3,975,375.15	$3,956,157.56	$82,985.63
	Per Intersection	$19,392.08	$19,298.35	$404.81
NCDOT Blanket Replacement Costs	Total	$1,604,258.56	$1,595,406.47	$31,447.24
	Per Intersection	$7,825.65	$7,782.47	$153.40
NCDOT Signal Head Spot Replacement Costs	Total	$474,754.12	$473,681.93	$14,358.52
	Per Intersection	$2,315.87	$2,310.64	$70.04
NCDOT Module Spot Replacement Costs	Total	$1,896,362.47	$1,891,262.99	$40,740.74
	Per Intersection	$9,250.54	$9,225.65	$198.73
NCDOT Labor Hours Required	Total	2562.79	2552.58	53.66
	Per Intersection	12.49	12.44	0.26
Contractor Total Replacement Costs	Total	$5,785,924.14	$5,765,481.56	$92,343.19
	Per Intersection	$28,224.02	$28,124.30	$450.46
Contractor Blanket Replacement Costs	Total	$2,982,842.56	$2,973,990.47	$31,447.24
	Per Intersection	$14,550.46	$14,507.26	$153.40
Contractor Signal Head Spot Replacement Costs	Total	$510,674.12	$509,481.93	$15,379.08
	Per Intersection	$2,491.10	$2,485.29	$75.02
Contractor Module Spot Replacement Costs	Total	$2,292,407.47	$2,286,242.98	$49,249.22
	Per Intersection	$11,182.47	$11,152.40	$240.23
NCDOT Supervisory Labor Hours Required	Total	820.00	820.00	0.00
	Per Intersection	4.10	4.10	0.00

Each of the NCDOT and Contractor Yearly Summary files use the same format. Table 6.6 provides an example of the structure within the file that is used to track metrics. The list of metrics tracked is the same as those listed in column 1 of Table 6.5. Note that data for all 205 intersections within the simulation (a total) and for each intersection are recorded for both NCDOT and Contractor work for every alternative.

Table 6.6 Output Example for Yearly Data (Both NCDOT and Contractor)

Year	Metric 1 (Average)	Metric 1 (Median)	Metric 1 (Std. Dev.)	Metric 2 (Average)	Metric 2 (Median)	Metric 2 (Std. Dev.)
1						
2						
3						
4						
…						
30						

Further analysis of this output will allow conclusions to be drawn from the comparison of alternative replacement strategies.

7.0 Validation

"*Validation* is the *process* of determining whether a simulation model is an accurate representation of the system, *for the particular objectives of the study* (Mustafee et al. 2019)." This chapter of the report will discuss how the simulation developed for this project is an accurate representation of the LED Traffic Signal System in place for NCDOT. Keep in mind that modeling a complex system via simulation will only ever result in an approximation of the true system. Absolute validity of a complex simulation is impossible.

Averill M. Law & Associates, Inc. presented a set of techniques to be used when developing a valid and credible model in their 2019 paper (Mustafee et al. 2019). These techniques consist of:

1. Formulating the Problem Precisely
2. Utilizing Subject-Matter Experts
3. Interacting with Decision-Makers on a Regular Basis
4. Using Quantitative Techniques to Validate Components of the Model
5. Developing the Assumptions Document
6. Performing a Structured Walk Through of the Assumptions Document
7. Performing Sensitivity Analyses to Determine Important Model Factors
8. Validating the Output from the Overall Simulation Model

Throughout this chapter, each of these techniques, and how they apply to the simulation developed for this project will be discussed, ultimately showing that the model is valid.

7.1 Formulating the Problem Precisely

This project began as an exploration into the true lifespan of LED Modules in 2019 (all of which were 5-year modules at the time). At the project got started, in late 2020 and early 2021, an industry shift occurred, tripling the warrantied life of commonly available LED Modules from five years to fifteen years. At this point the research team met with the NCDOT Steering Committee to discuss the future direction of the project. The Kickoff Meeting with the Steering Committee occurred on January 12th of 2021, after which the following project problem (in the form of a question) was determined: "Given that LED Modules are now expected to last for fifteen years, what are the timing and data tracking elements of a replacement strategy which NCDOT should implement moving forward?"

This problem was accompanied by anticipated influence on NCDOT, categorized into Guidance, Practice and Operation, and Evaluation Criteria. Specific anticipated influences were reported in the Kick-Off Implementation Commitment Document as follows:

Guidance: This project will provide NCDOT with firm ground to establish guidance regarding the maintenance and replacement of all LED traffic modules in the state.

Practice & Operation: This project will provide NCDOT with a recommended timeline for maintenance and replacement of LED Signal Modules as well as the tools needed to update the timeline as future technology emerges.

Evaluation Criteria: This project will provide NCDOT with the most up to date evaluation criteria needed for determining the useful life of an LED module. It will also provide NCDOT with potential future criteria based on anticipated technological improvements.

Any precisely articulated problem is accompanied by some measure of success. The research team identified three areas by which to measure the success of the project: Monetary, Workforce and Operations

Savings, and Safety. The specifics of those measures of success were included in the Kick-Off Implementation Commitment Document as follows:

Monetary: This project will allow NCDOT to order LED modules less frequently, providing some monetary savings in inventory.

Workforce & Operations Savings: The longer maintenance and replacement timeline provided by this project will save NCDOT valuable dollars in the realm of labor and equipment costs for operations. The exact numbers will be determined with further research, but a preliminary estimate is a savings of approximately $300,000/year.

Safety: The safety of NCDOT personnel will be improved by reducing the number of hours that workers must be in the field maintaining and replacing modules. Currently no hazard to drivers has been identified with a 5-year replacement plan, however it is possible that the research team will also be able to improve driver safety through determining a new LED module replacement strategy.

Incorporating a problem statement, anticipated influences upon finding a solution, and various measures for success ensures that the project was precisely formulated from the beginning.

7.2 Utilizing Subject Matter Experts

Throughout this project there were several kinds of subject matter experts called upon for input. Those experts included:

- LED Manufacturers
- NCDOT Central Office Personnel
- NCDOT Division Office Personnel
- NCDOT Division Signal Technicians

As discussed in Chapter 2: Literature Review, specifically in Section 2.3: Manufacturer Warranties, the research team was able to contact multiple LED Manufacturing companies. Informal interviews and discussion of new and improving LED technology were held with each of these companies. These discussions led to the development of the LED Module failure curve used in the simulation.

Chapter 4: Current Practices, discusses the findings from the series of informational interviews that were conducted with NCDOT personnel. These interviews ranged in topic from specifics on how LED Modules and Signal Heads are replaced in the field, to discussions of budgeting practices and accounting norms. Along with informational interviews, the research team was able to conduct in-field observations of LED Modules being changed by NCDOT Signal Technicians.

7.3 Interacting with Decision Makers on a Regular Basis

Throughout the duration of the project, the research team was in regular contact with decision makers at NCDOT, providing updates and seeking clarification. Updates were provided on a quarterly basis to the NCDOT Steering Committee, containing summaries of work completed towards understanding current practices as well as model development. Each of these quarterly reports also contained a set of appendices with additional detailed information for the committee's review.

After the Kick-Off Meeting, two additional formal meetings were conducted with the Steering committee to update them on research progress and receive feedback on work completed. The first of these took place in October of 2021, the second took place in January of 2023.

Relationships between the research team and the NCDOT decision makers were such that as a question or point for clarification arose during the project, the research team could reach out via email or phone call to discuss the topic. This led to increased interactions between the research team and the decision makers on an informal but highly productive basis.

7.4 Using Quantitative Techniques to Validate Components of the Model

When possible, it is valuable to use quantitative techniques on available data to add to the validity of the model developed. Chapter 6: Development of Simulation discussed how each of the input parameters were defined in detail. However, here is a list of the parameters which were based on quantitative analysis of existing NCDOT data or statistical methods related to simulation development:

- Quantity of Intersections (Section 6.3.1)
- Quantity of Signal Heads (Section 6.3.1)
- Quantity of Modules (Section 6.3.1)
- Travel Distance (Section 6.3.4)
- Quantity of Iterations (Section 6.3.8)

Of the 15 inherent parameters in the model (those not input by the user to test alternatives), 33% are based on quantitative evaluation. Another seven are based on NCDOT data points, meaning a total of 12 of the 15 inherent parameters (80%) are solidly grounded in NCDOT's past data and current practices. The three remaining parameters include the LED Module Failure Rate, the Signal Head Failure Rate, and the Speed of Travel all of which have been assumed based on discussions with manufacturers, NCDOT personnel, or the personal experience of the research team.

7.5 Developing the Assumptions Document

As the simulation was developed, the input parameters were created to hold most of the assumptions made about the system. In early stages of development, there were a few assumptions that were related to the order of work for the technicians. These assumptions were included in an early draft of cost estimates based on RS Means for labor (prior to receiving data from NCDOT) and are as follows:

- Technicians will begin their journey from the Division Headquarters due to the need to pick up materials.
- Only travel to the work site is included in a replacement activity, as travel to a subsequent site will be included with estimations for subsequent work.

Estimates for cost were updated based on provided NCDOT data (as described in Chapter 6), however these two assumptions remain in place and are used in the model to estimate labor hours required during blanket replacement (See Section 6.3.4). Outside of these two statements, all other assumptions have been included in the documentation related to input parameters.

7.6 Performing a Structured Walk Through of the Assumptions Document

As simulation documentation was developed, it was regularly submitted to NCDOT for review in the form of quarterly reports. Occasionally, questions related to certain parameters or various assumptions would arise, and the research team as able to discuss the assumptions and answer any questions from the NCDOT Steering Committee. In addition, the authors reviewed the simulation and its performance and made adjustments to reflect lessons learned.

7.7 Performing Sensitivity Analyses to Determine Important Model Factors

Once development of the simulation reached a point near completion, the research team conducted a single-factor sensitivity analysis on the model to identify input parameters to which the model was most sensitive. The parameters tested during this analysis include:

- Signal Head Estimated Lifespan
- Module Failure Rate
- Signal Head Failure Rate
- Cost of Labor and Equipment (Crew Costs)
- Cost of Materials
- Inflation

By conducting a single-factor sensitivity analysis, it is possible to know which of the parameters evaluated have the greatest impact on the simulation results. As multiple of the parameters in the model have been based on reasonable assumptions, this analysis can point NCDOT to specific parameters that may be worthy of additional investigation.

Simulation Defaults

A single-factor sensitivity analysis is conducted by holding all parameters in a simulation constant (in a "base scenario"), then adjusting them one at a time. This then allows for a comparison of the simulation results that will show the impact of each single parameter being changed. Table 7.1 identifies all of the parameters used within the simulation to set up the "base scenario." Analysis was then conducted by altering the value of each of the parameters identified above (in bold below) one at a time. Default is the term used here to describe the values determined for use in the model during Input Parameter determination. More detail related to those values can be found in Section 6.3: Input Parameters. Note that the Blanket Replacement Type contains two values, "Joint & Independent" replacement. In order to compare differences between the replacement types, it was necessary to conduct single-factor sensitivity analyses for both of these alternatives.

Table 7.1 "Base Scenario" Parameters and Values for Use in Sensitivity Analysis

Parameter	Value
Module Warranty	15 years
Replacement Cycle	15 years
Replacement Period	15 years
Blanket Replacement Type	Joint & Independent
Signal Head Expected Life	**30 years**
Inflation Rate	**0.0 %**
Module Failure Rate	**Default**
Signal Head Failure Rate	**Default**
Material Costs	**Default**
Crew Cost	**Default**
Inventory	None
Timeline	30 years
Intersections	205
Iterations	8

7.7.1 Results

Of the parameters listed in Section 7.7 and 7.7.1, all except Inflation are, to some degree, known values for transportation agencies. As discussed in Section 6.3: Input Parameters, failure rates for this simulation have been assumed. However, it would be possible (on further investigation) for NCDOT to identify failure rates based on data. Material and Crew costs can be controlled, to a point, by an agency. One goal of this analysis was to determine which of these parameters should be prioritized if additional research is conducted. An additional goal of this analysis was to illustrate which parameters have greater influence on simulation results as the simulation is used to compare replacement strategies.

Figure 7.1 shows the impact that a 5% relative change in parameter values has on the average 30-year cost of replacement for one intersection, assuming work completed by NCDOT with Independent Module replacement during the blanket process and only spot Signal Head replacement. A 5% relative increase to the material costs results in a 5.1% increase to the final estimated cost per intersection. Material Cost is the most impactful parameter of those tested. Crew costs are the second most impactful, with failure rates (for both Modules and Signal Heads) following behind. Note that Signal Head Estimated Lifespan has not been included in Figure 7.1, because the variation in lifespan is not adequately represented by a 5% change due to the unit being years. Impacts of change to the Signal Head expected life are discussed in Section 7.7.3.1. Depending on the change in Signal Head expected life, it may be the most impactful parameter other than inflation.

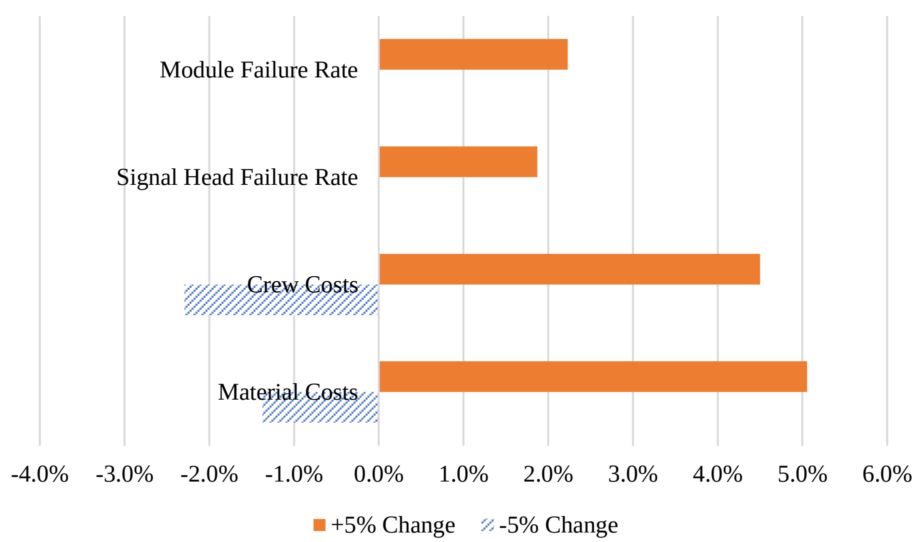


Figure 7.1 Observed Change in Average 30-year NCDOT Costs per Intersection (Independent Blanket Replacement) with a 5% Relative Change in Model Parameter Values

Figure 7.2 is similar to Figure 7.1 except that it shows the impact on the simulation run with a Joint blanket replacement occurring. A 5% relative increase to the material cost, with joint blanket replacement, results in a 3.4% increase to the final estimated cost per intersection. Module failure rate follows material cost as the second most impactful parameter during joint replacement, with a 5% relative increase in failure resulting in a 2.3% overall cost increase per intersection. The reduction in crew cost impact is likely due to the occurrence of joint LED Module and Signal Head replacement, which reduces crew field time during installation. Also, Signal Head failure occurs less frequently; therefore, the crews make fewer trips to the field for their spot replacement.

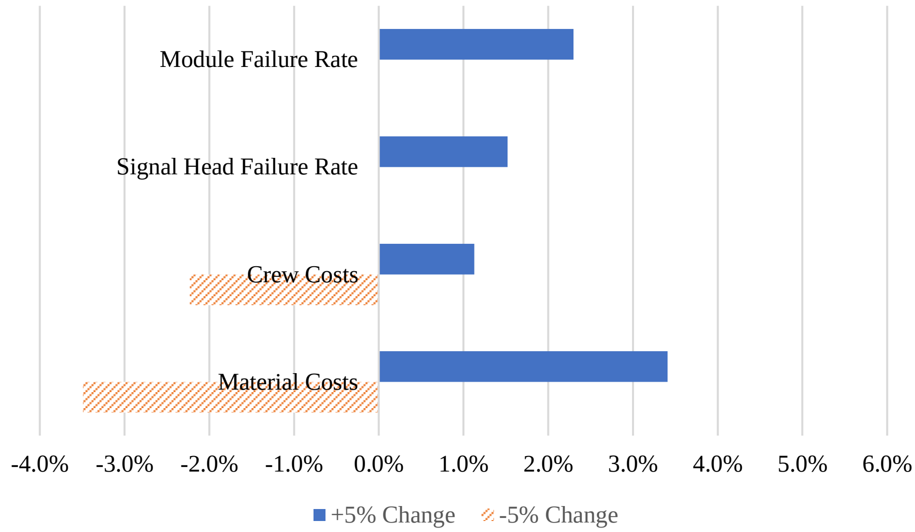


Figure 7.2 Observed Change in Average 30-year NCDOT Costs per Intersection (Joint Blanket Replacement) with a 5% Relative Change in Model Parameter Values

Figures 7.3 and 7.4 show the same parameters as Figure 7.1 and 7.2, with the addition of Inflation. Inflation is a unique parameter in that no additional research can accurately determine the rate of inflation for the next 30 years. However, it should be noted that introducing inflation to the model results in a much greater impact than changing any of the other parameters.

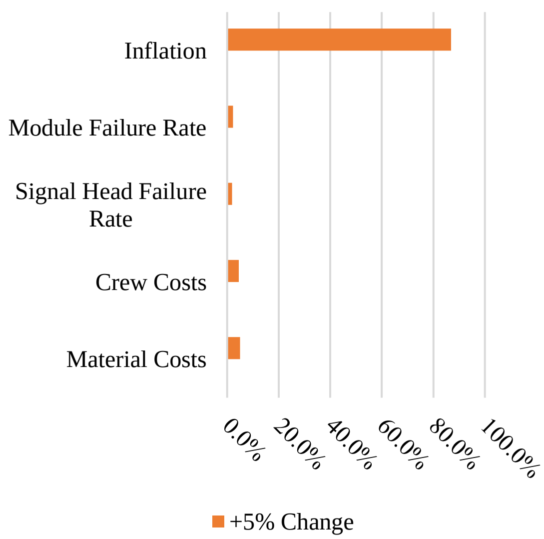


Figure 7.3 - Independent

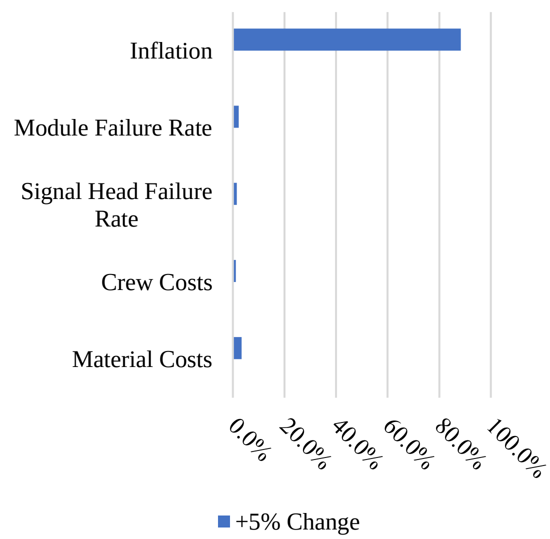


Figure 7.4 - Joint

Figure 7.3 Observed Change in Average 30-year NCDOT Costs per Intersection (Independent Blanket Replacement) with a 5% Relative Change in Model Parameter Values, including Inflation

Figure 7.4 Observed Change in Average 30-year NCDOT Costs per Intersection (Joint Blanket Replacement) with a 5% Relative Change in Model Parameter Values, including Inflation

7.7.2 Discussion of Individual Parameters

This discussion will focus on independent replacement, a similar discussion can be found in Appendix D related to joint replacement. Each of the individual parameters (including Signal Head expected lifespan) and its influence on the simulation overall will be discussed.

7.7.2.1 Signal Head Estimated Lifespan

This discussion of the Signal Head Estimated Lifespan evaluates the effect that changing this variable has on the annual cost of replacement for both NCDOT and contracted work. It also evaluates the effects over the whole 30-year span of the simulation. Within the simulation, it is possible to input the expected life of the signal heads used by a transportation agency. As described in Chapter 6, a standard value of 30 years is used for running the simulation for strategy alternative evaluation. However, it is important to understand how a change in the expected lifespan of the Signal Heads may influence simulation results.

To understand this influence, runs of the simulation have been conducted using a range of signal head estimated lifespans. The output variables observed include Average Total Cost per Intersection. Cost refers to the cost of both Module and Signal Head replacements. Figure 7.5 illustrates the anticipated change in cost per intersection to NCDOT annually for the next 30 years. Each line within the chart represents a different assumed Signal Head expected lifespan. No matter the expected lifespan of the Signal Head, estimated costs remain the same until around year 16. At that point there begin to be some differences observed. Shorter expected lifespans (i.e. 15 or 18 years) result in higher anticipated costs, while longer expected lifespans result in lower anticipated costs.

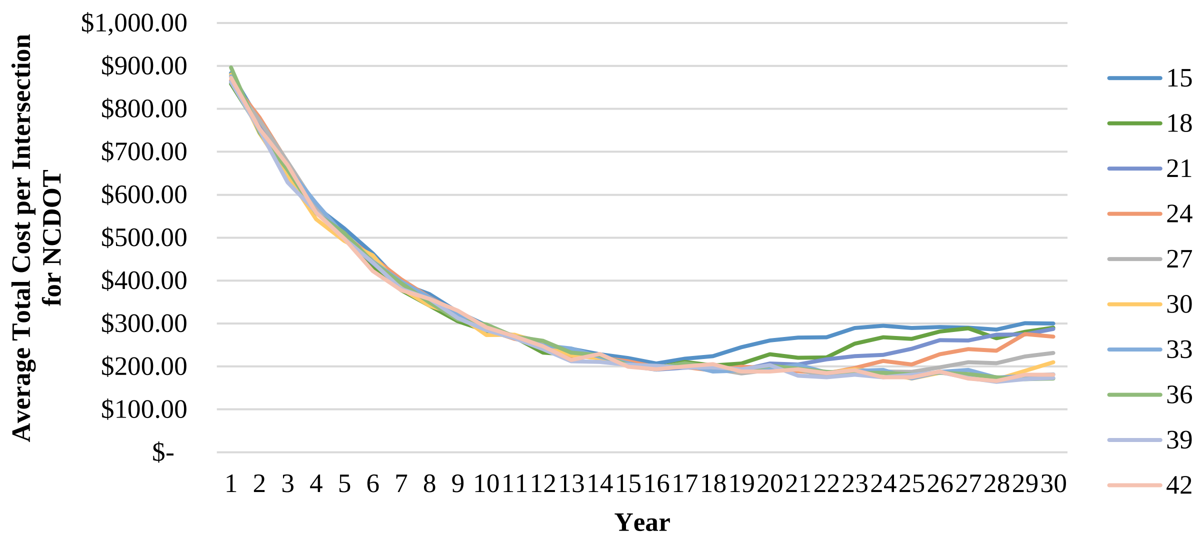


Figure 7.5 Average Total Cost per Intersection for NCDOT Over Time with Varying Signal Head Life Expectancies

As the simulation runs over a 30-year span, Figure 7.6 shows Average Total Cost of Signal Head and Module Replacement per Intersection for the full period. When estimated Signal Head lifespan is assumed to be 30 years, the 30-year cost for NCDOT is approximately $9,100 (or $303/year) while the 30-year cost to contract out all of the work is approximately $16,700 (or $557/year) per intersection. The short I-shaped bars on the chart indicate the standard deviation determined for each lifespan value. Note that the standard deviation for both outputs remains relatively small, maxing out at $310 for NCDOT work and $345 for Contractor work ($10.3/year and $11.5/year, respectively). This indicates that variation within the simulation due to estimated lifespan does not have a strong influence on the variation of the replacement cost predictions.

Change in expected lifespan of Signal Heads has a slight influence on the overall cost of the replacement work, for both NCDOT and contracted work. The trendlines shown in Figure 7.6 slope downward, decreasing as the expected lifespan of the Signal Heads increases. This is logical, because if the Signal Head assets last longer in the field they will require less frequent replacement, lowering costs.

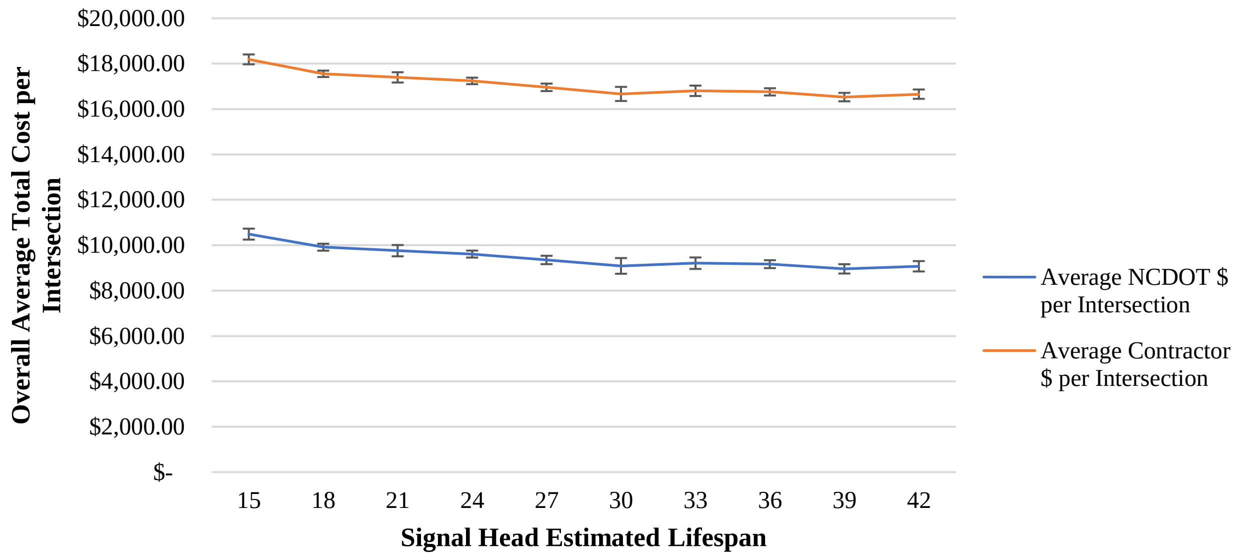


Figure 7.6 Average 30-year Cost per Intersection (over 30 years) with Varying Signal Head Estimated Lifespans

Table 7.2 provides the average percent change in cost that NCDOT could expect to experience based on changing lifespan when using this simulation. For instance, if an agency finds that their Signal Heads have a lifespan of 15 years, rather than 30, they can expect for the cost per intersection to increase by up to 15.41%. If the same agency finds their Signal Heads last 39 years, then they can expect costs to decrease by 1.44%. Note that the percent change for Contractor costs is lower than that of in-house work. This is due to the contractor costs being higher than in-house costs at every point, therefore the increase in cost is less impactful. Note that changes for lifespans of 33 and 36 years have been calculated as increases in cost.

Table 7.2 Percent Change in Average Total Cost per Intersection as Signal Head Lifespan Changes

Change in Lifespan (years)	% Change in Average 30-year Costs	
	NCDOT	Contractor
-15 (15 years)	15.41 %	9.14 %
-12 (18 years)	9.07 %	5.32 %
-9 (21 years)	7.38 %	4.38 %
-6 (24 years)	5.74 %	3.44 %
-3 (27 years)	2.88 %	1.75 %
0 (30 years)	0.00 %	0.00 %
+3 (33 years)	1.30 %	0.83 %
+6 (36 years)	0.85 %	0.55 %
+9 (39 years)	-1.44 %	-0.83 %
+15 (42 years)	-0.18 %	-0.06 %

This is likely attributed to the minimal impact that is anticipated overall for such a small change in lifespan.

7.7.2.2 Module Failure Rate

This discussion of the Module Failure Rate evaluates the effect that changing this variable has on the annual cost of replacement for both NCDOT and contracted work. It also evaluates the effects over the whole 30-year span of the simulation. Each module created in the simulation contains an inherent failure rate (see Section 6.3.2 for additional details). The default values for this failure rate are assumed, therefore, sensitivity testing of the rates is required to know whether additional research should be conducted to verify failure rates. As the failure rate is incremented in this analysis, the assumption is that each section of the failure curve is increased by the same proportion. For example, a relative increase of 1% would raise each section of the failure curve by 1% of its original value.

To understand the influence of the failure rate, runs of the simulation have been conducted using increased rates of failure for the Modules. Output observed includes Average Total Cost per Intersection. Cost here refers to replacement cost for both Modules and Signal Heads. Figure 7.7 illustrates the anticipated change in cost per intersection to NCDOT annually for a 30-year period. Each line within the chart represents a different rate of failure for the modules. Due to the minimal impact that a relative increase to the failure rate provides, the lines for every set of runs are practically on top of one another. This shows that the overall cost per intersection will not change significantly with a relative increase in the Module failure rate.

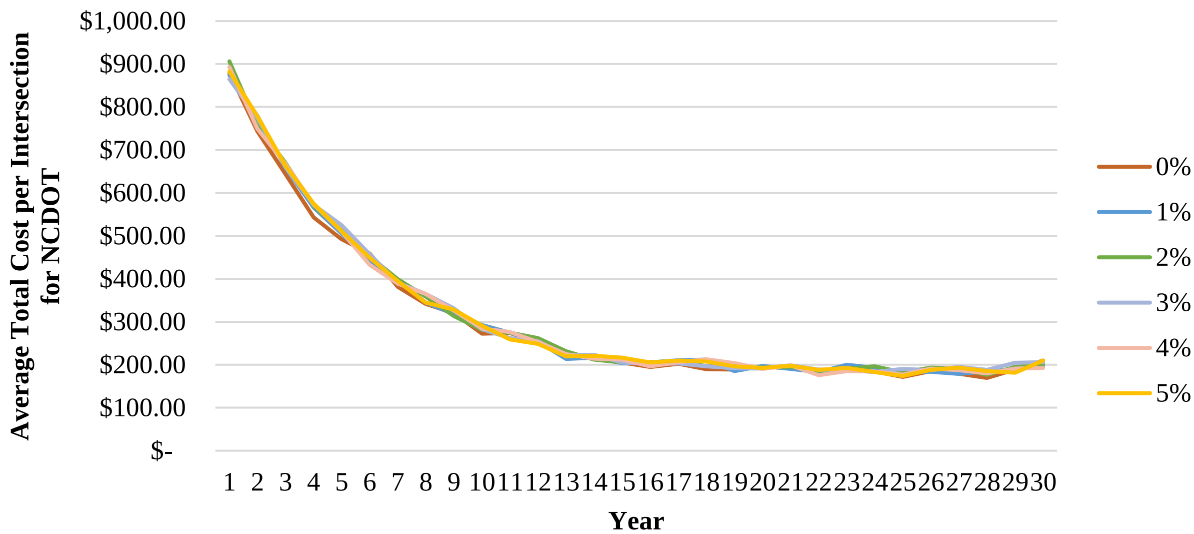


Figure 7.7 Average Total Cost per Intersection for NCDOT Over Time with Varying Relative Increases to Module Failure Rate

A relative increase in Module failure rate was also found to have minimal impact on the overall cost of replacement work for both NCDOT and contracted work. Figure 7.8 provides additional insight by displaying the estimated costs for the whole 30-year period. The cost per intersection appears to follow a straight horizontal line, indicating that there is no significant change as relative failure rates increase.

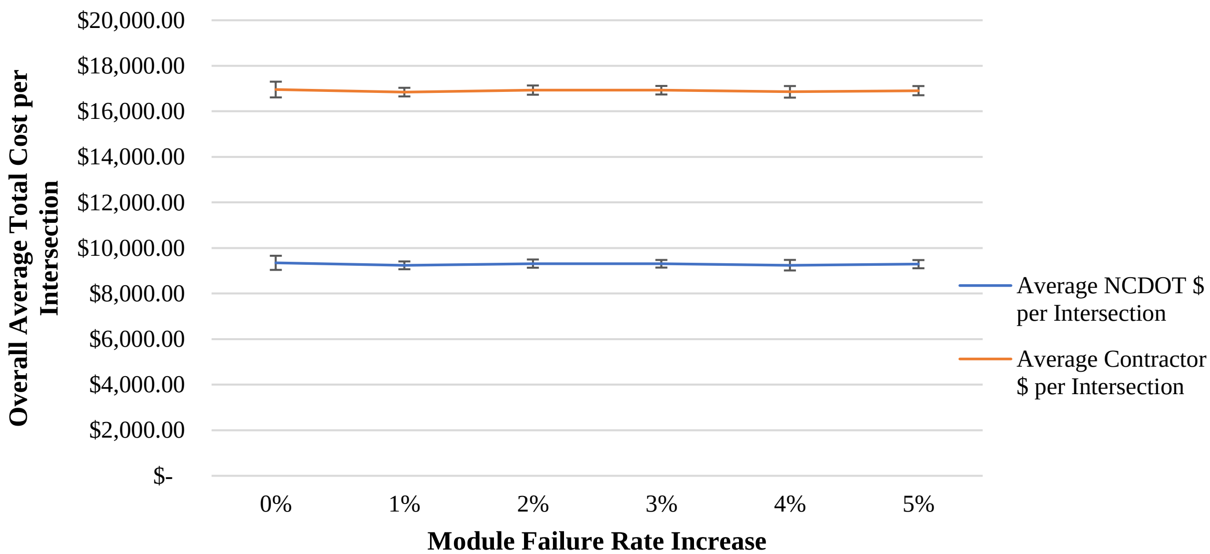


Figure 7.8 Average Total Cost per Intersection (over 30 years) with Varying Module Failure Rates

7.7.2.3 Signal Head Failure Rate

This discussion of the Signal Head Failure Rate evaluates the effect that changing this variable has on the annual cost of replacement for both NCDOT and contracted work. It also evaluates the effects over the whole 30-year span of the simulation. Each Signal Head created within the simulation contains an inherent failure curve (see Section 6.3.2 for additional details). It is important to note that the default assumed lifespan of the Signal Heads is 30-years. The default values for the failure rate are assumed, therefore, sensitivity testing of the rates is required to know whether additional research should be conducted to verify failure rates. The curve utilized is based on the equation below. For each increment to the failure curve, it is assumed that the intersection point will increase by that percentage of the original value.

$$Failure\ Rate = \left(\frac{Current\ Age - 0.8 * Anticipated\ Life}{2}\right)^2 + (0.05 * (1 + increase))$$

Equation 7.1 Signal Head Failure Curve

To understand Signal Head failure rate influence, runs of the simulation have been conducted using increased rates of failure. Output observed includes Average Total Cost per Intersection. Cost refers to replacement costs for both Modules and Signal Heads. Figure 7.9 illustrates the anticipated change in cost per intersection to NCDOT annually over a 30-year period. Each line within the chart represents a different rate of failure for the Signal Heads. Each of the lines plotted is practically on top of the others, indicating that a relative change to the Signal Head failure rate will have minimal impact on the overall cost per year for replacement of Modules and Signal Heads.

Figure 7.10 reinforces this finding by showing the estimated 30-year cost per intersection at various rates of failure. The data shown in the figure follows a nearly straight horizontal line, indicating that no significant impact on cost is made by a relative change to the failure rate.

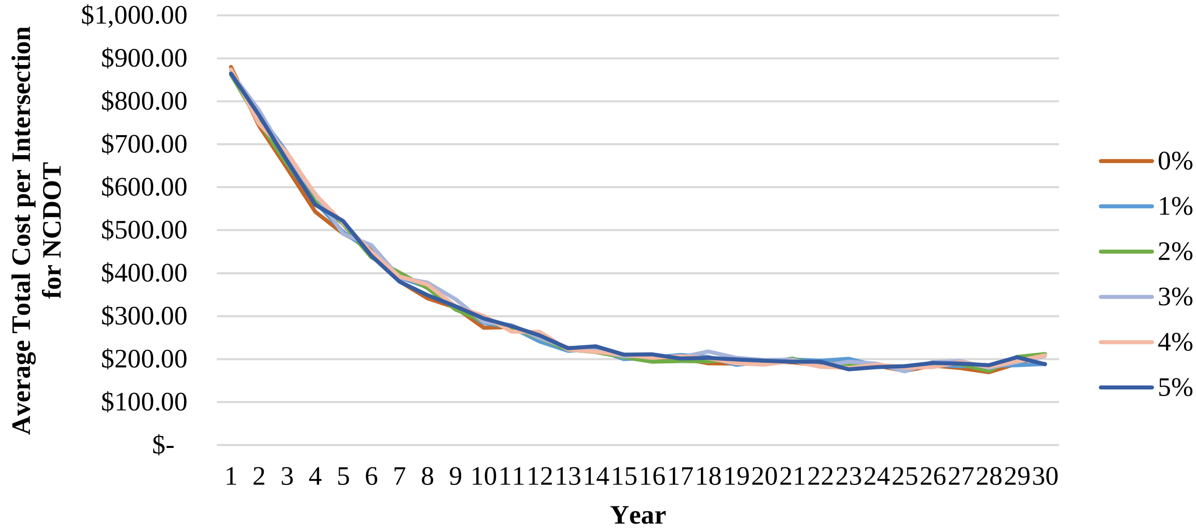


Figure 7.9 Average Total Cost per Intersection for NCDOT Over Time with Varying Increases to Signal Head Failure Rate

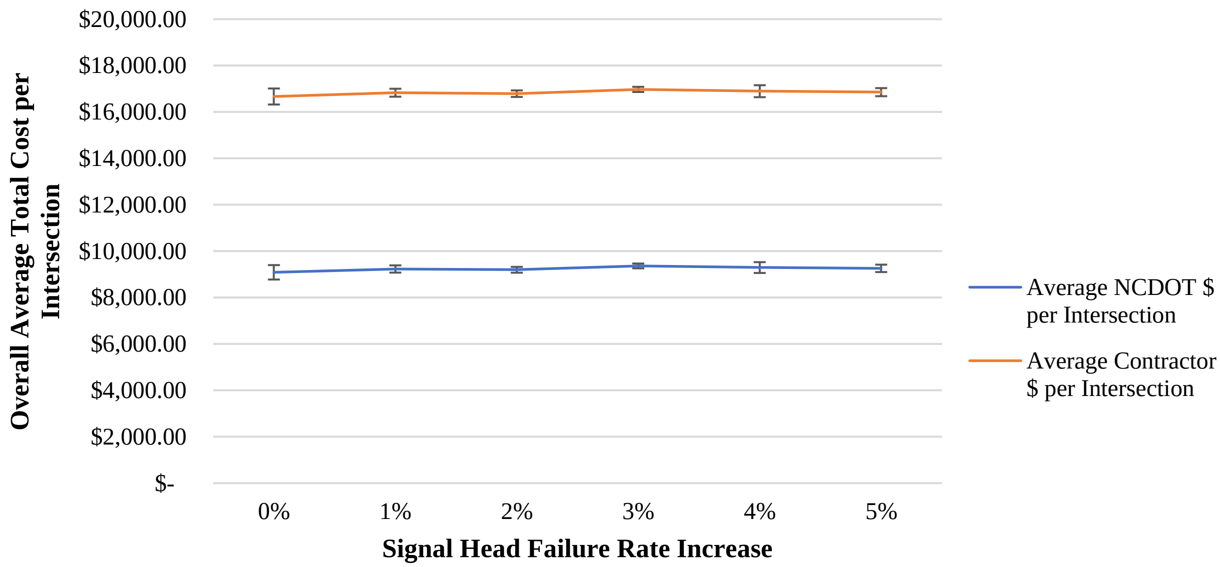


Figure 7.10 Average Total Cost per Intersection (over 30 years) with Varying Increases to Signal Head Failure Rate

7.7.2.4 Cost of Labor and Equipment (Crew Costs)

This discussion of the cost of labor and equipment (Crew Costs) evaluates the effect that changing this variable has on the annual cost of replacement for both NCDOT and contracted work. It also evaluates the effects over a the whole 30-year span of the simulation. Within the simulation, there are both NCDOT replacement crews and Contractor replacement crews. Each crew's costs are considered with each spot and blanket replacement. The default values have been set (as described in Section 6.3.5 & 6.3.6), based on NCDOT data. Due to the structure of the available data, labor and equipment have been combined in to one unit and are considered as 'crew costs.'

To understand the influence of crew costs, runs of the simulation were conducted using varied costs. Crew costs may vary over time as NCDOT is perhaps able to increase hourly rates due to cost of living, or may find themselves lowering rates as needed. Output observed includes Average Total Cost per Intersection. Cost refers to the replacement cost per intersection. Figure 7.11 illustrates the anticipated change in cost per intersection to NCDOT annually over a 30-year period as crew costs are relatively changed. Each line in the chart represents a different change to the base crew costs. During the first 15-year replacement cycle there are visible differences in the overall cost. This is the period when more spot replacements are anticipated due to existing 5-year warrantied modules. As crews are called to the field more often, the cost incurred for their time is greater. During the second 15-year replacement cycle, changes in cost are less distinct.

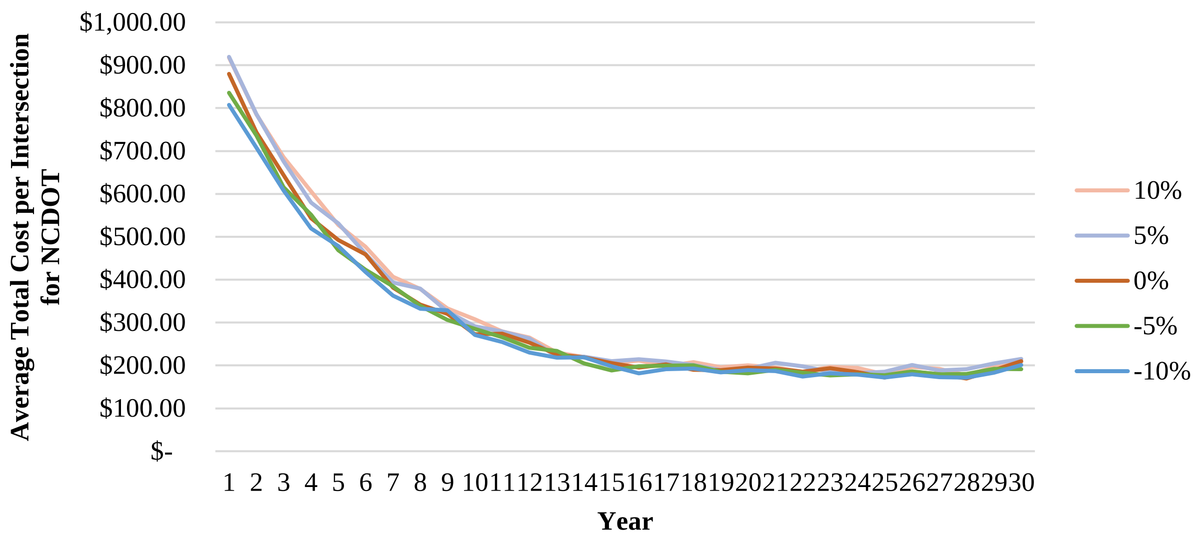


Figure 7.11 Average Total Cost per Intersection for NCDOT Over Time with Varying Labor and Equipment Costs

While changes to the Crew Costs do not appear to have a large impact on the overall cost of replacement work, there is a slight impact. Figure 7.12 shows this impact using the 30-year costs for both NCDOT and Contracted work. Each of the trendlines shown increases as the crew cost is increased.

Table 7.3 provides the percent change in Average Total Cost that can be expected based on changing the crew costs while using this simulation. For instance, if an agency raises their base crew costs for replacement by 5%, they can expect total costs per intersection to increase by 4.5%. Note that Contractor percent change in costs is higher than that of in-house work. This is due to the Contractor cost per replacement being higher than in-house costs for every type of activity.

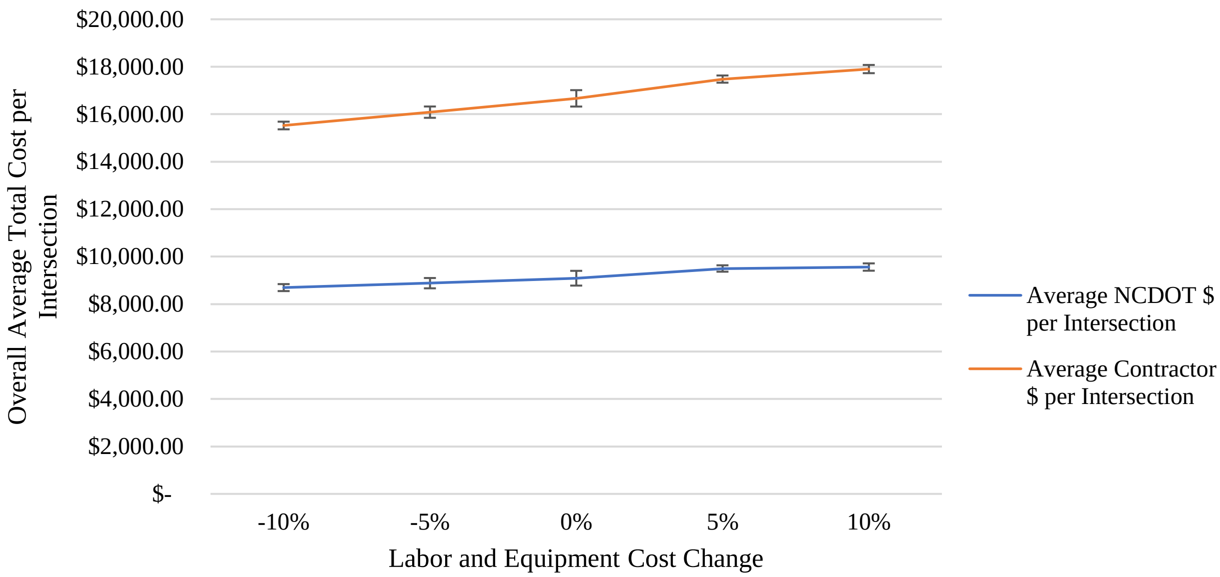


Figure 7.12 Average Total Cost per Intersection with Varying Labor and Equipment Costs

Table 7.3 Percent Change in Average Total Cost per Intersection as Crew Costs Change

Increase to Crew Cost (%)	% Change in Average 30-year Costs	
	NCDOT	Contractor
-10	-4.35 %	-6.86 %
-5	-2.29 %	-3.49 %
0	0.0 %	0.0 %
+5	4.50 %	4.87 %
+10	5.17 %	7.41 %

7.7.2.5 Cost of Materials

This discussion of the cost of materials (Modules and Signal Heads) evaluates the effect that changing these variables has on the annual cost of replacement for both NCDOT and contracted work. It also evaluates the effects over the whole 30-year span of the simulation. Within the simulation, each asset (module or signal head) is assigned an inherent material cost based on their type (see Section 6.3.3 for additional details). With every replacement, material costs are incurred. To understand the influence that changing material costs may have, runs of the simulation have been conducted using varied material costs. Output observed includes Average Total Cost per Intersection. Cost refers to the replacement cost of Modules and Signal Heads. Figure 7.13 shows that there is minimal impact on overall cost with an increase in material costs. Similar to an increase in Crew Cost, there data appears slightly more distinct at the beginning of the simulation, leveling out as the years progress. This may be due to the increased quantity of spot replacements occurring during the first few years of the simulation.

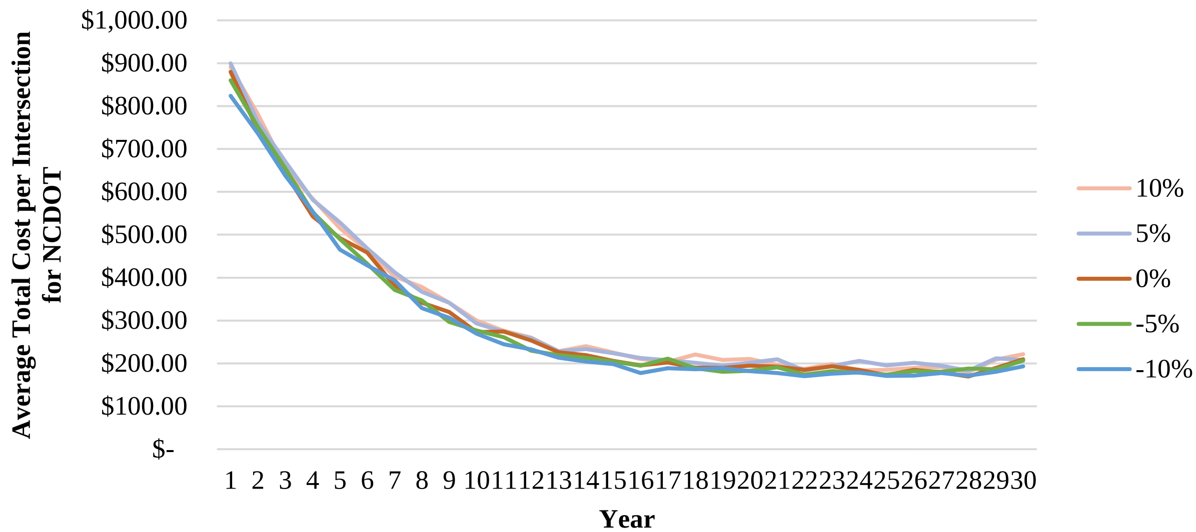


Figure 7.13 Average Total Cost per Intersection for NCDOT Over Time with Varying Material Costs

Changes to material cost do appear to have a slight impact on the overall cost, which is shown again in Figure 7.14. Each data point represents the anticipated cost per intersection for the entire 30-year span. Both trendlines are seen to go up slightly as the cost of materials increases.

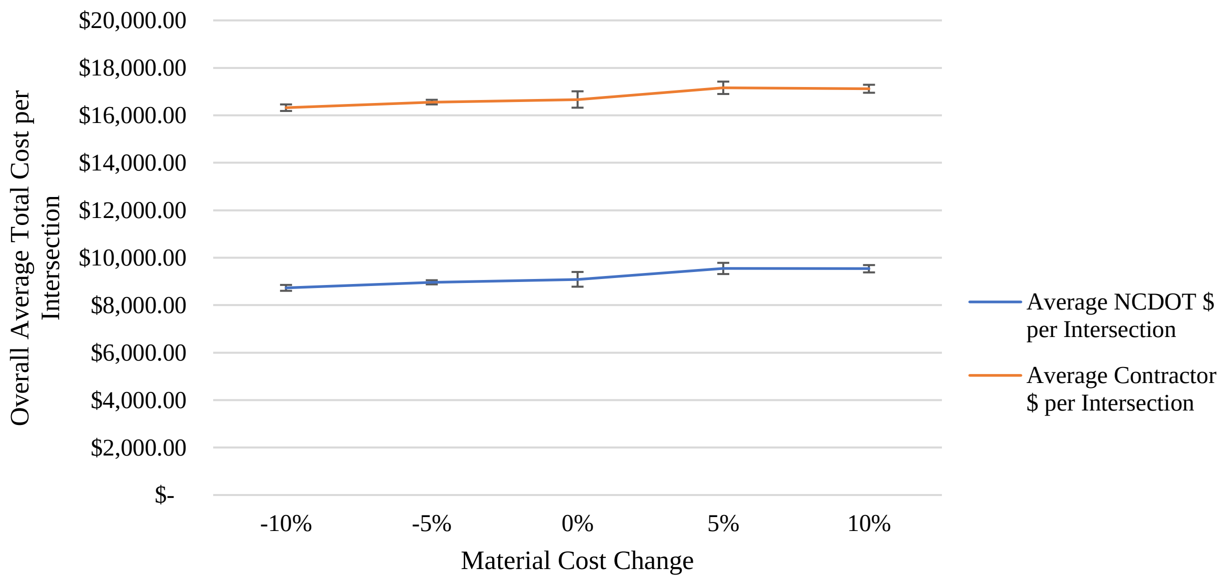


Figure 7.14 Average Total Cost per Intersection (over 30 years) with Varying Material Costs

Table 7.4 provides the percent change in average total cost that can be expected based on changing the material costs while using this simulation. For instance, if a manufacturer raises their base material costs by 5%, a transportation agency can expect total costs per intersection to increase by 5.06%. Note that the percent increases for 10% in this case are less than those for 5%. This is likely due to differences in the individual runs of the simulation that were conducted for this analysis. Due to the quantity of runs required for sensitivity analysis, only one run per change occurred. For additional insight, an agency may complete a similar study using more runs of the simulation for each incremented change.

Table 7.4 Percent Change in Average Total Cost per Intersection as Material Costs Change

Increase to Material Cost (%)	% Change in Average 30-year Costs	
	NCDOT	Contractor
-10	-3.69 %	-2.08 %
-5	-1.37 %	-0.66 %
0	0.0 %	0.0 %
+5	5.06 %	2.95 %
+10	4.92 %	2.71 %

7.7.2.6 Inflation

This discussion of the rate of inflation evaluates the effect that changing this variable has on the annual cost of replacement for both NCDOT and contracted work. It also evaluates the effect over the whole 30-year span of the simulation. While inflation is not a parameter that any transportation agency can control, it is important to understand the impacts that it may have on the estimates provided with this simulation. Within the simulation the user can input an anticipated rate of inflation. At the end of each year, both material costs and crew costs are increased based on this rate. This occurs every year, for all 30 years observed. Cost values are reset at the start of each model iteration, allowing for comparison across iterations. To understand the impact of inflation, runs of the simulation have been conducted using varied rates. Output observed includes Average Total Cost per Intersection. Cost refers to replacement costs of Modules and Signal Heads. Figure 7.15 shows that inflation has an exponential impact on the cost for each intersection, as would be expected.

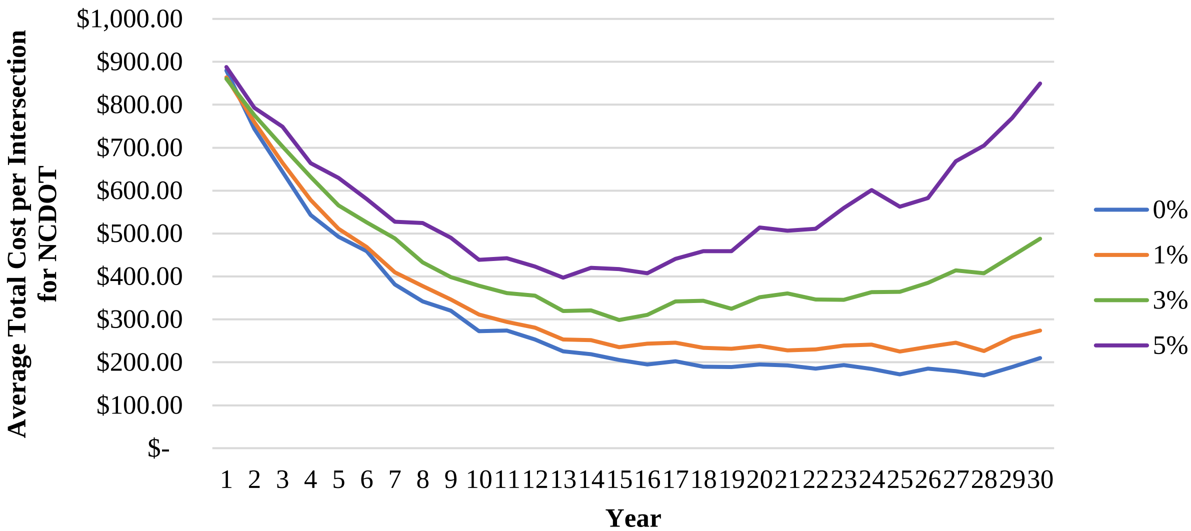


Figure 7.15 Average Total Cost per Intersection for NCDOT Over Time with Varying Inflation Rates

Changing the rate of inflation has a major impact on the overall cost of replacement work, for both NCDOT and Contracted work. Figure 7.16 shows this impact, the trend lines for both NCDOT and Contractor work quickly increase as inflation rates increase. The scale of this figure has not been standardized to match the other 30-year figures, as the total costs exceed the $20,000 cap that was identified with other parameter changes.

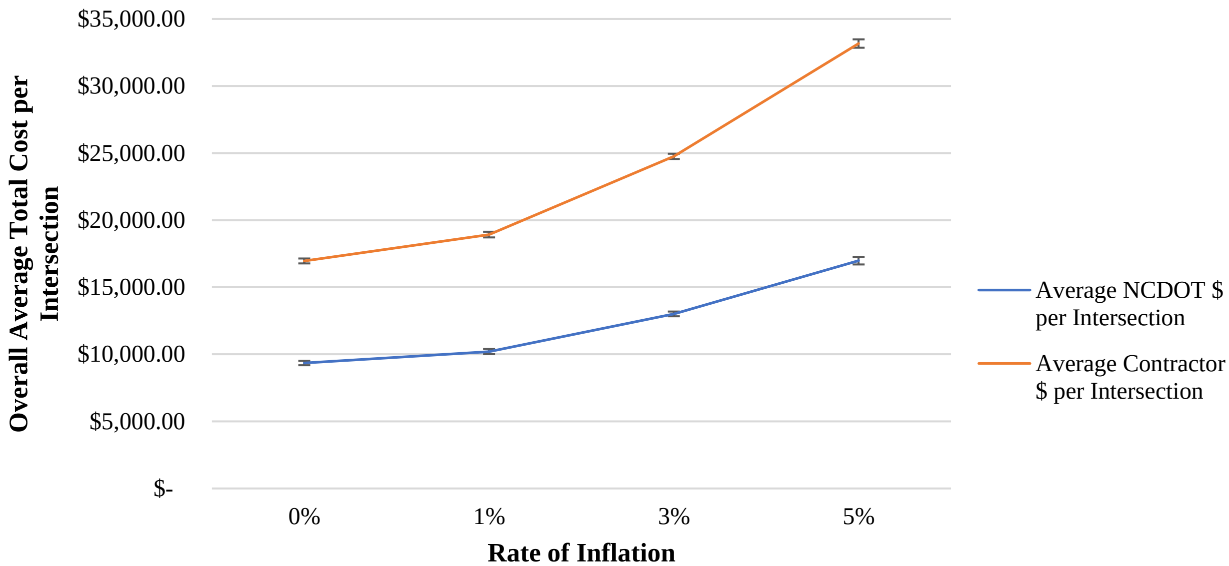


Figure 7.16 Average Cost per Intersection (over 30 years) with Varying Inflation Rates

Table 7.5 provides the percent change in average total cost that can be expected based on changing the inflation rate while using this simulation. For instance, if an agency anticipates an inflation rate of 3%, they can expect 30-year costs per intersection to increase by 43%. Note that Contractor percent change is higher than that of in-house work due to the higher base cost of contracted work.

Table 7.5 Percent Change in Average Total Cost per Intersection as Inflation Rate Changes

Increase to Inflation Rate (%)	% Change in Average 30-year Costs	
	NCDOT	Contractor
0	0.0 %	0.0 %
1	12.27 %	13.55 %
3	43.16 %	48.53 %
5	86.85 %	98.99 %

7.7.3 Conclusions

As a result of the single-parameter sensitivity analysis, users of the simulation know that crew costs and material costs have the greatest impact of the controllable parameters. Clearly, inflation has the largest impact, however, as discussed, there is no way for transportation agencies to conduct research resulting in a more accurate anticipated inflation rate. Our only certainty is that today's costs are likely, in the long run, to be significantly lower than tomorrow's costs. If additional research is conducted, transportation agencies should focus on determining failure curves for both LED Modules and Signal Heads, as these parameters were assumed and determining actual values would be groundbreaking.

7.8 Validating the Output from the Overall Model Simulation

To determine whether the output from the model met logical expectations, a series of calculations was performed mimicking a single iteration utilizing the failure and replacement rates utilized in the model (See Section 6.3.2). By comparing the results of these calculations with output from the simulation, it was determined that the model is functioning as expected.

Specifically, calculations were performed for the 1-year replacement period, independent replacement alternative, as it is the simplest. Each year, the quantity of Signal Heads and Modules which were expected to fail were calculated. This was done for each of the 30 years. The first three years of calculations are shown below. Ultimately, these calculations were performed using excel due to volume and complexity.

For these calculations, it is assumed that there are 205 intersections, containing 1,796 Signal Heads and 5,846 Modules. Calculations shown below determine the quantity of Modules and Signal Heads expected to fail each year based on their status as existing or new, and their age. Total replacements (due to blanket and spot failure) are totaled at the end of each year and summed over time to show the total quantity of LED Modules and Signals Heads replaced at the end of 30 years.

Year 1

Blanket Replacement
Modules Only: 5,846

Spot Replacement
Modules Existing = 0
Modules Age: 1 = 5,846
Modules Likely to Fail:
5,846 * 0.003 = 18

Signal Heads Existing: 1,796
Signal Heads Likely to Fail:
1,796 * 0.03 = 54
54 SH Failures = min. of 162 Modules

Total Replacements Year 1
Modules: 5,846 + 18 + 162 = **6,026**
Signal Heads: **54**

Year 2

Blanket Replacement
Modules Only: 0

Spot Replacement
Modules Existing = 0
Modules Age: 1 = 18
Modules Age: 2 = 5,828
Modules Likely to Fail:
(18 * 0.003) + (5,828 * 0.001) = 6

Signal Heads Existing: 1,742
Signal Heads Age: 1 = 54
Signal Heads Likely to Fail:
(1,742 * 0.03) + (54 * 0.0005) = 52
52 SH Failures = min. of 156 Modules

Total Replacements Year 2
Modules: 0 + 6 + 156 = 162
Signal Heads: 52

Total Replacements **Overall**
Modules: 6,026 + 162 = **6,188**
Signal Heads: 54 + 52 = **106**

Year 3

Blanket Replacement
Modules Only: 0

Spot Replacement
Modules Existing = 0
Modules Age: 1 = 6
Modules Age: 2 = 18
Modules Age: 3 = 5,822
Modules Likely to Fail:
(6 * 0.003) + (18 * 0.001) + (5,822 * 0.0005) = 3

Signal Heads Existing: 1,690
Signal Heads Age: 1 = 52
Signal Heads Age: 2 = 54
Signal Heads Likely to Fail:
(1,690 * 0.03) + (52 * 0.0005) + (54 * 0.0005) = 50
50 SH Failures = min. of 150 Modules

Total Replacements Year 3
Modules: 0 + 3 + 150 = 153
Signal Heads: 50

Total Replacements **Overall**
Modules: 6,188 + 153 = **6,341**
Signal Heads: 106 + 50 = **156**

Once calculations have been completed for all 30 years, a mathematical *minimum* quantity of modules replaced during the span of the simulation can be determined. Table 7.6 contains the results of such a set of calculations. Column 1 identifies the year, while columns 2 and 3 show the quantity of blanket replaced Modules and Signal Heads. Columns 4 and 5 contain the quantities of spot replaced Modules and Signal Heads. Column 6 contains a minimum estimate of the quantity of LED Modules that would be replaced with the Signal Heads that are replaced. If each Signal Head contains only 3 modules (the most common number, but also the minimum), Column 6 is three times the quantity of Column 5. Finally, Column 7 contains the total quantity of modules replaced each year (the sum of columns 2, 4, 6) and, whether that be through individual module replacement, or within a signal head which was replaced.

Per the Simulation Summary for the 1-year period, independent replacement strategy, there were a total of 15,484 LED Modules and 1,103 Signal Heads replaced during the 30-year simulation. Those quantities are similar enough to the calculated replacement totals shown in Table 7.6 (14,785 Modules replaced) that users can be confident the simulation is following the outlined logic. Full tables showing the annual calculations for these values can be found in Appendix E. Remember, Table 7.6 shows the minimum quantity of LED Modules replaced in one iteration. There is no element of randomness accounted for in the calculations shown. When the model runs, a new set of 205 intersections is generated each iteration, containing varying quantities of Signal Heads and Modules (as described in Section 6.3.1). Each Module and Signal Head then has an inherent failure rate which may be triggered by a random number generator crossing a failure threshold. Once this occurs over 30 years within the simulation, for eight iterations, an increase in quantity of Modules replaced is expected compared to the value calculated in Table 7.6.

Table 7.6 'Reality Check' Calculations for Simulation Comparison

Year	Blanket Replacement		Spot Replacement		Modules Replaced with Signal Heads	Total Modules Replaced
	Modules	Signal Heads	Modules	Signal Heads		
1	5,846.00	-	17.54	53.88	161.64	6,025.18
2	-	-	5.88	52.29	156.87	162.75
3	-	-	2.95	50.75	152.24	155.19
4	-	-	2.93	49.25	147.75	150.69
5	-	-	2.93	47.80	143.39	146.33
6	-	-	2.93	46.39	139.16	142.10
7	-	-	2.93	45.02	135.06	137.99
8	-	-	2.93	43.69	131.07	134.01
9	-	-	2.93	42.40	127.21	130.14
10	-	-	2.93	41.15	123.46	126.39
11	-	-	2.93	39.94	119.81	122.74
12	-	-	2.93	38.76	116.28	119.21
13	-	-	2.93	37.62	112.85	115.78
14	-	-	5.83	36.51	109.52	115.35
15	-	-	17.41	35.43	106.29	123.70
16	5,846.00	-	17.54	34.38	103.15	5,966.69
17	-	-	5.88	33.37	100.11	105.99
18	-	-	2.95	32.39	97.16	100.10
19	-	-	2.93	31.43	94.29	97.22
20	-	-	2.93	30.50	91.51	94.44
21	-	-	2.93	29.60	88.81	91.74
22	-	-	2.93	28.73	86.19	89.12
23	-	-	2.93	27.88	83.65	86.58
24	-	-	2.93	27.06	81.18	84.11
25	-	-	2.93	26.26	78.78	81.72
26	-	-	2.93	0.59	1.78	4.71
27	-	-	2.93	1.10	3.31	6.24
28	-	-	2.93	2.27	6.82	9.75
29	-	-	5.83	4.35	13.06	18.89
30	-	-	17.41	7.58	22.75	40.16
TOTAL	**11,692.00**	**0.00**	**157.84**	**978.39**	**2,935.16**	**14,785.00**

8.0 Results

This chapter contains the resulting output of running the simulation for the 9 alternate scenarios discussed in Chapter 5.0: Development of Replacement Strategy Alternatives. Each Alternate Scenario will be discussed independently, after which comparisons will be made between them. The Baseline scenario (Alternative 1) will be discussed in detail, while discussion of the remaining scenarios will highlight only similarities and differences of interest.

For all replacement strategy alternatives, costs are reported which assume that NCDOT does all of the work in-house (the NCDOT Total). Additionally, costs are reported which assume that a Contractor is brought in to do all work with minimal NCDOT labor (the Contractor Total). These costs are further disaggregated into NCDOT doing only blanket replacement, NCDOT doing only spot replacement, a contractor doing only blanket replacement, and a contractor doing only spot replacement. Using the disaggregated data, it is possible to determine total costs with a mix of NCDOT and contractor involvement. Elements of this data will be highlighted in the discussions for each scenario.

Due to the simulation running multiple iterations for each scenario, it is important to look at summary metrics surrounding the data. Typically, the average is used to provide a look at the overall scope of the data. However, the median can also be useful because it excludes any outlying values and may be more reliable for planning purposes. The standard deviation has also been provided as a measure of the dispersion of the data around the average (to show whether the output is tightly clustered around the average, or spread over a larger range).

8.1 Alternative 1: 'Baseline' 5-year Replacement Period, 5-year Replacement Cycle

Alternative 1 utilizes the 5-year warranty modules that have been used since their introduction. The alternative represents the continuation of past practice, assuming changes in technology are not incorporated. By providing a set of benchmark costs and labor hours, this baseline alternative highlights the cost and labor savings that may be experienced by implementing one of the other replacement strategies. This Baseline scenario utilizes a 5-year replacement period within a 5-year replacement cycle, meaning that one fifth of the LED Modules across the state will be replaced each year over a 5-year period. This alternative is meant to represent the ideal operating conditions for NCDOT's past, and will serve as a comparison point between the past and possible future cost and labor savings. Independent replacement indicates that during blanket replacement, only the Modules are replaced. Signal Heads are not part of blanket replacement and are only replaced if required due to spot failure.

The following input variables were used when running this scenario

- Iterations: 8
- Intersections: 205
- Signal Head Life Expectancy: 30 years
- Timeline: 30 years
- Replacement Cycle **5 years**
- Replacement Period: **5 years**
- Joint Replacement: **False**
- Module Warranty: **5 years**
- Inflation: 0.00%

8.1.1 <u>Annual Costs</u>

Figure 8.1 shows a summary of the replacement costs, per intersection, to NCDOT over the 30-year span of the simulation. Both average and median values have been plotted for the Total cost, ■, (the sum of blanket and spot) as well as for blanket replacement (▲) and spot replacement (◆). These costs assume that NCDOT is completing all the work related to replacement of LED Modules and Signal Heads in-house. None of the work has been contracted out. As shown, the average (represented by solid lines) and median (represented by dashed lines and shapes marking the data points) costs closely follow one another, indicating that either cost could reasonably be used for planning purposes. The costs follow one another so closely that they appear at one line on the chart.

Figure 8.2 provides a similar summary of replacement costs; however, it is assumed that a contractor has been brought in to do both blanket and spot replacements for LED Modules and Signal Heads. Note that in each case, NCDOT Technician labor-hours are required. Based on information provided by Divisions, an NCDOT Technician must inspect and approve all work done by Contractors, adding an average of 0.40 NCDOT Technician Labor Hours per intersection, per year (or 12 labor hours per intersection over the 30-year span).

All existing LED Modules are replaced within the first 5-year replacement cycle. This is evident in the drastic decrease that is seen in spot replacement rates for the first five years. Based on past practices, this alternative assumes that modules with 5-year warranties are used throughout the entire timeframe. However, due to the consistent annual replacement of one fifth of the modules, spot failure rates remain consistently low after year 5 (once all existing modules have been replaced). Blanket replacement remains constant, which is consistent with past practices.

The scale of both Figures 8.1 and 8.2 have been set to match so that a visual comparison of costs can be done with ease. Figure 8.1 shows Total Costs per Intersection for NCDOT reaching only ~$1,000 per year as a maximum, while Figure 8.2 shows Total Costs per Intersection for contracted work reaching a maximum of ~$1,800 per year. Contractor costs will always be greater than NCDOT in-house work due to the increased crew costs associated with hiring a contractor (see Sections 6.3.5 and 6.3.6 for specific per-activity costs).

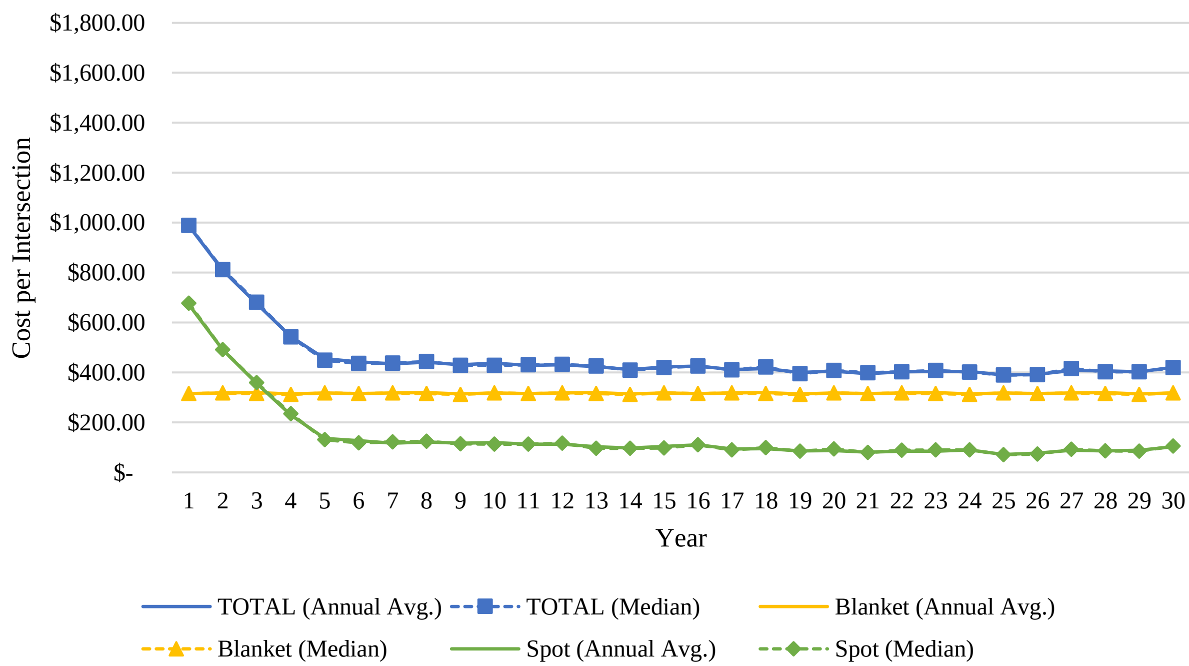


Figure 8.1 Replacement Costs to NCDOT (per Intersection) Over Time
5-year Cycle, 5-year Period, Independent Replacement

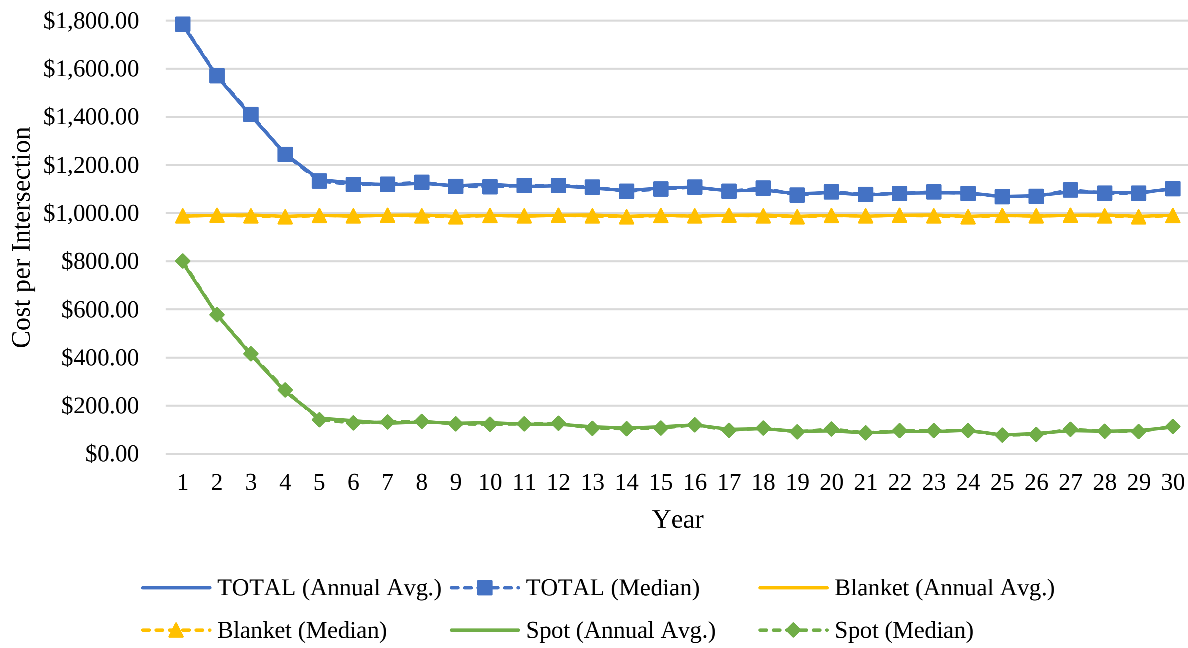


Figure 8.2 Replacement Costs for Contractor (per Intersection) Over Time
5-year Cycle, 5-year Period, Independent Replacement

Table 8.1 contains an excerpt of the annual cost data, per intersection, recorded for each year of the simulation. The full tables are rather lengthy and can be found in Appendix F: Annual Cost Data for Alternative Scenarios, Tables F1 and F2. In the full tables, one can find not only the Total Cost, but also the specific costs associated with Blanket and Spot replacement for each year (for both NCDOT in-house work and contracted work). Columns two through five in Table 8.1 provide estimates of the total cost were NCDOT to conduct all replacement work. There is then a gap in the table which, in the appendices, contains the disaggregated data related to NCDOT Blanket replacement costs and NCDOT Spot replacement costs. Columns six through eight of Table 8.1 provide estimates of the total cost were all replacement work to be contracted out. Additional disaggregated data follows in the appendix, showing estimates for Contractor Blanket replacement and Contractor Spot replacement costs.

Table 8.1 Excerpt of Annual Cost Data (per Intersection)
5-year Cycle, 5-year Period, Independent Replacement

Year	NCDOT Total Cost (Average)	NCDOT Total Cost (Median)	NCDOT Total Cost (Std. Dev.)	…	Contractor Total Cost (Average)	Contractor Total Cost (Median)	Contractor Total Cost (Std. Dev.)
1	$987.19	$989.30	$35.36		$1,781.89	$1,785.00	$40.14
2	$809.87	$812.20	$15.98		$1,567.96	$1,570.64	$19.14
3	$676.51	$680.98	$18.15		$1,404.36	$1,410.47	$19.68
4	$543.76	$542.16	$17.12		$1,245.92	$1,243.42	$17.41
5	$454.98	$449.20	$30.15		$1,138.83	$1,133.00	$32.00
6	$442.09	$436.90	$28.70		$1,125.18	$1,119.24	$30.39
7	$435.61	$437.80	$23.14		$1,117.77	$1,120.45	$24.09
8	$441.70	$444.62	$35.92		$1,124.21	$1,127.74	$37.72
9	$430.90	$429.06	$10.85		$1,113.16	$1,111.30	$11.52
10	$437.76	$428.36	$19.69		$1,120.12	$1,110.10	$21.17
11	$428.52	$431.70	$17.82		$1,110.63	$1,114.23	$19.01
12	$431.31	$432.38	$20.02		$1,113.35	$1,115.40	$21.00
13	$422.94	$426.45	$22.70		$1,104.42	$1,107.70	$24.29
14	$412.16	$409.54	$15.77		$1,093.10	$1,090.30	$16.91
15	$422.26	$419.18	$20.10		$1,103.68	$1,100.44	$21.75
16	$425.61	$425.79	$11.82		$1,107.58	$1,108.03	$12.25
17	$411.88	$410.99	$17.25		$1,092.24	$1,090.49	$18.53
…	…	…	…		…	…	…
30	$420.78	$419.96	$21.52		$1,102.11	$1,101.51	$23.14

8.1.2 Replacement Quantities

Whether the work is done by NCDOT, or contracted out, the quantity of LED Modules and Signal Heads required for replacement will remain the same. Figure 8.3 shows how many Signal Heads and Modules are at each intersection to start. Meaning, how many Modules and Signal Heads exist at the intersection and will go through the replacement process. These quantities are provided by the blue ■ and grey ▲ lines. Additionally, the average and median quantities of LED Modules (◆) and Signal Heads (●) replaced each year, per intersection, are plotted. Again, both the average values (represented by a solid line) and the median values (represented by a dashed line with shaped data points) have been provided. However, these two values follow one another so closely that they almost completely overlap in the chart – giving the appearance of a single line.

Mirroring the patterns found in Figures 8.1 and 8.2, there is a slight drop in the quantity of LED Modules replaced over the first five years, after which both the quantity of LED Modules and Signal Heads replaced at each intersection each year remains consistent for the following 25 years. This is aligned with expectations, as the same quantity of Modules will be replaced during the blanket replacement process each year. Spot replacements of both Modules and Signal Heads will occur, however they will be infrequent (after year 5). This is shown in the fraction of a Signal Head that is anticipated to be required at each intersection each year and the leveling-off of the quantity of Modules per intersection.

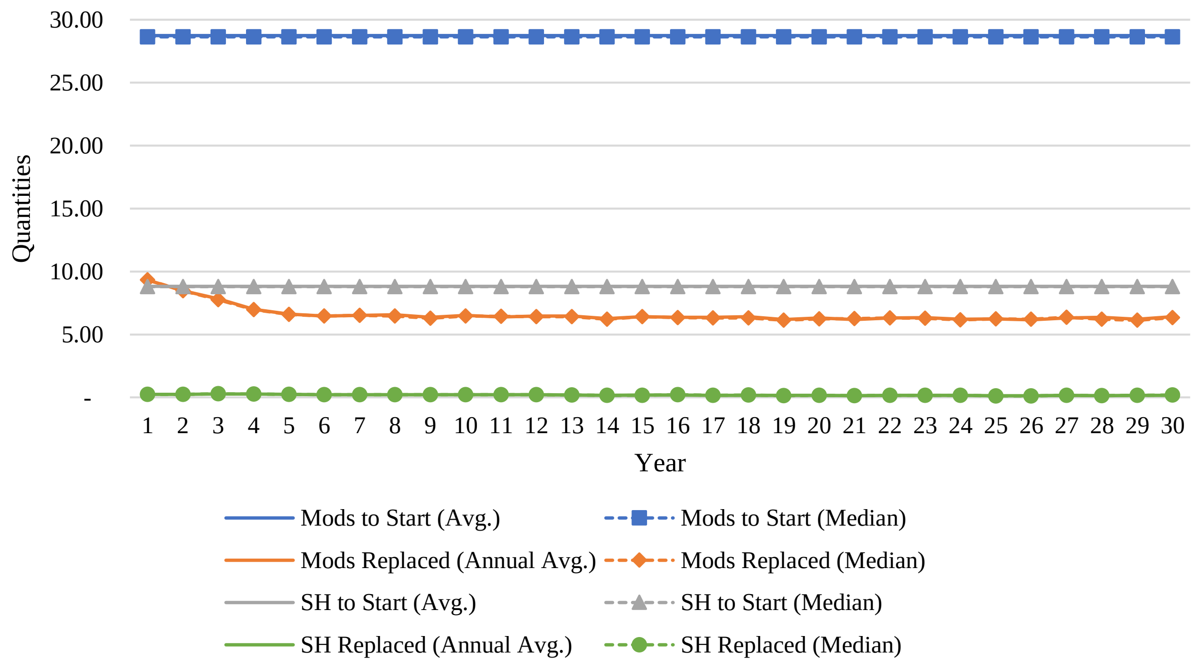


Figure 8.3 Quantities of LED Modules and Signal Heads Replaced (per Intersection) Over Time 5-year Cycle, 5-year Period, Independent Replacement

Table 8.2 contains an excerpt of the annual replacement quantity data, per intersection, recorded for each year of the simulation. The full tables are rather lengthy and can be found in Appendix G: Annual Replacement Quantity Data for Alternative Scenarios, Table G1. Columns two through five of Table 8.2 provide data related to the quantity of modules which were generated by the simulation at each intersection. There is then a gap in the table, indicating additional data to be found in the appendix. This additional data will contain estimates of the quantity of Modules replaced each year and the quantity of Signal Heads generated for each intersection by the simulation (per intersection). Columns six through eight of Table 8.2 provide estimates of the quantity of Signal Heads which were replaced each year, per intersection.

Table 8.2 Excerpt of Annual Replacement Quantity Data (per Intersection)
5-year Cycle, 5-year Period, Independent Replacement

Year	Modules in Place (Average)	Modules in Place (Median)	Modules in Place (Std. Dev.)	…	Signal Heads Replaced (Average)	Signal Heads Replaced (Median)	Signal Heads Replaced (Std. Dev.)
1	28.74	28.64	0.76		0.25	0.25	0.03
2	28.74	28.64	0.76		0.24	0.24	0.02
3	28.74	28.64	0.76		0.27	0.28	0.02
4	28.74	28.64	0.76		0.26	0.27	0.03
5	28.74	28.64	0.76		0.25	0.24	0.05
6	28.74	28.64	0.76		0.22	0.20	0.04
7	28.74	28.64	0.76		0.21	0.22	0.03
8	28.74	28.64	0.76		0.21	0.22	0.05
9	28.74	28.64	0.76		0.21	0.21	0.02
10	28.74	28.64	0.76		0.21	0.20	0.03
11	28.74	28.64	0.76		0.20	0.20	0.03
12	28.74	28.64	0.76		0.20	0.20	0.03
…	…	…	…		…	…	…
30	28.74	28.64	0.76		0.17	0.18	0.03

8.1.3 Summary

This section provides summary information regarding the overall costs and labor hours estimated for NCDOT over a 30-year period based on a 5-year replacement cycle, a 5-year replacement period and independent replacement, with 5-year warrantied LED Modules. Table 8.3 provides a summary of all output data provided by the simulation for Alternative 1 (5-year Replacement Period, Independent Replacement, 5-year warrantied modules). Column 1 indicates the metric observed. Column 2 shows whether the scope of the value is relevant for the whole simulation (205 intersections) or on an intersection level. Columns 3 through 5 provide the average, median, and standard deviation for the estimated value of the observed metric.

Keep in mind that the simulation was run for only 205 intersections to provide representative estimates while keeping the runtime of the simulation manageable (see Section 6.3.1 for details). NCDOT is responsible for approximately 8,200 intersections. To effectively scale the estimates found by the simulation, a per-intersection value was determined for each metric. This per-intersection value allows for scaling to the Division level or to the State level, whichever is more useful to the planners using these estimates. Table 8.3 contains raw simulation output for both the quantity of intersections within the simulation (which can be adjusted by the user) and a per-intersection estimate.

For example, Modules in Place is the first metric, row 1 of column 3 shows that for all 205 intersections in the simulation, approximately 5,890 modules were created, while row 2 indicates that is approximately 29 modules per intersection. An example using cost shows that, for NCDOT Total replacement costs, the 30-year average cost estimate for the whole simulation (205 intersections) is $2.84M, while the 30-year average cost per intersection was estimated to be $14,000.

To understand the scale of funding required for regular LED Module and Signal Head replacement at the state level, it is necessary to scale up the costs. Multiplying each of the cost and labor hour per-intersection values found in Table 8.3 by the 8,200 intersections that NCDOT is responsible for, results in the values provided in

Table 8.4. For example, NCDOT's Total Replacement Cost (for in-house work), for the whole state, was estimated to be approximately $113.7M. Contractor Total Cost estimates were approximately $283.3M, a little less than twice the cost of NCDOT.

Table 8.3 5-year Cycle, 5-year Period, Independent Replacement Simulation Lifetime Summary Output Data (for 205 Intersections)

Metric	Scope	Average	Median	Standard Deviation
Modules in Place	Total	5,892.38	5,870.50	144.99
	Per Intersection	28.74	28.64	0.71
Signal Heads at Start	Total	1,808.50	1,803.50	42.73
	Per Intersection	8.82	8.80	0.21
Modules Replaced	Total	40,565.75	40,368.00	1,107.43
	Per Intersection	197.87	196.92	5.41
Signal Heads Replaced	Total	1,137.38	1,122.00	44.78
	Per Intersection	5.56	5.48	0.21
NCDOT Total Replacement Costs	Total	$2,842,415.22	$2,827,872.14	$61,562.61
	Per Intersection	$13,865.44	$13,794.50	$300.31
NCDOT Blanket Replacement Costs	Total	$1,950,614.30	$1,946,265.99	$30,811.35
	Per Intersection	$9,515.20	$9,493.98	$150.28
NCDOT Signal Head Spot Replacement Costs	Total	$604,577.74	$596,705.27	$26,637.11
	Per Intersection	$2,949.16	$2,910.76	$129.94
NCDOT Module Spot Replacement Costs	Total	$287,223.18	$286,816.18	$6,919.31
	Per Intersection	$1,401.09	$1,399.11	$33.74
NCDOT Labor Hours Required	Total	7,617.92	7,617.83	46.80
	Per Intersection	37.16	37.16	0.22
Contractor Total Replacement Costs	Total	$7,083,647.22	$7,068,641.74	$64,291.57
	Per Intersection	$34,554.37	$34,481.18	$313.61
Contractor Blanket Replacement Costs	Total	$6,086,366.30	$6,082,017.99	$30,811.35
	Per Intersection	$29,689.60	$29,668.38	$150.28
Contractor Signal Head Spot Replacement Costs	Total	$650,072.74	$641,585.27	$28,410.39
	Per Intersection	$3,171.09	$3,129.70	$138.59
Contractor Module Spot Replacement Costs	Total	$347,208.18	$346,716.18	$8,364.37
	Per Intersection	$1,693.72	$1,691.33	$40.81
NCDOT Supervisory Labor Hours Required	Total	2,460.00	2,460.00	-
	Per Intersection	12.00	12.00	-

These costs can be mixed and matched. For instance, if NCDOT were to manage all spot replacement, but contract out all blanket replacement work, the total estimated cost would be approximately $279.1M over a 30-year period. This is found by summing the estimates for the individual elements of the replacement process based on who is expected to conduct the work. Note that the cost of additional NCDOT supervisory labor (which is required when Contract blanket replacement work is completed) has not been incorporated into these cost estimates. Instead, an estimate of the time required has been provided.

Sections pertaining to the other eight alternative will include similar tables and figures, however the discussion of the replacement strategies will be limited to highlight only unique characteristics.

Table 8.4 5-year Cycle, 5-year Period, Independent Replacement State-wide Output Summary

Metric	Scope	Average	Median	Std. Dev.
NCDOT Total Replacement Costs	State Wide	$113,696,608.00	$113,114,900.00	$2,462,509.20
NCDOT Blanket Replacement Costs	State Wide	$78,024,640.00	$77,850,636.00	$1,232,271.40
NCDOT Signal Head Spot Replacement Costs	State Wide	$24,183,112.00	$23,868,232.00	$1,065,516.20
NCDOT Module Spot Replacement Costs	State Wide	$11,488,938.00	$11,472,702.00	$276,692.60
NCDOT Labor Hours Required	State Wide	304,712.00	304,712.00	1,787.60
Contractor Total Replacement Costs	State Wide	$283,345,834.00	$282,745,676.00	$2,571,634.80
Contractor Blanket Replacement Costs	State Wide	$243,454,720.00	$243,280,716.00	$1,232,271.40
Contractor Signal Head Spot Replacement Costs	State Wide	$26,002,938.00	$25,663,540.00	$1,136,462.60
Contractor Module Spot Replacement Costs	State Wide	$13,888,504.00	$13,868,906.00	$334,609.20
NCDOT Supervisory Labor Hours Required	State Wide	98,400.00	98,400.00	-

8.2 Alternative 2: Spot Replacement Only, 15-year Modules

Alternative 2 utilizes only spot replacement with 15-year warrantied modules with no blanket replacement strategy having been implemented. Signal Heads will also be replaced on a spot replacement basis. This replacement strategy represents the current practices that have been reported by several Divisions within NCDOT due to either personnel restraints, budget shortfalls, or both. To understand how utilizing only spot replacement impacts efficiency, it is important to model that scenario.

Without blanket replacement, Alternative 2 is reliant entirely on the lifespans and failure rates provided for use in the model. While values for lifespan and failure rates are based on information from NCDOT and Led Module manufacturers, it is important to remember that 15-year warrantied modules have not been in the field long enough for long-term studies to be completed to verify the lifespan and failure rates. An additional concern utilizing spot only replacement is that the human eye alone is not capable of determining whether an LED Module has degraded below the ITE minimum luminosity standard unless that module is already significantly below the threshold and visibly dim. To stay within ITE standards, NCDOT will need to incorporate the regular use of luminosity detection into their inspections. As described in Chapter 2 (Literature Review), accurate luminosity detection is typically accomplished by removing the modules and testing them in a lab setting. There are also in-place methods of testing, which require the use of a bucket truck. The financial cost and labor required to maintain ITE standards with spot only replacement have not been incorporated into the discussion around this scenario, as they will be determined by the strategy that NCDOT selects to do their monitoring, and other strategies utilizing blanket replacement provide ample avenues for ensuring that ITE standards are met.

The following input variables were used when running this scenario

- Iterations: 8
- Intersections: 205
- Signal Head Life Expectancy: 30 years
- Timeline: 30 years
- Replacement Cycle: **-**
- Replacement Period: **-**
- Joint Replacement: **False**
- Module Warranty: 15 years
- Inflation: 0.00%

8.2.1 Annual Costs

Figures 8.4 and 8.5 provide summaries of the replacement costs per intersection over the 30-year span of the simulation. Both average and median values have been plotted for the Total cost, ■, (the sum of blanket and spot) as well as for blanket replacement (▲) and spot replacement (◆). Again, these values overlap giving the appearance of a single line. Note that there is no blanket replacement occurring, so in this instance, the total cost and the spot replacement cost are the same. Because all labor hours estimates are tied to blanket replacement, there are no estimates to report with this scenario. Both figures show that cost per year will slowly decrease until around year 18, at which point the first installed 15-year modules will begin to fail and the replacement rate increases again.

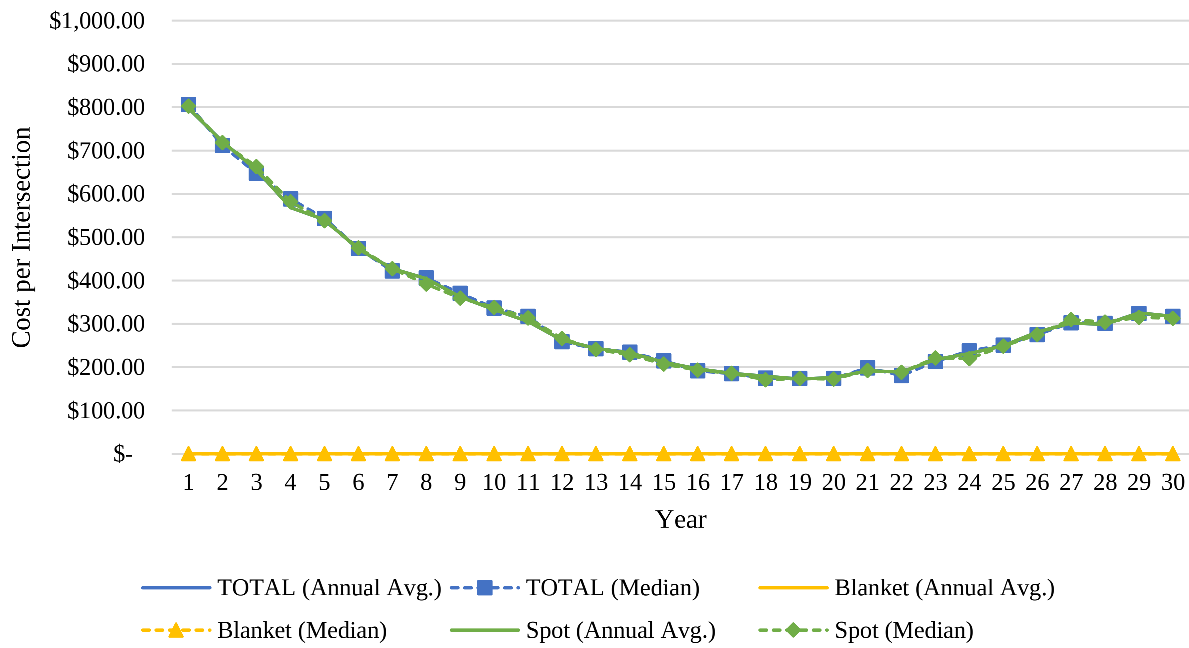


Figure 8.4 Replacement Costs to NCDOT (per Intersections) Over Time Spot Replacement Only

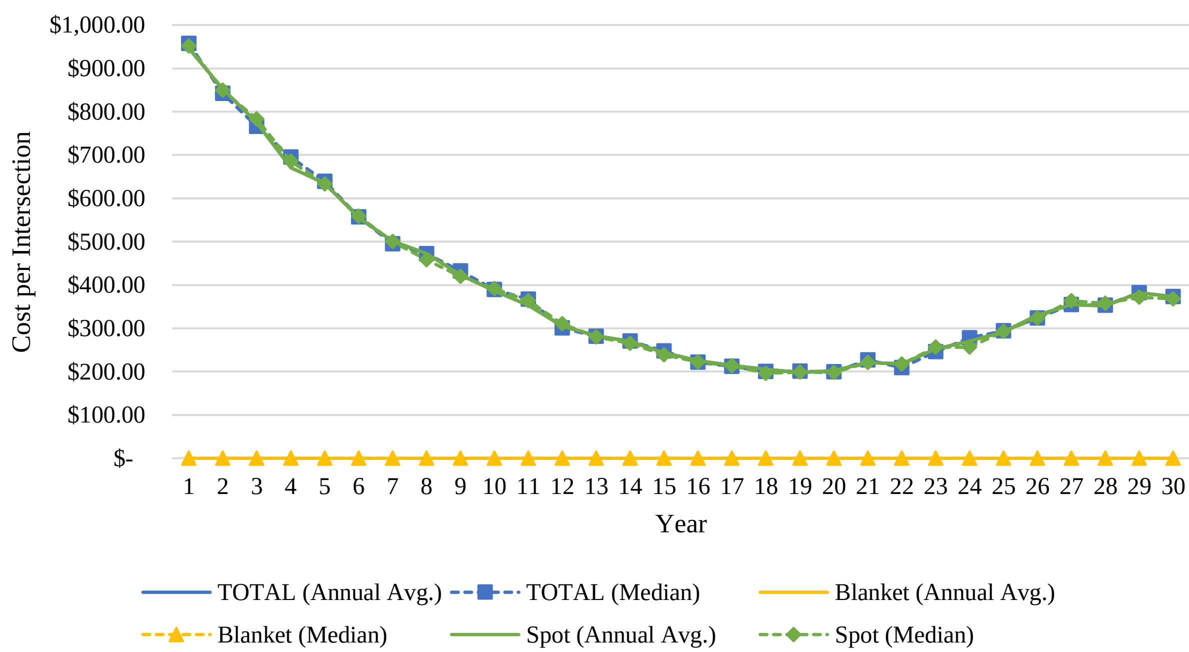


Figure 8.5 Replacement Costs to Contractor (per Intersection) Over Time Spot Replacement Only

Note that there is no point in time at which costs level off or become uniform. This means that the cost per year will not be consistent, and may be difficult to plan for with a budget based on previous expenditures.

Table 8.5 contains an excerpt of the annual cost data, per intersection, recorded for each year of the simulation. The full tables are rather lengthy and can be found in Appendix F: Annual Cost Data for Alternative Scenarios, Tables F3 and F4.

Table 8.5 Excerpt of Annual Cost Data (per Intersection)
Spot Replacement Only

Year	NCDOT Total Cost (Average)	NCDOT Total Cost (Median)	NCDOT Total Cost (Std. Dev.)	…	Contractor Total Cost (Average)	Contractor Total Cost (Median)	Contractor Total Cost (Std. Dev.)
1	$797.22	$806.56	$37.69		$946.09	$957.39	$44.99
2	$720.30	$711.96	$32.07		$852.20	$842.02	$37.13
3	$655.56	$647.38	$40.47		$774.73	$766.21	$46.48
4	$568.17	$588.58	$38.03		$670.98	$695.34	$44.25
5	$540.03	$543.53	$17.47		$634.88	$638.95	$20.26
6	$472.39	$473.51	$21.61		$555.20	$556.83	$23.91
7	$427.58	$422.06	$23.29		$501.02	$495.32	$25.95
8	$404.73	$405.96	$26.50		$472.78	$472.40	$29.26
9	$362.41	$370.46	$15.94		$423.51	$432.21	$18.33
…	…	…	…		…	…	…
30	$317.59	$317.17	$19.93		$373.05	$373.08	$22.93

8.2.2 Replacement Quantities

Figure 8.6 shows how many Signal Heads and Modules are at each intersection to start and how many are replaced each year. The pattern of Signal Head and Module replacement follows that of the curve shown in Figures 8.4 and 8.5 – there is a slow and steady decrease in quantity per year until year 18, then a slight increase begins again.

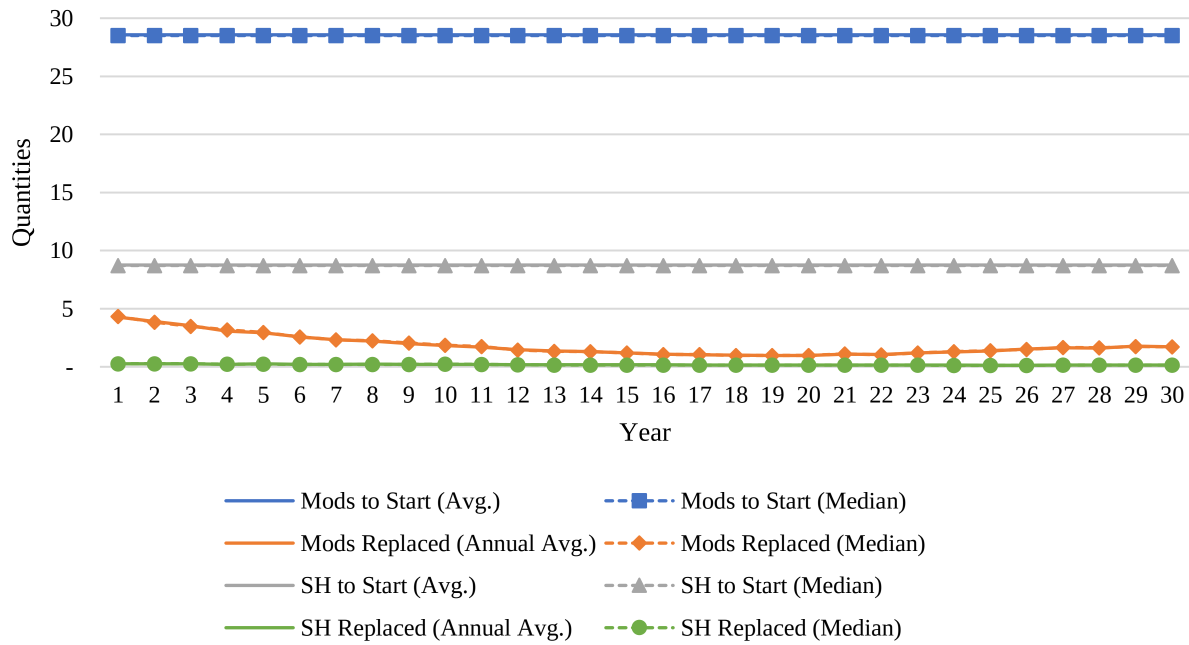


Figure 8.6 Quantities of LED Modules and Signal Heads Replaced (per Intersection) Over Time Spot Replacement Only

Table 8.6 contains an excerpt of the annual replacement quantity data, per intersection, recorded for each year of the simulation. The full tables are rather lengthy and can be found in Appendix G: Annual Replacement Quantity Data for Alternative Scenarios, Table G2.

Table 8.6 Excerpt of Annual Replacement Quantity Data (per Intersection) Spot Replacement Only

Year	Modules in Place (Average)	Modules in Place (Median)	Modules in Place (Std. Dev.)	…	Signal Heads Replaced (Average)	Signal Heads Replaced (Median)	Signal Heads Replaced (Std. Dev.)
1	28.57	28.51	0.54		0.25	0.26	0.03
2	28.57	28.51	0.54		0.26	0.27	0.04
3	28.57	28.51	0.54		0.25	0.26	0.04
4	28.57	28.51	0.54		0.22	0.24	0.03
5	28.57	28.51	0.54		0.25	0.24	0.03
6	28.57	28.51	0.54		0.22	0.22	0.03
…	…	…	…		…	…	…
30	28.57	28.51	0.54		0.15	0.15	0.02

8.2.3 Summary

This section provides summary information regarding the overall costs and labor hours estimated for NCDOT over the next 30 years based on only conducting spot replacement. Table 8.7 provides a summary of all output data provided by the simulation for Alternative 2 (Spot Replacement Only). For example, NCDOT's Total Replacement Cost (for in-house work) was found to be, on average, $2.06M. This is the total cost of replacement estimated for 205 intersections over 30 years. The NCDOT Total Replacement Cost per intersection, over a 30-year timespan, was found to be approximately $10,000, on average.

Table 8.7 15-year, Independent Replacement Simulation Lifetime Summary Output Data (for 205 Intersections)

Metric	Scope	Average	Median	Standard Deviation
Modules in Place	Total	5,857.63	5,845.00	103.43
	Per Intersection	28.57	28.51	0.50
Signal Heads at Start	Total	1,795.63	1,787.50	29.75
	Per Intersection	8.76	8.72	0.14
Modules Replaced	Total	11,295.12	11,243.00	237.45
	Per Intersection	55.09	54.84	1.17
Signal Heads Replaced	Total	1,107.62	1,116.00	26.75
	Per Intersection	5.42	5.46	0.13
NCDOT Total Replacement Costs	Total	$2,060,244.34	$2,050,094.39	$43,385.34
	Per Intersection	$10,049.97	$10,000.47	$211.63
NCDOT Blanket Replacement Costs	Total	$-	$-	$-
	Per Intersection	$-	$-	$-
NCDOT Signal Head Spot Replacement Costs	Total	$590,586.77	$596,190.16	$14,341.88
	Per Intersection	$2,880.92	$2,908.26	$69.96
NCDOT Module Spot Replacement Costs	Total	$1,469,657.57	$1,458,596.72	$31,801.36
	Per Intersection	$7,169.05	$7,115.09	$155.13
NCDOT Labor Hours Required	Total	-	-	-
	Per Intersection	-	-	-
Contractor Total Replacement Costs	Total	$2,411,479.34	$2,398,374.39	$50,746.31
	Per Intersection	$11,763.32	$11,699.38	$247.54
Contractor Blanket Replacement Costs	Total	$-	$-	$-
	Per Intersection	$-	$-	$-
Contractor Signal Head Spot Replacement Costs	Total	$634,891.77	$640,830.16	$15,371.05
	Per Intersection	$3,097.02	$3,126.00	$74.98
Contractor Module Spot Replacement Costs	Total	$1,776,587.57	$1,763,216.72	$38,442.90
	Per Intersection	$8,666.28	$8,601.06	$187.52
NCDOT Supervisory Labor Hours Required	Total	-	-	-
	Per Intersection	-	-	-

To understand the scale of funding required for regular LED Module and Signal Heads replacement at the state level, it is necessary to scale up the costs. Multiplying each of the cost and labor hour per-intersection values found in Table 8.7 by the 8,200 intersections that NCDOT is responsible for, results in the values provided in Table 8.8. For example, NCDOT's Total Replacement Cost (for in-house work), for the whole state, was estimated to be approximately $82.4M. Contractor Total Cost estimates were approximately $96.5M.

Table 8.8 15-year Independent Replacement State-wide Output Summary

Metric	Scope	Average	Median	Std. Dev.
NCDOT Total Replacement Costs	State Wide	$82,409,754.00	$82,003,854.00	$1,735,349.60
NCDOT Blanket Replacement Costs	State Wide	$-	$-	$-
NCDOT Signal Head Spot Replacement Costs	State Wide	$23,623,544.00	$23,847,732.00	$573,680.20
NCDOT Module Spot Replacement Costs	State Wide	$58,786,210.00	$58,343,738.00	$1,272,074.20
NCDOT Labor Hours Required	State Wide	-	-	-
Contractor Total Replacement Costs	State Wide	$96,459,224.00	$95,934,916.00	$2,029,828.00
Contractor Blanket Replacement Costs	State Wide	$-	$-	$-
Contractor Signal Head Spot Replacement Costs	State Wide	$25,395,564.00	$25,633,200.00	$614,852.40
Contractor Module Spot Replacement Costs	State Wide	$71,063,496.00	$70,528,692.00	$1,537,647.60
NCDOT Supervisory Labor Hours Required	State Wide	-	-	-

8.3 Alternative 3: 15-year Replacement Period, Independent Replacement

Alternative 3 utilizes a 15-year replacement period, meaning that one fifteenth of the LED Modules across the state will be replaced each year. Independent replacement indicates that during blanket replacement, only the Module are replaced. Signal Heads are not part of blanket replacement and are only replaced if required due to spot failure.

The following input variables were used when running this scenario

- Iterations: 8
- Intersections: 205
- Signal Head Life Expectancy: 30 years
- Timeline: 30 years
- Replacement Cycle 15 years
- Replacement Period: **15 years**
- Joint Replacement: **False**
- Module Warranty: 15 years
- Inflation: 0.00%

8.3.1 Annual Costs

Figures 8.7 and 8.8 provide summaries of the replacement costs per intersection over the 30-year span of the simulation. Both average and median values have been plotted for the Total cost, ■, (the sum of blanket and spot) as well as for blanket replacement (▲) and spot replacement (◆). Again, these values overlap giving the appearance of a single line. Figure 8.7 shows the cost for NCDOT to complete all work in-house. Figure 8.8 shows the cost for a contractor to be hired to complete all module replacement activities. Note that in each case, NCDOT Technician labor-hours are required. Based on information provided by Divisions, an NCDOT Technician must inspect and approve all work done by Contractors, adding an average of 0.137 NCDOT Technician Labor Hours per intersection, per year (or 4.10 labor hours per intersection over the 30-year span).

Both figures indicate that spot replacement costs remain somewhat high throughout the majority of the first 15 years. This is due to the slow, steady replacement of currently-in-place LED Modules and Signal Heads.

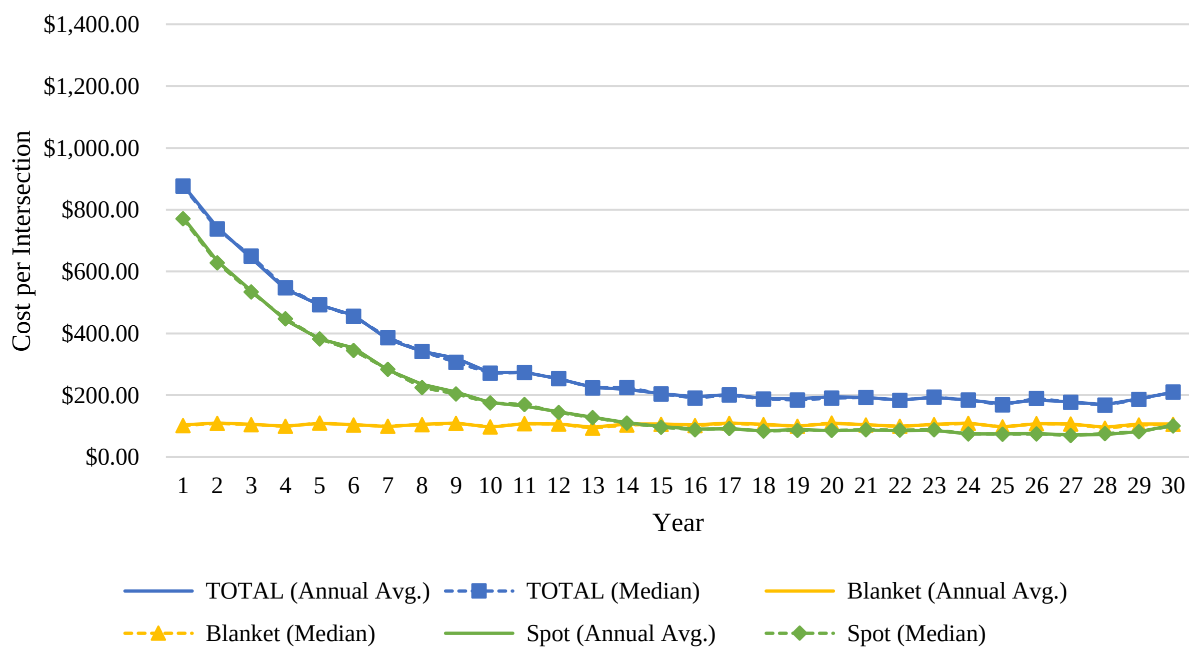


Figure 8.7 Replacement Costs to NCDOT (per Intersection) Over Time 15-year Period, Independent Replacement

Spot replacement costs are seen to drop dramatically and become steady once all existing Modules and Signal Heads have been replaced with new 15-year warrantied modules.

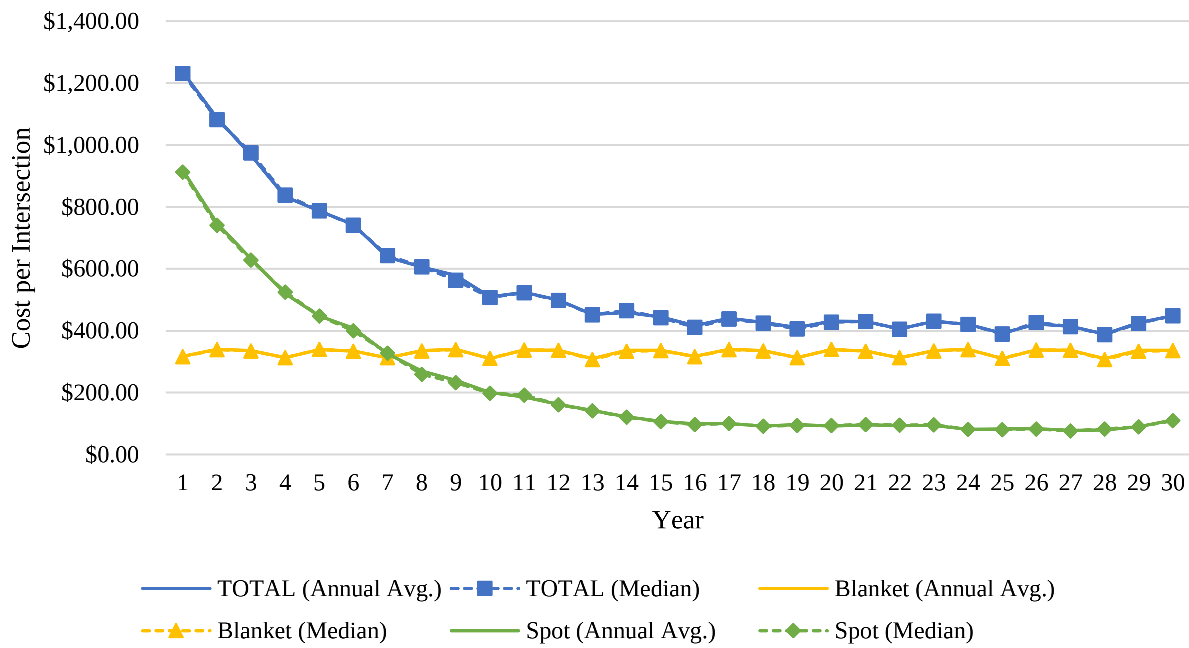


**Figure 8.8 Replacement Costs for Contractor (per Intersection) Over Time
15-year Period, Independent Replacement**

Table 8.9 contains an excerpt of the annual cost data, per intersection, recorded for each year of the simulation. The full tables are rather lengthy and can be found in Appendix F: Annual Cost Data for Alternative Scenarios, Tables F5 and F6.

**Table 8.9 Excerpt of Annual Cost Data (per Intersection)
15-year Period, Independent Replacement**

Year	NCDOT Total Cost (Average)	NCDOT Total Cost (Median)	NCDOT Total Cost (Std. Dev.)	…	Contractor Total Cost (Average)	Contractor Total Cost (Median)	Contractor Total Cost (Std. Dev.)
1	$879.82	$876.31	$30.04		$1,236.12	$1,231.68	$35.09
2	$743.53	$738.52	$43.33		$1,087.08	$1,082.19	$50.18
3	$644.02	$649.79	$35.93		$967.79	$974.54	$41.74
4	$543.18	$547.54	$36.06		$832.92	$838.72	$41.15
5	$492.29	$493.22	$24.51		$786.41	$788.03	$28.79
6	$458.64	$455.77	$32.26		$743.12	$741.20	$36.18
7	$381.17	$386.88	$31.39		$637.88	$643.33	$35.92
8	$341.71	$342.02	$18.07		$606.17	$606.22	$20.45
9	$320.20	$306.88	$29.14		$579.02	$563.24	$32.70
…	…	…	…		…	…	…
30	$209.89	$210.47	$14.19		$448.25	$448.54	$14.86

8.3.2 <u>Replacement Quantities</u>

Figure 8.9 shows how many Signal Heads and Modules are at each intersection to start and how many are replaced each year. As expected, the quantity of Modules replaced each year decreases over the first 15 years of the simulation, as the existing modules are slowly replaced. There is a miniscule decrease in the quantity of Signal Heads replaced each year as well. That is due to the per intersection view of the values, few Signal Heads are replaced in the total system every year, making the per intersection quantity only a fraction.

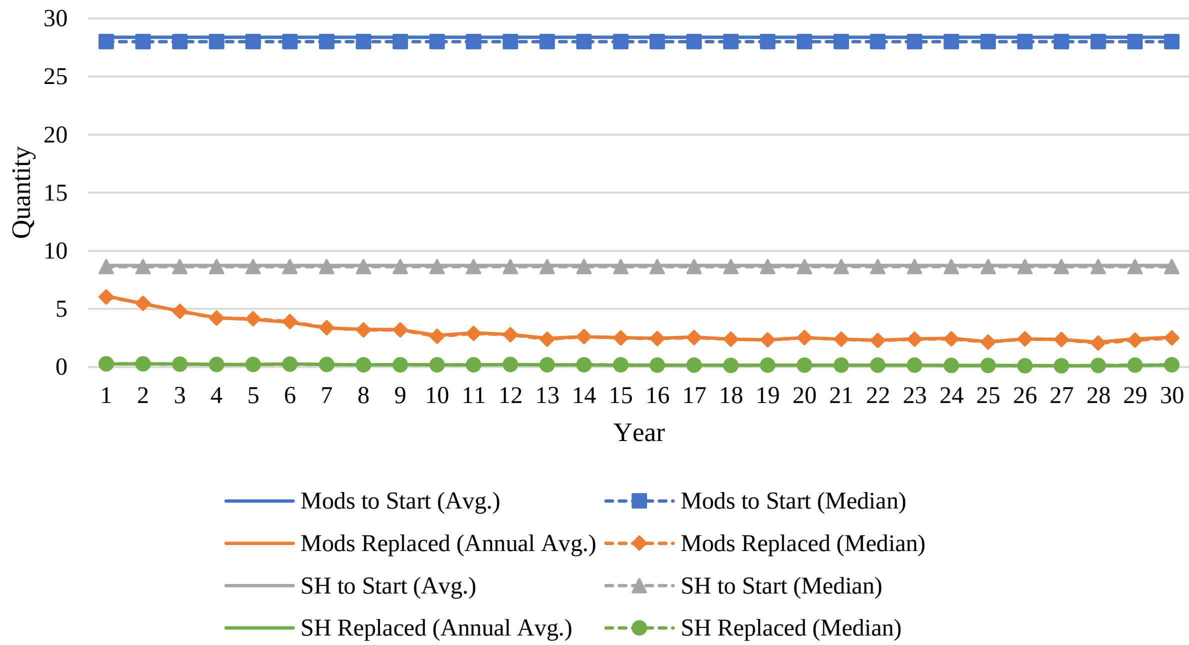


Figure 8.9 Quantities of LED Modules and Signal Heads Replaced (per Intersection) Over Time 15-year Period, Independent Replacement

Table 8.10 contains an excerpt of the annual replacement quantity data, per intersection, recorded for each year of the simulation. The full tables are rather lengthy and can be found in Appendix G: Annual Replacement Quantity Data for Alternative Scenarios, Table G3.

Table 8.10 Excerpt of Annual Replacement Quantity Data (per Intersection) 15-year Period, Independent Replacement

Year	Modules in Place (Average)	Modules in Place (Median)	Modules in Place (Std. Dev.)	…	Signal Heads Replaced (Average)	Signal Heads Replaced (Median)	Signal Heads Replaced (Std. Dev.)
1	28.38	28	0.93		0.27	0.27	0.03
2	28.38	28	0.93		0.26	0.26	0.03
3	28.38	28	0.93		0.26	0.24	0.04
4	28.38	28	0.93		0.22	0.22	0.03
5	28.38	28	0.93		0.22	0.22	0.02
6	28.38	28	0.93		0.27	0.24	0.05
…	…	…	…		…	…	…
30	28.38	28	0.93		0.18	0.18	0.02

8.3.3 Summary

This section provides summary information regarding the overall costs and labor hours estimated for NCDOT over the next 30 years based on a 15-year replacement period and independent replacement. Table 8.11 provides a summary of all output data provided by the simulation for Alternative 3 (15-year Replacement Period, Independent Replacement). For example, NCDOT's Total Replacement Cost (for in-house work) was found to be, on average, $1.86M. This is the total cost of replacement estimated for 205 intersections over 30 years. The NCDOT Total Replacement Cost per intersection, over a 30-year timespan, was found to be approximately $9,100, on average.

Table 8.11 15-year, Independent Replacement Simulation Lifetime Summary Output Data (for 205 Intersections)

Metric	Scope	Average	Median	Standard Deviation
Modules in Place	Total	5,818.88	5,738.50	179.05
	Per Intersection	28.38	28.00	0.87
Signal Heads at Start	Total	1,791.63	1,773.00	49.98
	Per Intersection	8.74	8.65	0.24
Modules Replaced	Total	18,541.00	18,219.00	670.40
	Per Intersection	90.44	88.88	3.27
Signal Heads Replaced	Total	1,122.12	1,103.50	44.20
	Per Intersection	5.49	5.39	0.22
NCDOT Total Replacement Costs	Total	1,863,137.00	1,836,496.97	63,659.54
	Per Intersection	9,088.47	8,958.50	310.54
NCDOT Blanket Replacement Costs	Total	645,334.66	640,009.01	12,682.79
	Per Intersection	3,148.00	3,122.03	61.87
NCDOT Signal Head Spot Replacement Costs	Total	594,276.43	584,107.93	25,809.90
	Per Intersection	2,898.90	2,849.30	125.90
NCDOT Module Spot Replacement Costs	Total	623,525.92	618,450.37	27,185.50
	Per Intersection	3,041.59	3,016.84	132.61
NCDOT Labor Hours Required	Total	2,566.77	2,569.29	20.49
	Per Intersection	12.53	12.54	0.11
Contractor Total Replacement Costs	Total	3,416,826.00	3,387,880.97	70,843.07
	Per Intersection	16,667.45	16,526.26	345.59
Contractor Blanket Replacement Costs	Total	2,023,918.66	2,018,593.01	12,682.79
	Per Intersection	9,872.76	9,846.77	61.86
Contractor Signal Head Spot Replacement Costs	Total	639,161.43	628,247.93	27,558.56
	Per Intersection	3,117.86	3,064.62	134.44
Contractor Module Spot Replacement Costs	Total	753,745.92	747,610.37	32,863.05
	Per Intersection	3,676.84	3,646.90	160.32
NCDOT Supervisory Labor Hours Required	Total	820.00	820.00	-
	Per Intersection	4.10	4.10	-

To understand the scale of funding required for regular LED Module and Signal Heads replacement at the state level, it is necessary to scale up the costs. Multiplying each of the cost and labor hour per-intersection values found in Table 8.11 by the 8,200 intersections that NCDOT is responsible for, results in the values provided in Table 8.12. For example, NCDOT's Total Replacement Cost (for in-house work), for the whole state, was estimated to be approximately $74.6M. Contractor Total Cost estimates were approximately $136.7M, a little less than twice the cost of NCDOT. These costs can be mixed and matched. For instance, if NCDOT were to manage all spot replacement, but contract out all of the blanket replacement work, the total estimated cost would be approximately $129.7M over the next 30 years.

Table 8.12 15-year, Independent Replacement State-wide Output Summary

Metric	Scope	Average	Median	Std. Dev.
NCDOT Total Replacement Costs	State Wide	$74,525,454.00	$73,459,700.00	$2,546,428.00
NCDOT Blanket Replacement Costs	State Wide	$25,813,600.00	$25,600,646.00	$507,334.00
NCDOT Signal Head Spot Replacement Costs	State Wide	$23,770,980.00	$23,364,260.00	$1,032,380.00
NCDOT Module Spot Replacement Costs	State Wide	$24,941,038.00	$24,738,088.00	$1,087,402.00
NCDOT Labor Hours Required	State Wide	102,746.00	102,828.00	902.00
Contractor Total Replacement Costs	State Wide	$136,673,090.00	$135,515,332.00	$2,833,838.00
Contractor Blanket Replacement Costs	State Wide	$80,956,632.00	$80,743,514.00	$507,252.00
Contractor Signal Head Spot Replacement Costs	State Wide	$25,566,452.00	$25,129,884.00	$1,102,408.00
Contractor Module Spot Replacement Costs	State Wide	$30,150,088.00	$29,904,580.00	$1,314,624.00
NCDOT Supervisory Labor Hours Required	State Wide	33,620.00	33,620.00	0

8.4 Alternative 4: 15-year Replacement Period, Joint Replacement

Alternative 4 utilizes a 15-year replacement period, meaning that one fifteenth of the LED Modules across the state will be replaced each year. Joint replacement indicates that during blanket replacement, both the Signal Heads and the Modules are replaced. Throughout the simulation spot replacement is occurring for both Modules and Signal Heads.

The following input variables were used when running this scenario

- Iterations: 8
- Intersections: 205
- Signal Head Life Expectancy: 30 years
- Timeline: 30 years
- Replacement Cycle 15 years
- Replacement Period: **15 years**
- Joint Replacement: **True**
- Module Warranty: 15 years
- Inflation: 0.00%

8.4.1 Annual Costs

Figures 8.10 and 8.11 provide summaries of the replacement costs, per intersection, over the 30-year span of the simulation. Note that in each case, NCDOT Technician labor-hours are required. Based on information provided by Divisions, an NCDOT Technician must inspect and approve all work done by Contractors, adding an average of 0.137 NCDOT Technician Labor Hours per intersection, per year (or 4.10 labor hours per intersection over the 30-year span).

Both figures indicate that spot replacement costs remain somewhat high throughout the majority of the first 15 years. This is due to the slow, steady replacement of currently-in-place LED Modules and Signal Heads. Spot replacement costs are seen to drop dramatically and become steady once all existing Modules and Signal Heads have been replaced with new.

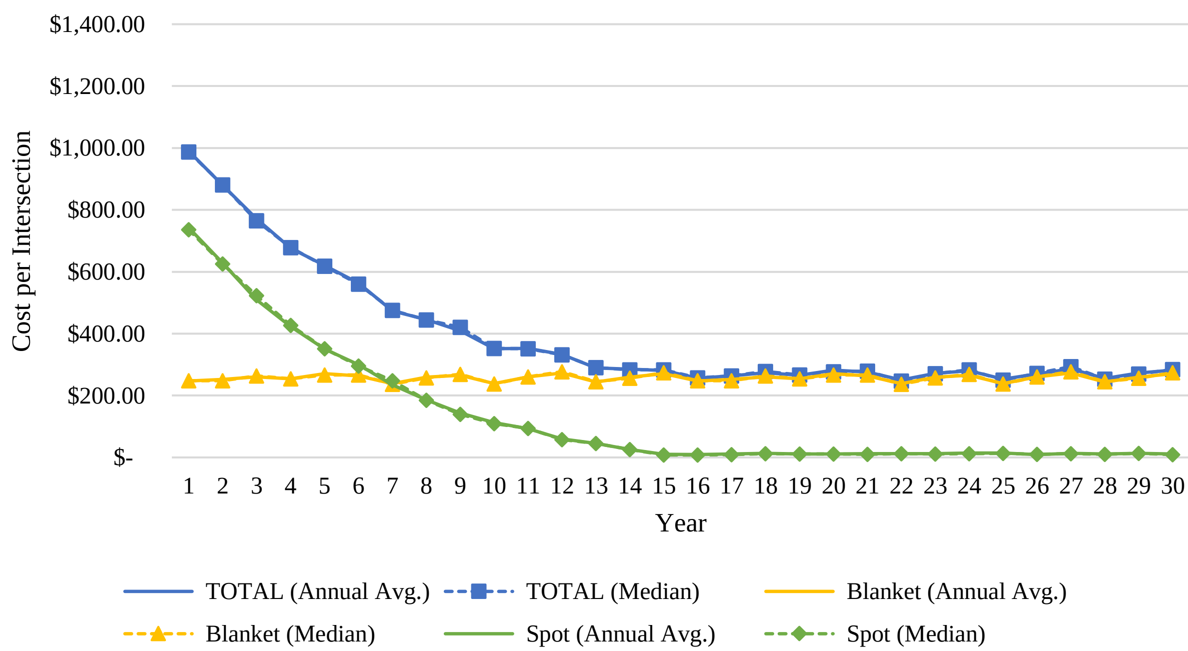


Figure 8.10 Replacement Costs to NCDOT (per Intersection) Over Time 15-year Period, Joint Replacement

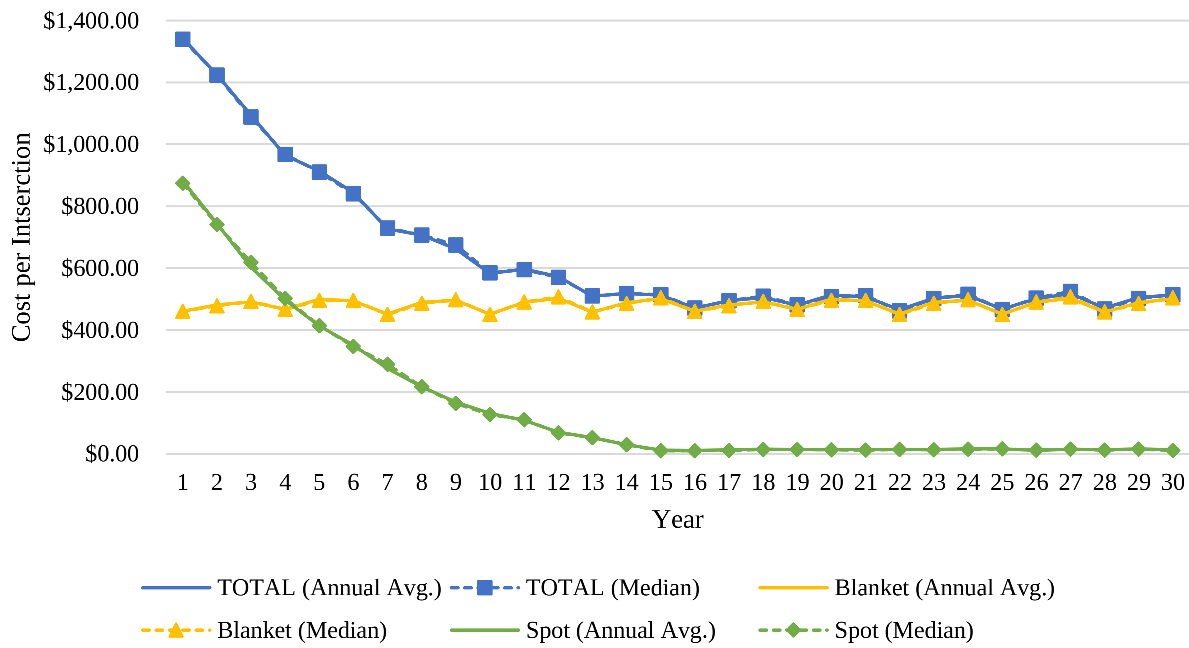


Figure 8.11 Replacement Costs for Contractor (per Intersection) Over Time 15-year Period, Independent Replacement

Table 8.13 contains an excerpt of the annual cost data, per intersection, recorded for each year of the simulation. The full tables are rather lengthy and can be found in Appendix F: Annual Cost Data for Alternative Scenarios, Tables F7 and F8.

Table 8.13 Excerpt of Annual Cost Data (per Intersection) 15-year Period, Joint Replacement

Year	NCDOT Total Cost (Average)	NCDOT Total Cost (Median)	NCDOT Total Cost (Std. Dev.)	…	Contractor Total Cost (Average)	Contractor Total Cost (Median)	Contractor Total Cost (Std. Dev.)
1	$989.64	$987.76	$29.30		$1,342.68	$1,340.01	$33.21
2	$880.34	$880.86	$38.89		$1,225.02	$1,224.04	$42.46
3	$770.89	$764.82	$37.15		$1,094.32	$1,088.70	$41.87
4	$676.50	$677.83	$40.72		$964.40	$967.64	$43.19
5	$620.81	$617.88	$34.32		$913.19	$910.82	$38.62
6	$563.36	$560.29	$39.40		$844.69	$840.54	$41.95
7	$473.59	$475.76	$14.20		$726.86	$729.18	$14.12
8	$445.31	$444.76	$20.29		$706.40	$706.58	$21.58
9	$409.21	$421.14	$31.07		$662.62	$674.67	$33.03
…	…	…	…		…	…	…
30	$281.98	$283.70	$19.70		$513.20	$514.79	$19.81

8.4.2 Replacement Quantities

Figure 8.12 shows how many Signal Heads and Modules are at each intersection to start and how many are replaced each year. As expected, the quantity of Modules replaced each year decreases over the first 15 years of the simulation, as the existing modules are slowly replaced. There is a miniscule decrease in the quantity of Signal Heads replaced each year as well. That is due to the per intersection view of the values, few Signal Heads are replaced in the total system (205 intersections) every year, making the per intersection quantity only a fraction.

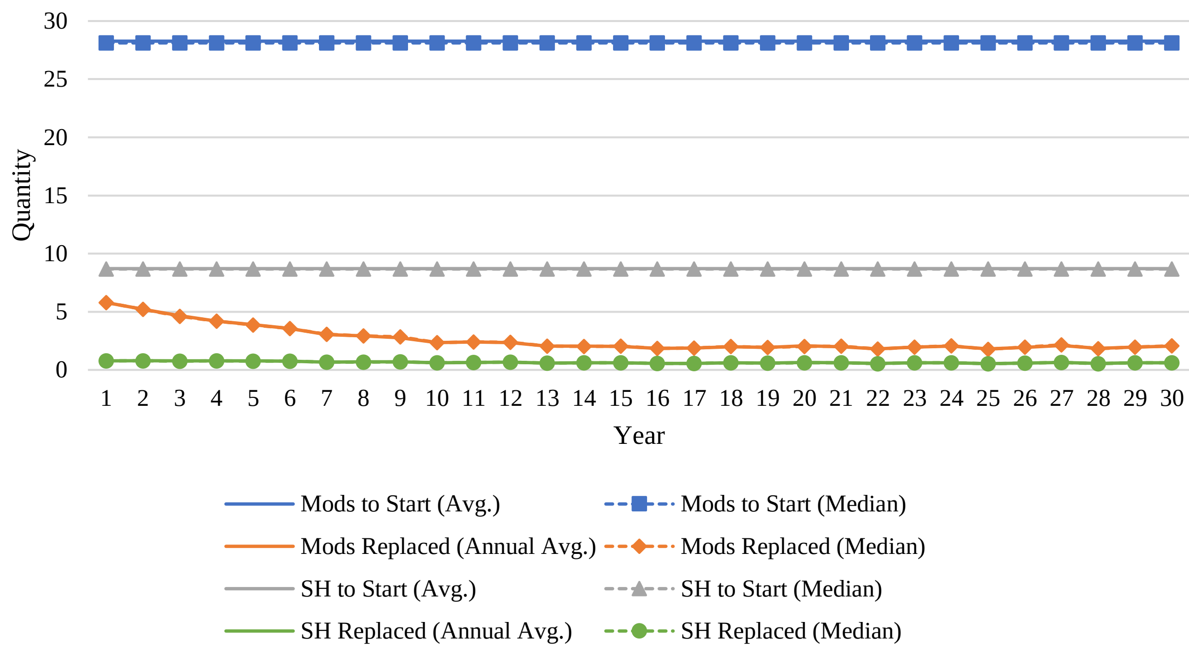


Figure 8.12 Quantities of LED Modules and Signal Heads Replaced (per Intersection) Over Time 15-year Period, Joint Replacement

Table 8.14 contains an excerpt of the annual replacement quantity data, per intersection, recorded for each year of the simulation. The full tables are rather lengthy and can be found in Appendix G: Annual Replacement Quantity Data for Alternative Scenarios, Table G4.

Table 8.14 Excerpt of Annual Replacement Quantity Data (per Intersection) 15-year Period, Joint Replacement

Year	Modules in Place (Average)	Modules in Place (Median)	Modules in Place (Std. Dev.)	…	Signal Heads Replaced (Average)	Signal Heads Replaced (Median)	Signal Heads Replaced (Std. Dev.)
1	28.27	28.12	0.63		0.77	0.78	0.04
2	28.27	28.12	0.63		0.79	0.79	0.08
3	28.27	28.12	0.63		0.77	0.76	0.04
4	28.27	28.12	0.63		0.77	0.79	0.08
5	28.27	28.12	0.63		0.77	0.76	0.03
6	28.27	28.12	0.63		0.75	0.75	0.07
…	…	…	…		…	…	…
30	28.27	28.12	0.63		0.62	0.62	0.05

8.4.3 <u>Summary</u>

This section provides summary information regarding the overall costs and labor hours estimated for NCDOT over the next 30 years based on a 15-year replacement period and joint replacement. Table 8.15 provides a summary of all output data provided by the simulation for Alternative 4 (15-year Replacement Period, Joint Replacement). For example, NCDOT's Total Replacement Cost (for in-house work) was found to be, on average $2.41M. This is the total cost of replacement estimated for 205 intersections over 30 years. The NCDOT Total Replacement Cost per intersection, over a 30-year timespan, was found to be approximately $11,800, on average.

Table 8.15 15-year, Joint Replacement Simulation Lifetime Summary Output Data (for 205 Intersections)

Metric	Scope	Average	Median	Standard Deviation
Modules in Place	Total	5,794.25	5,765.00	120.06
	Per Intersection	28.27	28.13	0.59
Signal Heads at Start	Total	1,784.75	1,779.00	31.54
	Per Intersection	8.71	8.68	0.15
Modules Replaced	Total	16,095.38	15,982.50	377.60
	Per Intersection	78.51	77.94	1.84
Signal Heads Replaced	Total	3,941.00	3,913.00	77.42
	Per Intersection	19.23	19.11	0.38
NCDOT Total Replacement Costs	Total	$2,410,943.05	$2,398,473.44	$56,410.98
	Per Intersection	$11,760.70	$11,699.90	$275.16
NCDOT Blanket Replacement Costs	Total	$1,582,278.00	$1,575,792.46	$33,141.33
	Per Intersection	$7,718.42	$7,686.81	$161.66
NCDOT Signal Head Spot Replacement Costs	Total	$196,592.10	$194,956.64	$11,605.72
	Per Intersection	$959.02	$951.04	$56.60
NCDOT Module Spot Replacement Costs	Total	$632,072.94	$630,708.29	$17,727.93
	Per Intersection	$3,083.28	$3,076.62	$86.49
NCDOT Labor Hours Required	Total	2,577.77	2,597.46	40.85
	Per Intersection	12.58	12.68	0.21
Contractor Total Replacement Costs	Total	$3,936,392.05	$3,923,597.44	$60,424.79
	Per Intersection	$19,201.91	$19,139.50	$294.75
Contractor Blanket Replacement Costs	Total	$2,960,862.01	$2,954,376.46	$33,141.33
	Per Intersection	$14,443.22	$14,411.56	$161.66
Contractor Signal Head Spot Replacement Costs	Total	$211,452.10	$209,776.64	$12,512.51
	Per Intersection	$1,031.46	$1,023.29	$61.03
Contractor Module Spot Replacement Costs	Total	$764,077.94	$762,428.29	$21,430.31
	Per Intersection	$3,727.22	$3,719.16	$104.54
NCDOT Supervisory Labor Hours Required	Total	820.00	820.00	-
	Per Intersection	4.10	4.10	-

To understand the scale of funding required for regular LED Module and Signal Heads replacement at the state level, it is necessary to scale up the costs. Multiplying each of the cost and labor hour per-intersection values found in Table 8.15 by the 8,200 intersections that NCDOT is responsible for, results in the values provided in Table 8.16. For example, NCDOT's Total Replacement Cost (for in-house work), for the whole state, was estimated to be approximately $96.4M. Contractor Total Cost estimates were approximately $157.5M.

These costs can be mixed and matched. For instance, if NCDOT were to manage all spot replacement, but contract out all blanket replacement work, the total estimated cost would be approximately $151.6M over the next 30 years. Note that the cost of additional NCDOT labor required when Contract work is completed has not been incorporated into these estimates. Instead, an estimate of the time required has been provided.

Table 8.16 15-year, Joint Replacement State-wide Output Summary

Metric	Scope	Average	Median	Std. Dev.
NCDOT Total Replacement Costs	State Wide	$96,437,740.00	$95,939,180.00	$2,256,344.80
NCDOT Blanket Replacement Costs	State Wide	$63,291,044.00	$63,031,842.00	$1,325,571.00
NCDOT Signal Head Spot Replacement Costs	State Wide	$7,863,964.00	$7,798,528.00	$464,120.00
NCDOT Module Spot Replacement Costs	State Wide	$25,282,896.00	$25,228,284.00	$709,209.80
NCDOT Labor Hours Required	State Wide	103,156.00	103,976.00	1,689.20
Contractor Total Replacement Costs	State Wide	$157,455,662.00	$156,943,900.00	$2,416,966.40
Contractor Blanket Replacement Costs	State Wide	$118,434,404.00	$118,174,792.00	$1,325,612.00
Contractor Signal Head Spot Replacement Costs	State Wide	$8,457,972.00	$8,390,978.00	$500,429.60
Contractor Module Spot Replacement Costs	State Wide	$30,563,204.00	$30,497,112.00	$857,187.00
NCDOT Supervisory Labor Hours Required	State Wide	33,620.00	33,620.00	-

8.5 Alternative 5: 5-year Replacement Period, Independent Replacement

Alternative 5 utilizes a 5-year replacement period, meaning that one fifth of the LED Modules across the state will be replaced each year for five years, then the following ten will include no blanket replacement. Independent replacement indicates that during blanket replacement, only the Modules are replaced. Throughout the simulation spot replacement is occurring for both Modules and Signal Heads.

The following input variables were used when running this scenario

- Iterations: 8
- Intersections: 205
- Signal Head Life Expectancy: 30 years
- Timeline: 30 years
- Replacement Cycle 15 years
- Replacement Period: **5 years**
- Joint Replacement: **False**
- Module Warranty: 15 years
- Inflation: 0.00%

8.5.1 Annual Costs

Figures 8.13 and 8.14 show summaries of the replacement costs, per intersection, over the 30-year span of the simulation. Note that in each case, NCDOT Technician labor-hours are required. Based on information provided by Divisions, an NCDOT Technician must inspect and approve all work done by Contractors, adding an average of 0.133 NCDOT Technician Labor Hours per intersection, per year (or 4.0 labor hours per intersection over the 30-year span).

Both figures indicate that spot replacement costs remain somewhat high throughout first replacement period (the first five years). After the initial replacement period, all existing LED Modules have been replaced, drastically lowering the amount of spot replacement required. Blanket replacement costs are applicable for only five years out of a fifteen-year replacement cycle, which is shown by the increase in blanket replacement costs from year one to year five, then again from year sixteen to year twenty. The remainder of the replacement cycle, there are no blanket replacement costs.

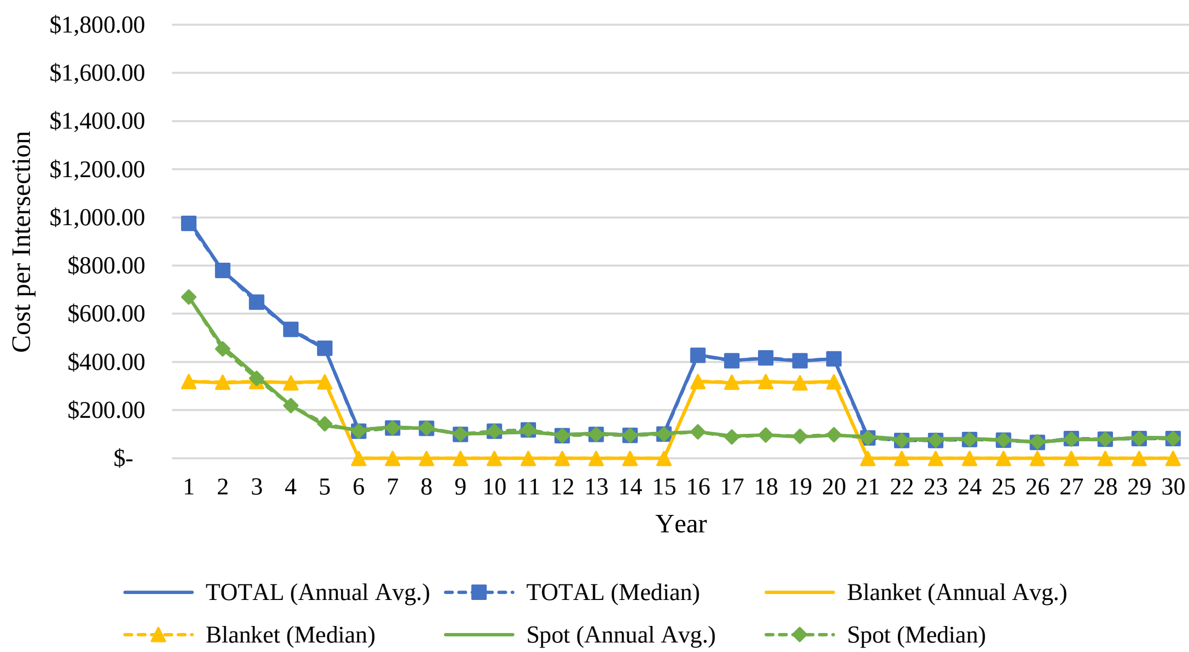


Figure 8.13 Replacement Costs to NCDOT (per Intersection) Over Time 5-year Period, Independent Replacement

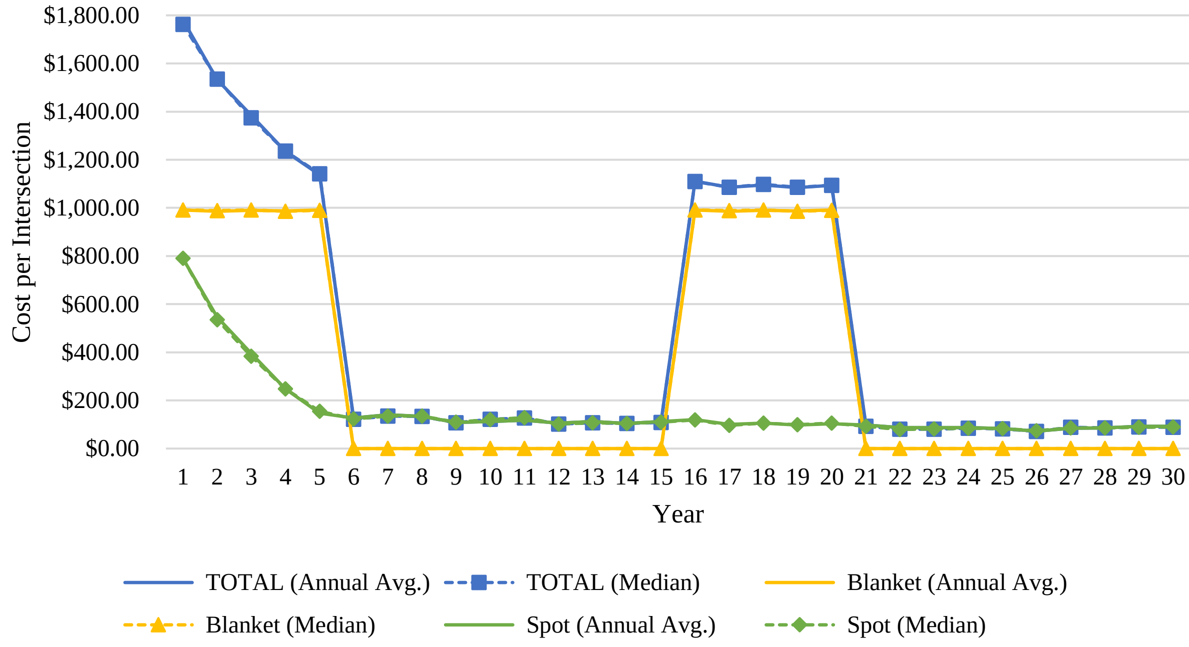


Figure 8.14 Replacement Costs for Contractor (per Intersection) Over Time 5-year Period, Independent Replacement

Table 8.17 contains an excerpt of the annual cost data, per intersection, recorded for each year of the simulation. The full tables are rather lengthy and can be found in Appendix F: Annual Cost Data for Alternative Scenarios, Tables F9 and F10.

Table 8.17 Excerpt of Annual Cost Data (per Intersection) 5-year Period, Independent Replacement

Year	NCDOT Total Cost (Average)	NCDOT Total Cost (Median)	NCDOT Total Cost (Std. Dev.)	…	Contractor Total Cost (Average)	Contractor Total Cost (Median)	Contractor Total Cost (Std. Dev.)
1	$986.81	$975.88	$46.74		$1,780.04	$1,762.90	$54.87
2	$777.47	$780.08	$26.68		$1,532.02	$1,535.16	$29.78
3	$658.30	$648.66	$23.87		$1,384.85	$1,373.92	$27.44
4	$533.06	$534.91	$17.32		$1,234.66	$1,235.76	$19.04
5	$454.02	$457.01	$27.92		$1,137.89	$1,141.01	$29.27
6	$117.36	$112.42	$15.07		$127.17	$121.98	$16.22
7	$130.35	$125.28	$15.71		$140.62	$134.83	$16.60
8	$123.67	$124.42	$12.22		$133.64	$133.69	$12.78
9	$100.44	$99.40	$10.13		$108.86	$107.60	$10.58
…	…	…	…		…	…	…
30	$84.40	$81.69	$12.68		$91.79	$89.02	$13.70

8.5.2 Replacement Quantities

Figure 8.15 shows how many Signal Heads and Modules are at each intersection to start and how many are replaced each year. As shown in Figures 8.13 and 8.14, the quantity of Modules replaced each year decreases over the first five years of the simulation, as the existing modules are slowly replaced. The quantity of modules replaced then reaches a steady state for the remaining 10 years of the replacement cycle. There is a miniscule decrease in the quantity of Signal Heads replaced each year as well.

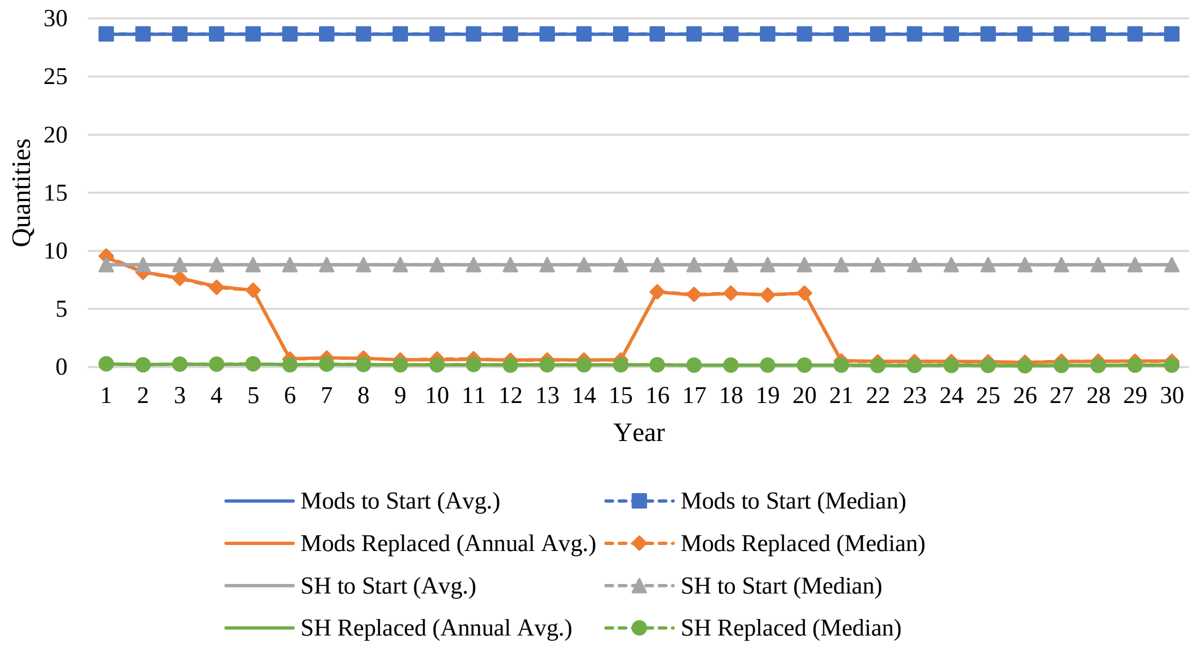


Figure 8.15 Quantities of LED Modules and Signal Heads Replaced (per Intersection) Over Time 5-year Period, Independent Replacement

Table 8.18 contains an excerpt of the annual replacement quantity data, per intersection, recorded for each year of the simulation. The full tables are rather lengthy and can be found in Appendix G: Annual Replacement Quantity Data for Alternative Scenarios, Table G5.

Table 8.18 Excerpt of Annual Replacement Quantity Data (per Intersection) 5-year Period, Independent Replacement

Year	Modules in Place (Average)	Modules in Place (Median)	Modules in Place (Std. Dev.)	…	Signal Heads Replaced (Average)	Signal Heads Replaced (Median)	Signal Heads Replaced (Std. Dev.)
1	28.64	28.66	0.36		0.26	0.27	0.03
2	28.64	28.66	0.36		0.22	0.20	0.03
3	28.64	28.66	0.36		0.24	0.24	0.03
4	28.64	28.66	0.36		0.23	0.24	0.03
5	28.64	28.66	0.36		0.24	0.26	0.04
6	28.64	28.66	0.36		0.21	0.2	0.02
…	…	…	…		…	…	…
30	28.64	28.66	0.36		0.15	0.15	0.03

8.5.3 Summary

This section provides summary information regarding the overall costs and labor hours estimated for NCDOT over the next 30 years based on a 15-year replacement period and joint replacement. Table 8.19 provides a summary of all output data provided by the simulation for Alternative 5 (5-year Replacement Period, Independent Replacement). For example, NCDOT's Total Replacement Cost (for in-house work) was found to be, on average $1.51M. This is the total cost of replacement estimated for 205 intersections over 30 years. The NCDOT Total Replacement Cost per intersection, over a 30-year timespan, was found to be approximately $7,400, on average.

Table 8.19 5-year Independent Replacement Simulation Lifetime Summary Output Data (for 205 Intersections)

Metric	Scope	Average	Median	Standard Deviation
Modules in Place	Total	5,870.13	5,875.00	68.48
	Per Intersection	28.64	28.66	0.33
Signal Heads at Start	Total	1,804.50	1,807.00	22.91
	Per Intersection	8.80	8.81	0.11
Modules Replaced	Total	16,771.62	16,835.50	212.21
	Per Intersection	81.81	82.12	1.04
Signal Heads Replaced	Total	1,105.00	1,105.50	17.74
	Per Intersection	5.40	5.40	0.09
NCDOT Total Replacement Costs	Total	$1,509,259.84	$1,515,740.14	$18,027.94
	Per Intersection	$7,362.24	$7,393.86	$87.95
NCDOT Blanket Replacement Costs	Total	$648,730.48	$649,053.50	$4,850.57
	Per Intersection	$3,164.54	$3,166.10	$23.66
NCDOT Signal Head Spot Replacement Costs	Total	$583,457.27	$582,940.80	$11,767.35
	Per Intersection	$2,846.13	$2,843.60	$57.41
NCDOT Module Spot Replacement Costs	Total	$277,072.09	$278,197.33	$8,754.25
	Per Intersection	$1,351.57	$1,357.06	$42.70
NCDOT Labor Hours Required	Total	$2,550.29	$2,538.76	$33.27
	Per Intersection	$12.44	$12.39	$0.17
Contractor Total Replacement Costs	Total	$2,989,908.84	$2,997,528.22	$19,641.89
	Per Intersection	$14,584.91	$14,622.06	$95.81
Contractor Blanket Replacement Costs	Total	$2,027,314.48	$2,027,637.50	$4,850.57
	Per Intersection	$9,889.34	$9,890.90	$23.66
Contractor Signal Head Spot Replacement Costs	Total	$627,657.27	$627,400.80	$12,428.71
	Per Intersection	$3,061.74	$3,060.50	$60.64
Contractor Module Spot Replacement Costs	Total	$334,937.09	$336,297.33	$10,582.53
	Per Intersection	$1,633.88	$1,640.51	$51.61
NCDOT Supervisory Labor Hours Required	Total	$820.00	$820.00	$-
	Per Intersection	$4.00	$4.00	$-

To understand the scale of funding required for regular LED Module and Signal Heads replacement at the state level, it is necessary to scale up the costs. Multiplying each of the cost and labor hour per-intersection values found in Table 8.19 by the 8,200 intersections that NCDOT is responsible for, results in the values provided in Table 8.20. For example, NCDOT's Total Replacement Cost (for in-house work), for the whole state, was estimated to be approximately $60.4M. Contractor Total Cost estimates were approximately $119.6M.

These costs can be mixed and matched. For instance, if NCDOT were to manage all spot replacement, but contract out all blanket replacement work, the total estimated cost would be approximately $115.5M over the next 30 years.

Table 8.20 5-year, Independent Replacement State-wide Output Summary

Metric	Scope	Average	Median	Std. Dev.
NCDOT Total Replacement Costs	State Wide	$60,370,368.00	$60,629,652.00	$721,165.40
NCDOT Blanket Replacement Costs	State Wide	$25,949,228.00	$25,962,020.00	$194,044.80
NCDOT Signal Head Spot Replacement Costs	State Wide	$23,338,266.00	$23,317,520.00	$470,721.00
NCDOT Module Spot Replacement Costs	State Wide	$11,082,874.00	$11,127,892.00	$350,172.80
NCDOT Labor Hours Required	State Wide	102,008.00	101,598.00	1,394.00
Contractor Total Replacement Costs	State Wide	$119,596,262.00	$119,900,892.00	$785,658.40
Contractor Blanket Replacement Costs	State Wide	$81,092,588.00	$81,105,380.00	$194,044.80
Contractor Signal Head Spot Replacement Costs	State Wide	$25,106,268.00	$25,096,100.00	$497,231.60
Contractor Module Spot Replacement Costs	State Wide	$13,397,816.00	$13,452,182.00	$423,234.80
NCDOT Supervisory Labor Hours Required	State Wide	32,800.00	32,800.00	-

8.6 Alternative 6: 5-year Replacement Period, Joint Replacement

Alternative 6 utilizes a 5-year replacement period, meaning that one fifth of the LED Modules across the state will be replaced each year for the first five years of the cycle, then the following ten years will require no blanket replacement. Joint replacement indicates that during blanket replacement, both the Signal Heads and the Modules are replaced. Throughout the simulation spot replacement is occurring for both Modules and Signal Heads.

The following input variables were used when running this scenario

- Iterations: 8
- Intersections: 205
- Signal Head Life Expectancy: 30 years
- Timeline: 30 years
- Replacement Cycle 15 years
- Replacement Period: **5 years**
- Joint Replacement: **True**
- Module Warranty: 15 years
- Inflation: 0.00%

8.6.1 Annual Costs

Figures 8.16 and 8.17 show summaries of the replacement costs, per intersection, over the 30-year span of the simulation. Note that in each case, NCDOT Technician labor-hours are required. Based on information provided by Divisions, an NCDOT Technician must inspect and approve all work done by Contractors, adding an average of 0.13 NCDOT Technician Labor Hours per intersection, per year (or 4.0 labor hours per intersection over the 30-year span).

Both figures indicate that spot replacement costs remain somewhat high throughout first replacement period (the first five years). After the initial replacement period, all existing LED Modules have been replaced, drastically lowering the amount of spot replacement required. Blanket replacement costs are applicable for only five years out of a fifteen-year replacement cycle, which is shown by the increase in blanket replacement costs from year one to year five, then again from year sixteen to year twenty. The remainder of the replacement cycle, there are no blanket replacement costs.

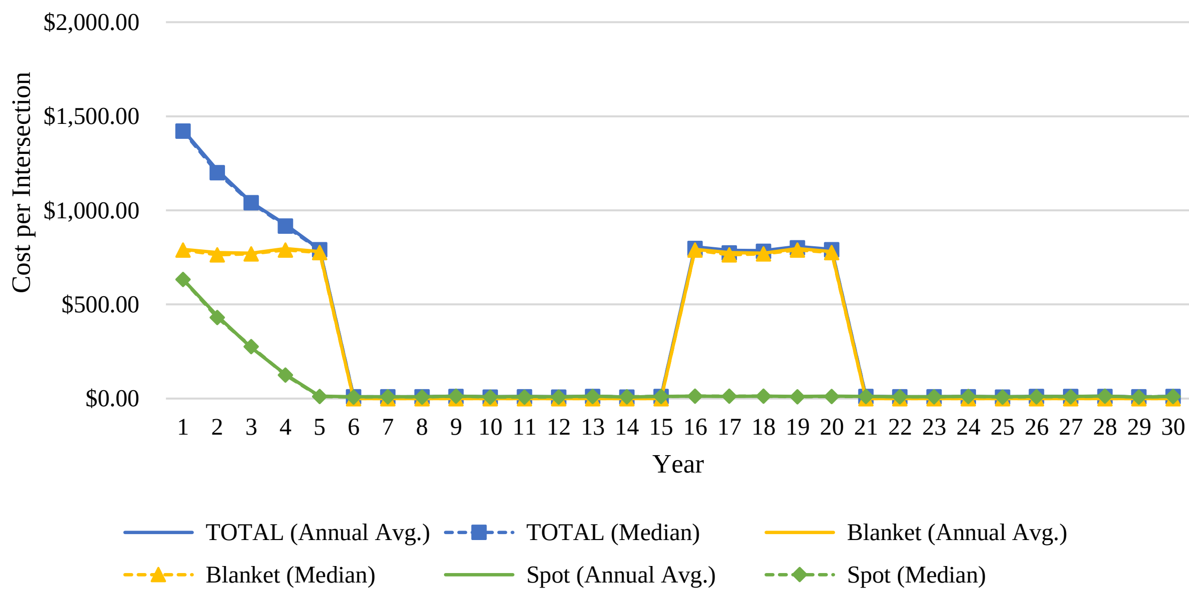


Figure 8.16 Replacement Costs to NCDOT (per Intersection) Over Time
5-year Period, Joint Replacement

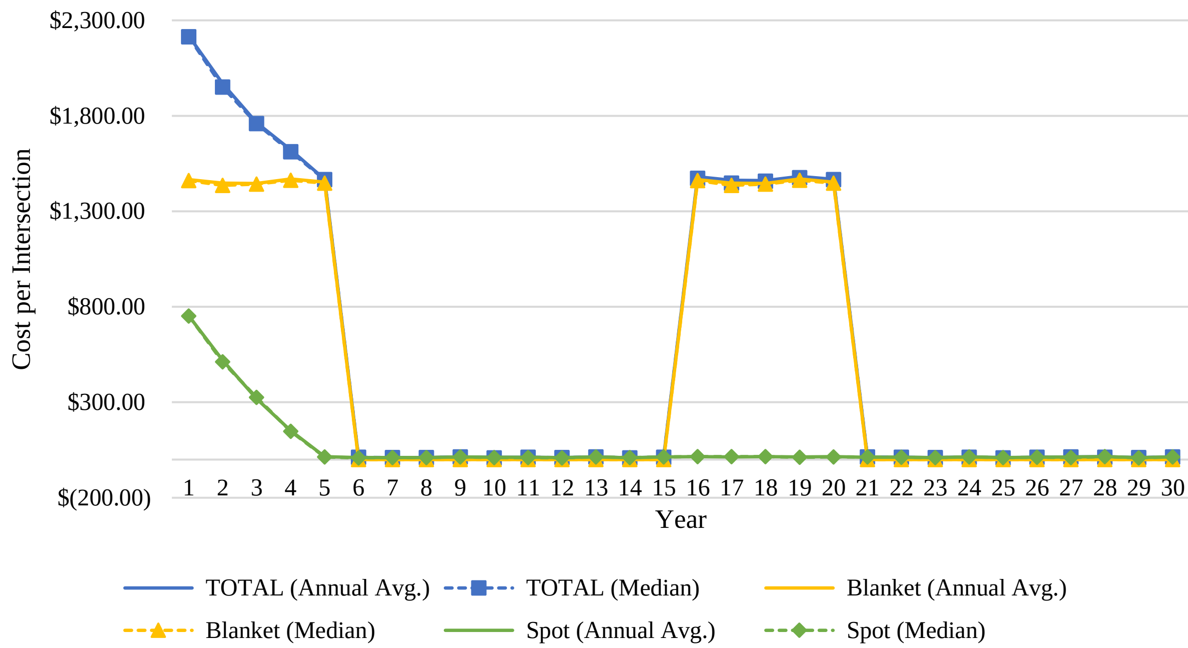


**Figure 8.17 Replacement Costs for Contractor (per Intersection) Over Time
5-year Period, Joint Replacement**

Table 8.21 contains an excerpt of the annual cost data, per intersection, recorded for each year of the simulation. The full tables are rather lengthy and can be found in Appendix F: Annual Cost Data for Alternative Scenarios, Tables F11 and F12.

**Table 8.21 Excerpt of Annual Cost Data (per Intersection)
5-year Period, Joint Replacement**

Year	NCDOT Total Cost (Average)	NCDOT Total Cost (Median)	NCDOT Total Cost (Std. Dev.)	…	Contractor Total Cost (Average)	Contractor Total Cost (Median)	Contractor Total Cost (Std. Dev.)
1	$1,426.87	$1,421.62	$23.84		$2,218.27	$2,213.23	$25.49
2	$1,214.28	$1,200.15	$53.26		$1,968.42	$1,951.46	$57.98
3	$1,043.31	$1,040.85	$26.75		$1,764.74	$1,759.86	$29.78
4	$925.96	$917.30	$40.42		$1,621.12	$1,611.64	$41.18
5	$793.52	$790.66	$44.88		$1,467.98	$1,465.98	$44.99
6	$9.28	$9.60	$3.44		$10.80	$11.17	$3.96
7	$9.46	$9.14	$3.04		$10.82	$10.60	$3.44
8	$9.53	$9.19	$3.81		$11.11	$10.46	$4.34
9	$12.36	$11.39	$5.69		$14.17	$12.96	$6.29
…	…	…	…		…	…	…
30	$12.11	$11.94	$3.33		$14.01	$13.66	$3.82

8.6.2 Replacement Quantities

Figure 8.18 shows how many Signal Heads and Modules are at each intersection to start and how many are replaced each year. The quantity of Modules and Signal Heads needed for replacement follows the same trends seen in Figures 8.16 and 8.17. There is a decrease in Modules and Signal Heads replaced for the first replacement period, eliminating all existing items. Rates of spot replacement are low for years six to fifteen, then blanket replacement starts in year sixteen and the cycle repeats.

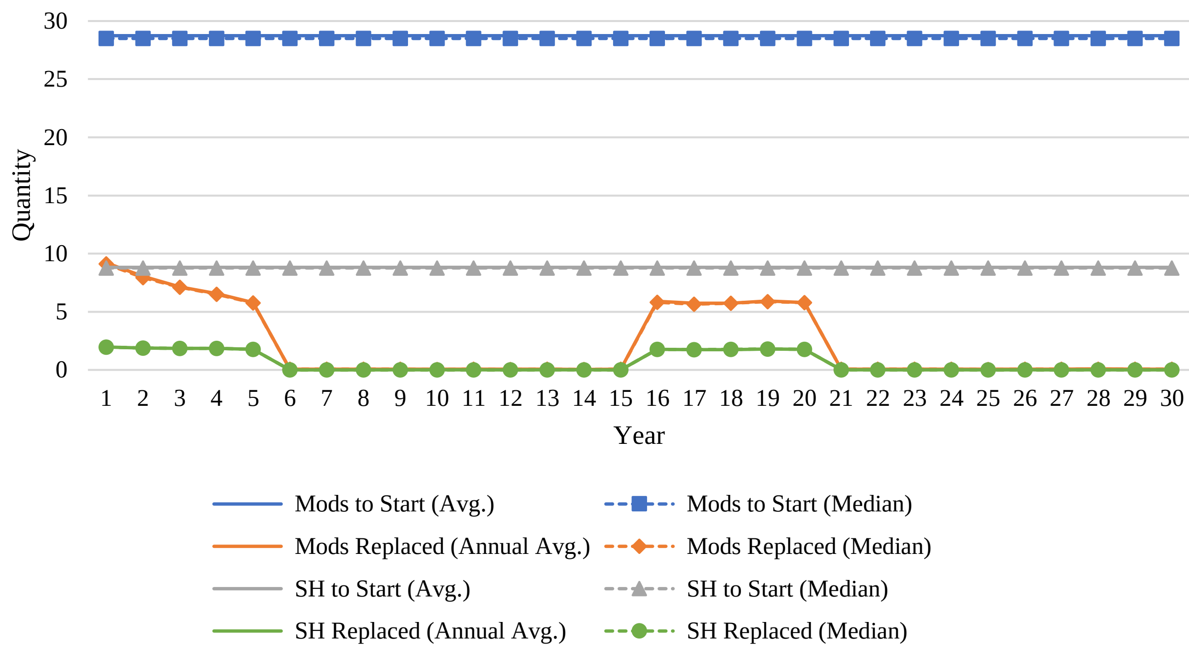


Figure 8.18 Quantities of LED Modules and Signal Heads Replaced (per Intersection) Over Time 5-year Period, Joint Replacement

Table 8.22 contains an excerpt of the annual replacement quantity data, per intersection, recorded for each year of the simulation. The full tables are rather lengthy and can be found in Appendix G: Annual Replacement Quantity Data for Alternative Scenarios, Table G6.

Table 8.22 Excerpt of Annual Replacement Quantity Data (per Intersection) 5-year Period, Joint Replacement

Year	Modules in Place (Average)	Modules in Place (Median)	Modules in Place (Std. Dev.)	…	Signal Heads Replaced (Average)	Signal Heads Replaced (Median)	Signal Heads Replaced (Std. Dev.)
1	28.74	28.50	0.71		1.97	1.97	0.06
2	28.74	28.50	0.71		1.88	1.88	0.08
3	28.74	28.50	0.71		1.86	1.85	0.07
4	28.74	28.50	0.71		1.86	1.85	0.09
5	28.74	28.50	0.71		1.76	1.76	0.11
6	28.74	28.50	0.71		-	-	0.01
…	…	…	…		…	…	…
30	28.74	28.50	0.71		0.01	0.01	0.01

8.6.3 <u>Summary</u>

This section provides summary information regarding the overall costs and labor hours estimated for NCDOT over the next 30 years based on a 5-year replacement period and joint replacement. Table 8.23 provides a summary of all output data provided by the simulation for Alternative 6 (5-year Replacement Period, Joint Replacement). For example, NCDOT's Total Replacement Cost (for in-house work) was found to be, on average $1.97M. This is the total cost of replacement estimated for 205 intersections over 30 years. The NCDOT Total Replacement Cost per intersection, over a 30-year timespan, was found to be approximately $9,600, on average.

Table 8.23 5-year, Joint Replacement Simulation
Lifetime Summary Output Data (for 205 Intersections)

Metric	Scope	Average	Median	Standard Deviation
Modules in Place	Total	5,891.25	5,844.00	135.52
	Per Intersection	28.74	28.51	0.66
Signal Heads at Start	Total	1,807.63	1,797.50	38.07
	Per Intersection	8.82	8.77	0.18
Modules Replaced	Total	13,736.00	13,626.00	328.39
	Per Intersection	66.98	66.44	1.60
Signal Heads Replaced	Total	3,763.75	3,737.00	82.20
	Per Intersection	18.32	18.20	0.40
NCDOT Total Replacement Costs	Total	$1,967,250.26	$1,954,455.63	$42,645.87
	Per Intersection	$9,596.34	$9,533.94	$208.03
NCDOT Blanket Replacement Costs	Total	$1,606,925.22	$1,597,490.66	$35,208.06
	Per Intersection	$7,838.65	$7,792.64	$171.74
NCDOT Signal Head Spot Replacement Costs	Total	$78,871.69	$79,091.84	$6,002.28
	Per Intersection	$384.79	$385.85	$29.28
NCDOT Module Spot Replacement Costs	Total	$281,453.34	$279,729.57	$7,790.08
	Per Intersection	$1,372.95	$1,364.54	$38.00
NCDOT Labor Hours Required	Total	2,547.23	2,552.70	26.75
	Per Intersection	12.43	12.46	0.13
Contractor Total Replacement Costs	Total	$3,410,554.26	$3,396,899.64	$44,231.21
	Per Intersection	$16,636.88	$16,570.28	$215.76
Contractor Blanket Replacement Costs	Total	$2,985,509.22	$2,976,074.66	$35,208.06
	Per Intersection	$14,563.45	$14,517.44	$171.74
Contractor Signal Head Spot Replacement Costs	Total	$84,811.69	$85,051.84	$6,430.94
	Per Intersection	$413.70	$414.88	$31.37
Contractor Module Spot Replacement Costs	Total	$340,233.34	$338,149.57	$9,417.00
	Per Intersection	$1,659.71	$1,649.54	$45.94
NCDOT Supervisory Labor Hours Required	Total	820.00	820.00	-
	Per Intersection	4.00	4.00	-

To understand the scale of funding required for regular LED Module and Signal Heads replacement at the state level, it is necessary to scale up the costs. Multiplying each of the cost and labor hour per-intersection values found in Table 8.23 by the 8,200 intersections that NCDOT is responsible for, results in the values provided in Table 8.24. For example, NCDOT's Total Replacement Cost (for in-house work), for the whole state, was estimated to be approximately $78.7M. Contractor Total Cost estimates were approximately $136.4M.

These costs can be mixed and matched. For instance, if NCDOT were to manage all spot replacement, but contract out all blanket replacement work, the total estimated cost would be approximately $133.8M over the next 30 years. Note that the cost of additional NCDOT labor required when Contract work is completed has not been incorporated into these estimates. Instead, an estimate of the time required has been provided.

Table 8.24 5-year Joint Replacement State-wide Output Summary

Metric	Scope	Average	Median	Std. Dev.
NCDOT Total Replacement Costs	State Wide	$78,689,988.00	$78,178,308.00	$1,705,846.00
NCDOT Blanket Replacement Costs	State Wide	$64,276,930.00	$63,899,648.00	$1,408,292.60
NCDOT Signal Head Spot Replacement Costs	State Wide	$3,155,278.00	$3,163,970.00	$240,079.60
NCDOT Module Spot Replacement Costs	State Wide	$11,258,190.00	$11,189,228.00	$311,583.60
NCDOT Labor Hours Required	State Wide	101,926.00	102,172.00	1,082.40
Contractor Total Replacement Costs	State Wide	$136,422,416.00	$135,876,296.00	$1,769,207.40
Contractor Blanket Replacement Costs	State Wide	$119,420,290.00	$119,043,008.00	$1,408,292.60
Contractor Signal Head Spot Replacement Costs	State Wide	$3,392,340.00	$3,402,016.00	$257,209.40
Contractor Module Spot Replacement Costs	State Wide	$13,609,622.00	$13,526,228.00	$376,691.60
NCDOT Supervisory Labor Hours Required	State Wide	32,800.00	32,800.00	-

8.7 Alternative 7: 1-year Replacement Period, Independent Replacement, 0% Inflation

Alternative 7 utilizes a 1-year replacement period, meaning that all the LED Modules across the state will be replaced in the first year of the replacement cycle, then the following fourteen years will require no blanket replacement. Independent replacement indicates that during blanket replacement, only the LED Modules are replaced, Signal Heads remain in place until they are removed due to spot failure. Throughout the simulation spot replacement is occurring for both Modules and Signal Heads.

The following input variables were used when running this scenario

- Iterations: 8
- Intersections: 205
- Signal Head Life Expectancy: 30 years
- Timeline: 30 years
- Replacement Cycle 15 years
- Replacement Period: 1 **years**
- Joint Replacement: **False**
- Module Warranty: 15 years
- Inflation: **0.00%**

8.7.1 Annual Costs

Figures 8.19 and 8.20 provide summaries of the replacement costs, per intersection, over the 30-year span of the simulation. Note that in each case, NCDOT Technician labor-hours are required. Based on information provided by Divisions, an NCDOT Technician must inspect and approve all work done by Contractors, adding an average of 0.13 NCDOT Technician Labor Hours per intersection, per year (or 4.0 labor hours per intersection over the 30-year span).

All LED Modules in the system are replaced in the first year. This means that the high levels of spot replacement at the start of the cycle due to slow replacement of existing LED Modules does not occur. When all LED Modules are replaced immediately, the spot replacement for them becomes relatively constant for the full replacement cycle. Blanket replacement in these strategies reaches higher peaks than any of the others, however all the blanket replacement is accomplished in a single year, rather than spreading the costs. This also appears to amplify the difference in cost between NCDOT in-house work and Contractor completed work, though the costs are simply more concentrated.

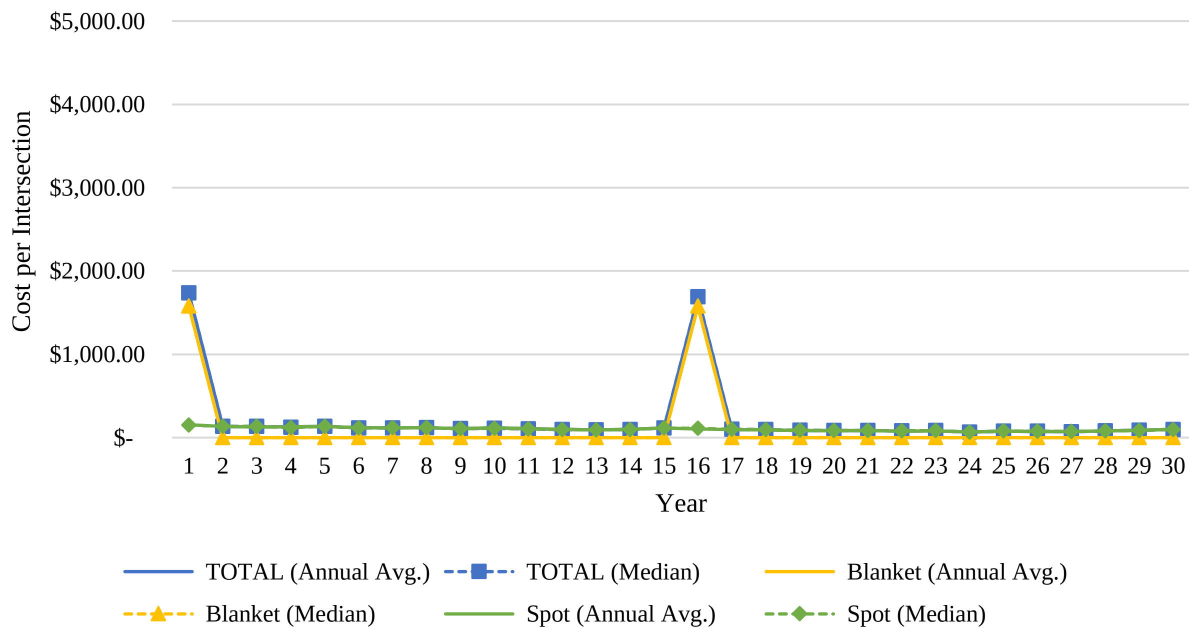


Figure 8.19 Replacement Costs to NCDOT (per Intersection) Over Time
1-year Period, Independent Replacement, 0% Inflation

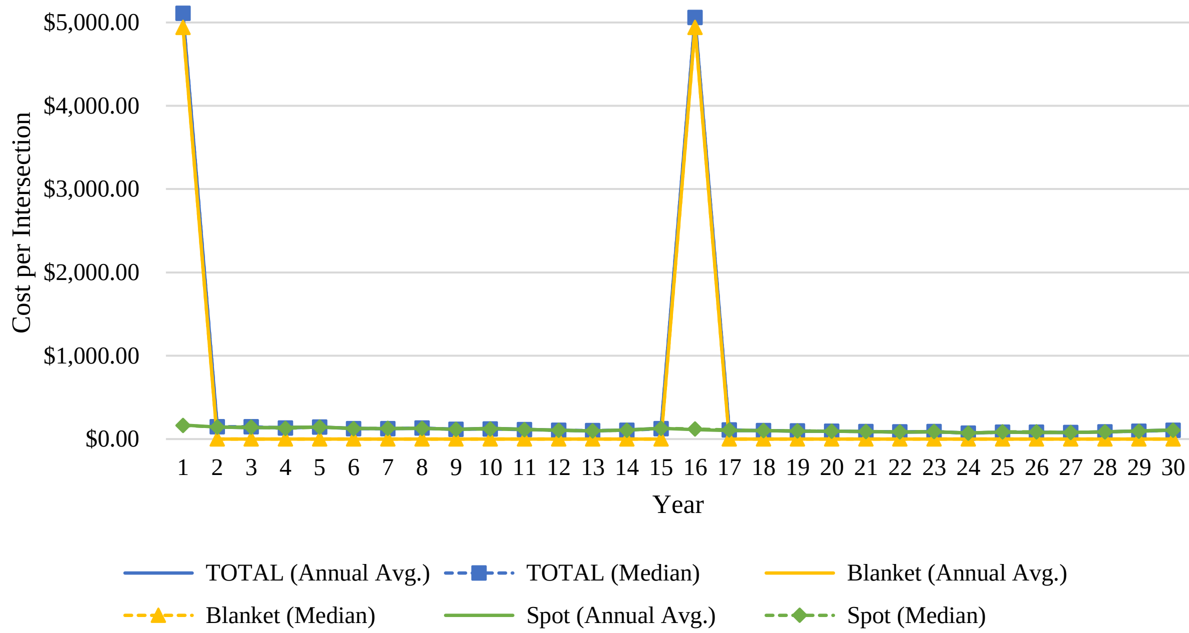


Figure 8.20 Replacement Costs for Contractor (per Intersection) Over Time
1-year Period, Independent Replacement, 0% Inflation

Table 8.25 contains an excerpt of the annual cost data, per intersection, recorded for each year of the simulation. The full tables are rather lengthy and can be found in Appendix F: Annual Cost Data for Alternative Scenarios, Tables F13 and F14.

Table 8.25 Excerpt of Annual Cost Data (per Intersection)
1-year Period, Independent Replacement, 0% Inflation

Year	NCDOT Total Cost (Average)	NCDOT Total Cost (Median)	NCDOT Total Cost (Std. Dev.)	…	Contractor Total Cost (Average)	Contractor Total Cost (Median)	Contractor Total Cost (Std. Dev.)
1	$1,732.78	$1,735.44	$30.26		$5,109.15	$5,111.88	$31.34
2	$133.90	$135.82	$10.25		$144.91	$147.24	$10.92
3	$125.72	$135.36	$23.65		$135.99	$146.38	$25.62
4	$130.29	$121.65	$24.21		$140.87	$131.89	$25.91
5	$134.03	$134.00	$22.26		$144.69	$144.43	$23.97
6	$118.33	$116.33	$13.79		$127.84	$125.80	$14.82
7	$117.29	$116.29	$24.10		$126.61	$125.56	$25.91
8	$119.07	$121.12	$13.31		$128.68	$131.17	$14.15
…	…	…	…		…	…	…
30	$98.78	$96.74	$9.78		$108.47	$106.30	$10.30

8.7.2 Replacement Quantities

Figure 8.21 shows how many Signal Heads and Modules are at each intersection to start and how many are replaced each year. The quantity of Modules and Signal Heads needed for replacement follows the same trends seen in Figures 8.19 and 8.20.

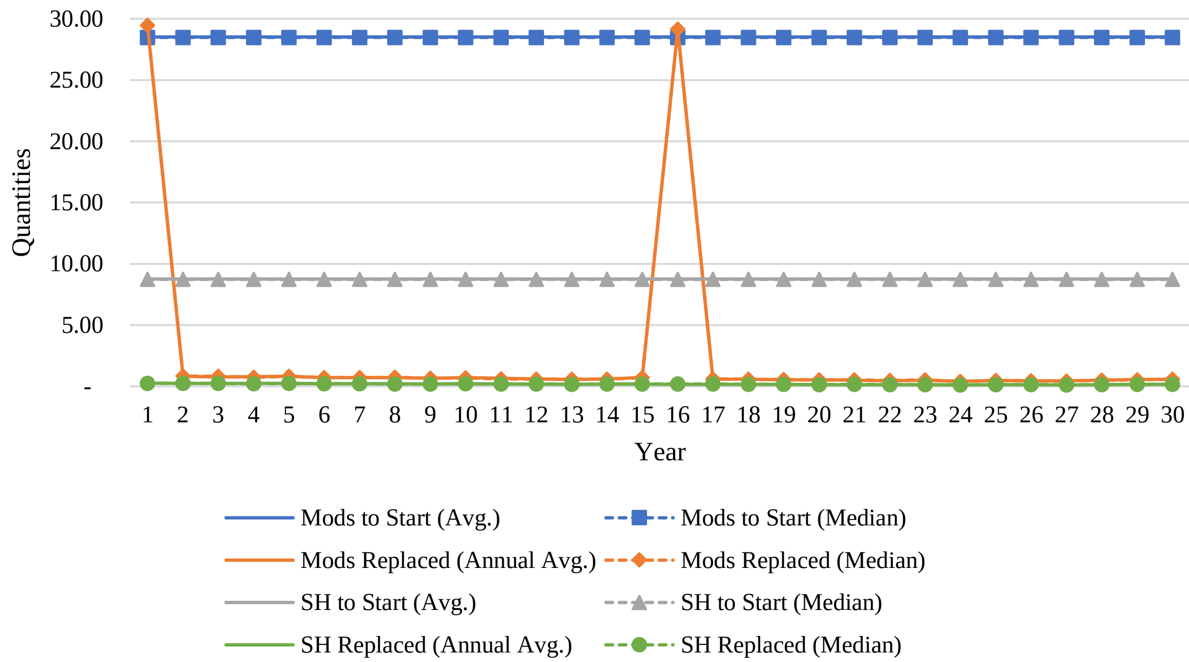


Figure 8.21 Quantities of LED Modules and Signal Heads Replaced (per Intersection) Over Time 1-year Period, Independent Replacement, 0% Inflation

Table 8.26 contains an excerpt of the annual replacement quantity data, per intersection, recorded for each year of the simulation. The full tables are rather lengthy and can be found in Appendix G: Annual Replacement Quantity Data for Alternative Scenarios, Table G7.

Table 8.26 Excerpt of Annual Replacement Quantity Data (per Intersection) 1-year Period, Independent Replacement, 0% Inflation

Year	Modules in Place (Average)	Modules in Place (Median)	Modules in Place (Std. Dev.)	…	Signal Heads Replaced (Average)	Signal Heads Replaced (Median)	Signal Heads Replaced (Std. Dev.)
1	28.52	28.48	0.63		0.26	0.25	0.02
2	28.52	28.48	0.63		0.25	0.25	0.02
3	28.52	28.48	0.63		0.23	0.24	0.04
4	28.52	28.48	0.63		0.23	0.22	0.05
5	28.52	28.48	0.63		0.24	0.24	0.04
6	28.52	28.48	0.63		0.21	0.21	0.02
…	…	…	…		…	…	…
30	28.52	28.48	0.63		0.16	0.16	0.02

8.7.3 Summary

This section provides summary information regarding the overall costs and labor hours estimated for NCDOT over the next 30 years based on a 1-year replacement period and independent replacement. Table 8.27 provides a summary of all output data provided by the simulation for Alternative 7 (1-year Replacement Period, Independent Replacement). For example, NCDOT's Total Replacement Cost (for in-house work) was found to be, on average $1.27M. This is the total cost of replacement estimated for 205 intersections over 30 years. The NCDOT Total Replacement Cost per intersection, over a 30-year timespan, was found to be approximately $6,200, on average.

Table 8.27 1-year, Independent Replacement (9% Inflation) Simulation Lifetime Summary Output Data (for 205 Intersections)

Metric	Scope	Average	Median	Standard Deviation
Modules in Place	Total	5,846.13	5,838.00	120.20
	Per Intersection	28.52	28.48	0.59
Signal Heads at Start	Total	1,796.63	1,789.50	39.37
	Per Intersection	8.76	8.73	0.19
Modules Replaced	Total	15,483.88	15,539.50	357.58
	Per Intersection	75.53	75.80	1.75
Signal Heads Replaced	Total	1,102.88	1,116.50	33.89
	Per Intersection	5.39	5.46	0.17
NCDOT Total Replacement Costs	Total	$1,270,353.43	$1,277,250.46	$26,437.17
	Per Intersection	$6,196.86	$6,230.50	$128.96
NCDOT Blanket Replacement Costs	Total	$647,140.24	$646,601.88	$8,514.08
	Per Intersection	$3,156.78	$3,154.15	$41.53
NCDOT Signal Head Spot Replacement Costs	Total	$583,111.59	$587,348.10	$17,806.13
	Per Intersection	$2,844.45	$2,865.11	$86.86
NCDOT Module Spot Replacement Costs	Total	$40,101.59	$39,167.89	$3,224.37
	Per Intersection	$195.62	$191.08	$15.72
NCDOT Labor Hours Required	Total	2,542.29	2,539.40	19.66
	Per Intersection	12.40	12.39	0.10
Contractor Total Replacement Costs	Total	$2,701,427.43	$2,708,854.46	$28,098.92
	Per Intersection	$13,177.70	$13,213.92	$137.05
Contractor Blanket Replacement Costs	Total	$2,025,724.24	$2,025,185.88	$8,514.08
	Per Intersection	$9,881.58	$9,878.95	$41.53
Contractor Signal Head Spot Replacement Costs	Total	$627,226.59	$632,168.10	$19,124.32
	Per Intersection	$3,059.64	$3,083.75	$93.29
Contractor Module Spot Replacement Costs	Total	$48,476.59	$47,347.88	$3,897.76
	Per Intersection	$236.53	$231.03	$19.01
NCDOT Supervisory Labor Hours Required	Total	820.00	820.00	-
	Per Intersection	4.00	4.00	-

To understand the scale of funding required for regular LED Module and Signal Heads replacement at the state level, it is necessary to scale up the costs. Multiplying each of the cost and labor hour per-intersection values found in Table 8.27 by the 8,200 intersections that NCDOT is responsible for, results in the values provided in Table 8.28. For example, NCDOT's Total Replacement Cost (for in-house work), for the whole state, was estimated to be approximately $50.8M. Contractor Total Cost estimates were approximately $108.1M.

These costs can be mixed and matched. For instance, if NCDOT were to manage all spot replacement, but contract out all blanket replacement work, the total estimated cost would be approximately $106M over the next 30 years. Note that the cost of additional NCDOT labor required when Contract work is completed has not been incorporated into these estimates. Instead, an estimate of the time required has been provided.

Table 8.28 1-year, Independent Replacement (0% Inflation) State-wide Output Summary

Metric	Scope	Average	Median	Std. Dev.
NCDOT Total Replacement Costs	State Wide	$50,814,252.00	$51,090,100.00	$1,057,439.20
NCDOT Blanket Replacement Costs	State Wide	$25,885,596.00	$25,864,030.00	$340,562.40
NCDOT Signal Head Spot Replacement Costs	State Wide	$23,324,490.00	$23,493,902.00	$712,235.60
NCDOT Module Spot Replacement Costs	State Wide	$1,604,084.00	$1,566,856.00	$128,904.00
NCDOT Labor Hours Required	State Wide	101,680.00	101,598.00	811.80
Contractor Total Replacement Costs	State Wide	$108,057,140.00	$108,354,144.00	$1,123,842.80
Contractor Blanket Replacement Costs	State Wide	$81,028,956.00	$81,007,390.00	$340,562.40
Contractor Signal Head Spot Replacement Costs	State Wide	$25,089,048.00	$25,286,750.00	$764,953.40
Contractor Module Spot Replacement Costs	State Wide	$1,939,546.00	$1,894,446.00	$155,865.60
NCDOT Supervisory Labor Hours Required	State Wide	32,800.00	32,800.00	-

8.8 Alternative 8: 1-year Replacement Period, Joint Replacement, 0% Inflation

Alternative 8 utilizes a 1-year replacement period, meaning that all the LED Modules across the state will be replaced in the first year of the replacement cycle, then the following fourteen years will require no blanket replacement. Joint replacement indicates that during blanket replacement, both the LED Modules and Signal Heads are replaced. Throughout the simulation spot replacement is occurring for both Modules and Signal Heads.

The following input variables were used when running this scenario

- Iterations: 8
- Intersections: 205
- Signal Head Life Expectancy: 30 years
- Timeline: 30 years
- Replacement Cycle 15 years
- Replacement Period: 1 **years**
- Joint Replacement: **True**
- Module Warranty: 15 years
- Inflation: **0.00%**

8.8.1 Annual Costs

Figures 8.22 and 23 show summaries of the replacement costs, per intersection, over the 30-year span of the simulation. Note that in each case, NCDOT Technician labor-hours are required. Based on information provided by Divisions, an NCDOT Technician must inspect and approve all work done by Contractors, adding an average of 0.13 NCDOT Technician Labor Hours per intersection, per year (or 4.0 labor hours per intersection over the 30-year span).

All LED Modules in the system are replaced in the first year. When all LED Modules are replaced immediately, the spot replacement for them becomes relatively constant for the full replacement cycle. Blanket replacement in these strategies reaches higher peaks than any of the others, however all the blanket replacement is accomplished in a single year, rather than spreading the costs. This also appears to amplify the difference in cost between NCDOT in-house work and Contractor completed work.

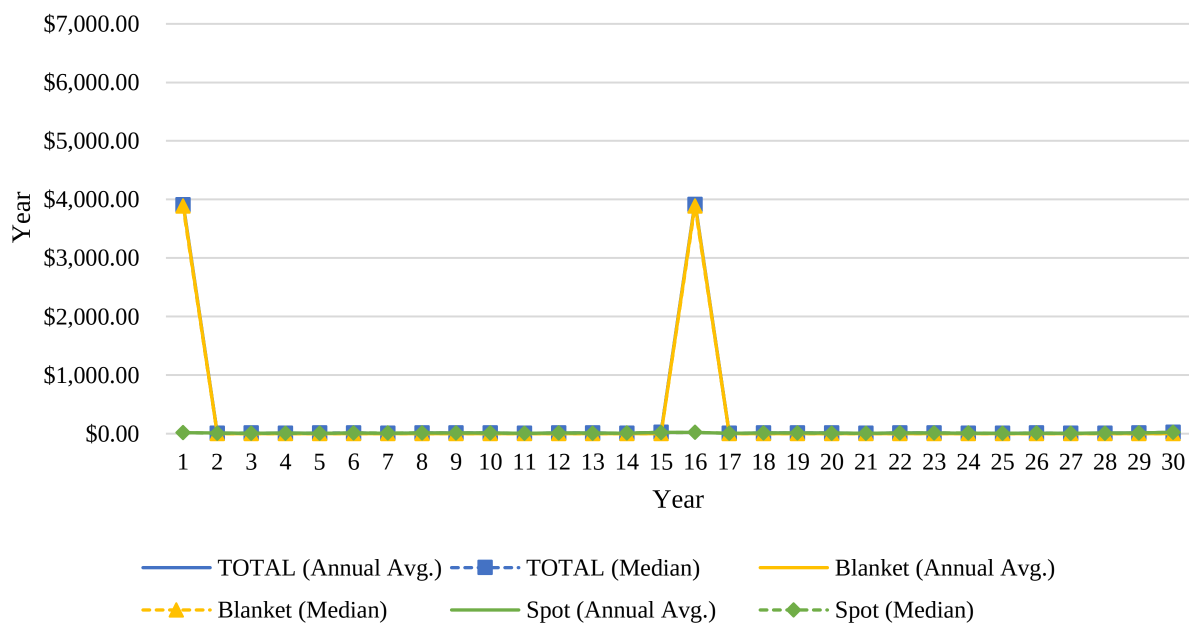


Figure 8.22 Replacement Costs to NCDOT (per Intersection) Over Time 1-year Period, Joint Replacement, 0% Inflation

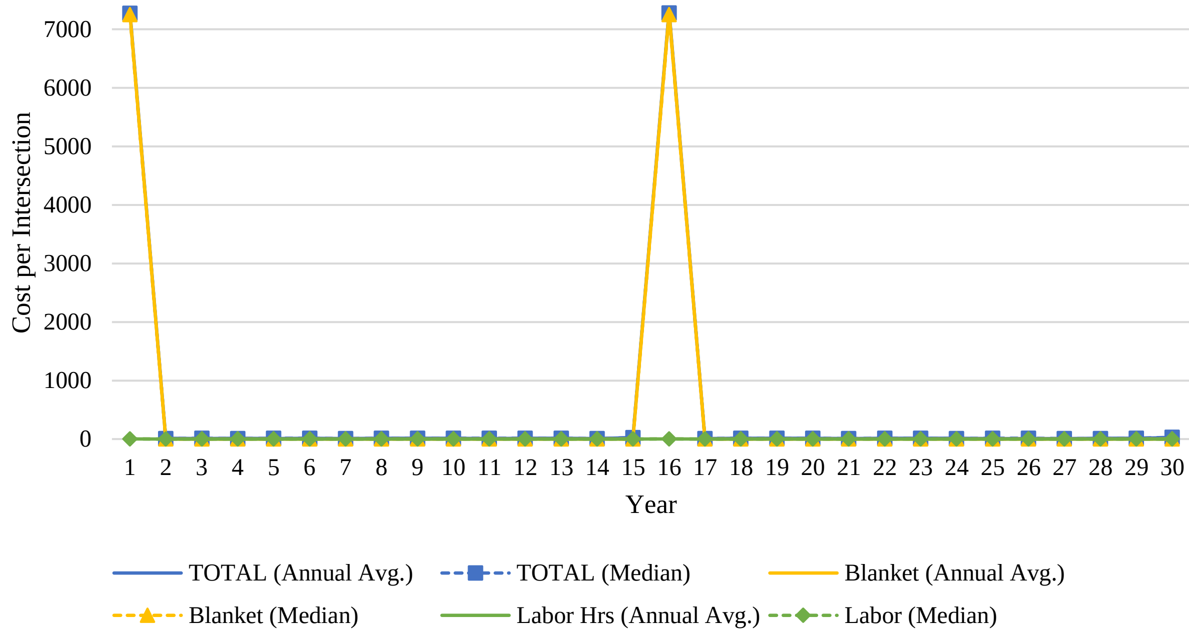


Figure 8.23 Replacement Costs for Contractor (per Intersection) Over Time
1-year Period, Joint Replacement, 0% Inflation

Table 8.29 contains an excerpt of the annual cost data, per intersection, recorded for each year of the simulation. The full tables are rather lengthy and can be found in Appendix F: Annual Cost Data for Alternative Scenarios, Tables F15 and F16.

Table 8.29 Excerpt of Annual Cost Data (per Intersection)
1-year Period, Joint Replacement, 0% Inflation

Year	NCDOT Total Cost (Average)	NCDOT Total Cost (Median)	NCDOT Total Cost (Std. Dev.)	…	Contractor Total Cost (Average)	Contractor Total Cost (Median)	Contractor Total Cost (Std. Dev.)
1	$3,951.68	$3,909.24	$97.12		$7,317.81	$7,275.00	$96.98
2	$10.31	$8.90	$3.02		$11.95	$10.46	$3.69
3	$9.10	$9.88	$3.65		$10.44	$11.44	$4.08
4	$10.01	$9.28	$6.62		$11.64	$10.55	$7.75
5	$8.68	$11.02	$5.32		$10.07	$12.59	$6.16
6	$12.61	$12.31	$3.84		$14.57	$14.36	$4.17
7	$9.41	$8.20	$4.35		$10.80	$9.48	$4.99
8	$11.21	$11.58	$4.84		$12.75	$13.14	$5.45
9	$11.43	$12.14	$3.50		$12.97	$13.80	$3.81
…	…	…	…		…	…	…
30	$20.58	$23.16	$9.08		$24.22	$27.54	$10.39

8.8.2 Replacement Quantities

Figure 8.24 shows how many Signal Heads and Modules are at each intersection to start and how many are replaced each year. The quantity of Modules and Signal Heads needed for replacement follows the same trends seen in Figures 8.22 and 8.23.

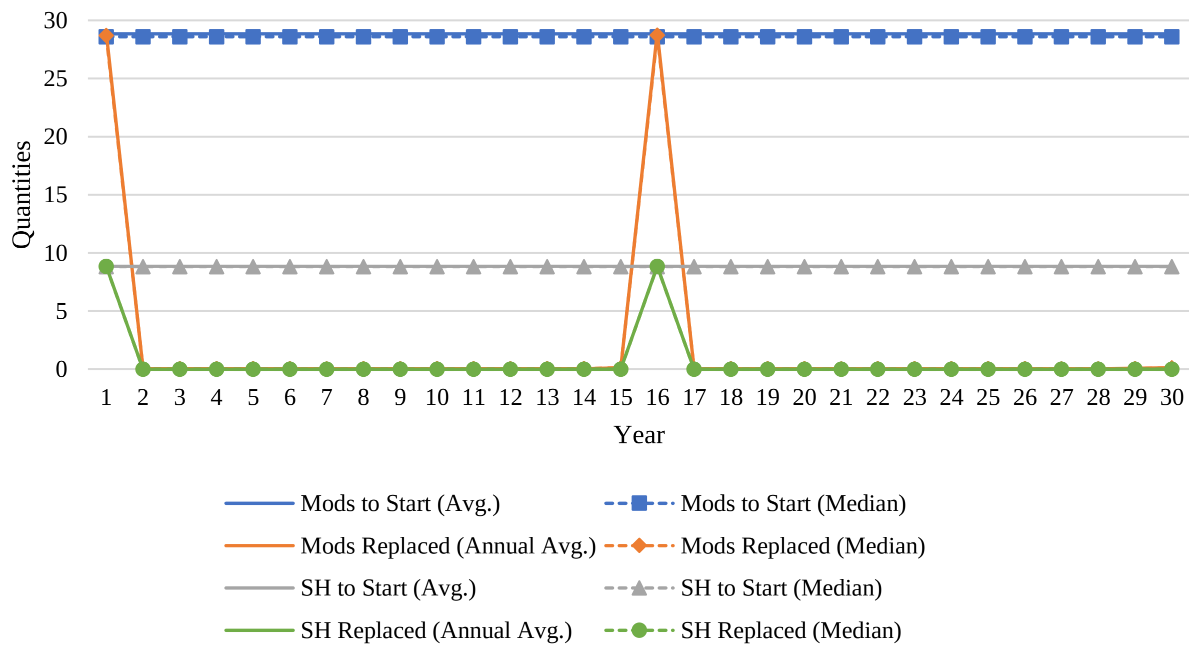


Figure 8.24 Quantities of LED Modules and Signal Heads Replaced (per Intersection) Over Time 1-year Period, Joint Replacement, 0% Inflation

Table 8.30 contains an excerpt of the annual replacement quantity data, per intersection, recorded for each year of the simulation. The full tables are rather lengthy and can be found in Appendix G: Annual Replacement Quantity Data for Alternative Scenarios, Table G8.

Table 8.30 Excerpt of Annual Replacement Quantity Data (per Intersection) 1-year Period, Joint Replacement, 0% Inflation

Year	Modules in Place (Average)	Modules in Place (Median)	Modules in Place (Std. Dev.)	…	Signal Heads Replaced (Average)	Signal Heads Replaced (Median)	Signal Heads Replaced (Std. Dev.)
1	28.84	28.59	0.76		8.86	8.84	0.21
2	28.84	28.59	0.76		-	-	0.01
3	28.84	28.59	0.76		-	-	0.01
4	28.84	28.59	0.76		-	-	0.01
5	28.84	28.59	0.76		-	-	0.01
6	28.84	28.59	0.76		0.01	-	0.01
…	…	…	…		…	…	…
30	28.84	28.59	0.76		0.01	-	0.01

8.8.3 Summary

This section provides summary information regarding the overall costs and labor hours estimated for NCDOT over the next 30 years based on a 1-year replacement period and joint replacement. Table 8.31 provides a summary of all output data provided by the simulation for Alternative 8 (1-year Replacement Period, Joint Replacement, 0% Inflation). For example, NCDOT's Total Replacement Cost (for in-house work) was found to be, on average $1.68M. This is the total cost of replacement estimated for 205 intersections over 30 years. The NCDOT Total Replacement Cost per intersection, over a 30-year timespan, was found to be approximately $8,200, on average.

Table 8.31 1-year, Joint Replacement (0% Inflation) Simulation Lifetime Summary Output Data (for 205 Intersections)

Metric	Scope	Average	Median	Standard Deviation
Modules in Place	Total	5,910.75	5,860.50	145.88
	Per Intersection	28.84	28.59	0.71
Signal Heads at Start	Total	1,814.13	1,810.00	39.80
	Per Intersection	8.85	8.83	0.20
Modules Replaced	Total	12,222.00	12,112.50	327.72
	Per Intersection	59.59	59.06	1.60
Signal Heads Replaced	Total	3,681.75	3,669.50	84.67
	Per Intersection	17.90	17.83	0.41
NCDOT Total Replacement Costs	Total	$1,683,495.38	$1,664,485.32	$43,320.22
	Per Intersection	$8,212.18	$8,119.45	$211.32
NCDOT Blanket Replacement Costs	Total	$1,611,841.04	$1,594,920.29	$40,401.93
	Per Intersection	$7,862.64	$7,780.10	$197.08
NCDOT Signal Head Spot Replacement Costs	Total	$28,200.97	$27,430.04	$4,015.14
	Per Intersection	$137.62	$133.85	$19.59
NCDOT Module Spot Replacement Costs	Total	$43,453.37	$44,243.43	$4,574.36
	Per Intersection	$211.98	$215.84	$22.31
NCDOT Labor Hours Required	Total	2,525.29	2,534.86	33.63
	Per Intersection	12.32	12.36	0.16
Contractor Total Replacement Costs	Total	$3,073,294.38	$3,054,389.32	$44,024.83
	Per Intersection	$14,991.72	$14,899.51	$214.74
Contractor Blanket Replacement Costs	Total	$2,990,425.04	$2,973,504.29	$40,401.93
	Per Intersection	$14,587.44	$14,504.90	$197.08
Contractor Signal Head Spot Replacement Costs	Total	$30,340.97	$29,450.04	$4,337.07
	Per Intersection	$147.98	$143.62	$21.16
Contractor Module Spot Replacement Costs	Total	$52,528.37	$53,483.43	$5,529.69
	Per Intersection	$256.27	$260.94	$26.97
NCDOT Supervisory Labor Hours Required	Total	820.00	820.00	-
	Per Intersection	4.00	4.00	-

To understand the scale of funding required for regular LED Module and Signal Heads replacement at the state level, it is necessary to scale up the costs. Multiplying each of the cost and labor hour per-intersection values found in Table 8.31 by the 8,200 intersections that NCDOT is responsible for, results in the values provided in Table 8.32. For example, NCDOT's Total Replacement Cost (for in-house work), for the whole state, was estimated to be approximately $67.3M. Contractor Total Cost estimates were approximately $122.9M.

These costs can be mixed and matched. For instance, if NCDOT were to manage all spot replacement, but contract out all blanket replacement work, the total estimated cost would be approximately $122.4M over the next 30 years. Note that the cost of additional NCDOT labor required when Contract work is completed has not been incorporated into these estimates. Instead, an estimate of the time required has been provided.

Table 8.32 Independent Replacement (0% Inflation) State-wide Output Summary

Metric	Scope	Average	Median	Std. Dev.
NCDOT Total Replacement Costs	State Wide	$67,339,876.00	$66,579,490.00	$1,732,791.20
NCDOT Blanket Replacement Costs	State Wide	$64,473,648.00	$63,796,820.00	$1,616,064.20
NCDOT Signal Head Spot Replacement Costs	State Wide	$1,128,484.00	$1,097,570.00	$160,621.60
NCDOT Module Spot Replacement Costs	State Wide	$1,738,236.00	$1,769,888.00	$182,909.20
NCDOT Labor Hours Required	State Wide	101,024.00	101,352.00	1,336.60
Contractor Total Replacement Costs	State Wide	$122,932,104.00	$122,175,982.00	$1,760,892.60
Contractor Blanket Replacement Costs	State Wide	$119,617,008.00	$118,940,180.00	$1,616,064.20
Contractor Signal Head Spot Replacement Costs	State Wide	$1,213,436.00	$1,177,684.00	$173,471.00
Contractor Module Spot Replacement Costs	State Wide	$2,101,414.00	$2,139,708.00	$221,162.20
NCDOT Supervisory Labor Hours Required	State Wide	32,800.00	32,800.00	-

8.9 Alternative 9: 1-year Replacement Period, Independent Replacement, 3% Inflation

Alternative 9 utilizes a 1-year replacement period and independent replacement. Throughout the simulation spot replacement is occurring for both Modules and Signal Heads. This simulation incorporated inflation. This has been included to show that is can be done, and may provide additional assistance to any planners using this report. Additional runs of the simulation can be completed upon request by NCDOT.

The following input variables were used when running this scenario

- Iterations: 8
- Intersections: 205
- Signal Head Life Expectancy: 30 years
- Timeline: 30 years
- Replacement Cycle 15 years
- Replacement Period: 1 **years**
- Joint Replacement: **False**
- Module Warranty: 15 years
- Inflation: **3.00%**

8.9.1 Annual Costs

Figures 8.25 and 8.26 show summaries of the replacement costs, per intersection, over the 30-year span of the simulation. Note that in each case, NCDOT Technician labor-hours are required. Based on information provided by Divisions, an NCDOT Technician must inspect and approve all work done by Contractors, adding an average of 0.13 NCDOT Technician Labor Hours per intersection, per year (or 4.0 labor hours per intersection over the 30-year span).

All LED Modules are replaced in the first year, which eliminates the slow replacement of existing LED Modules over time. Spot replacement of Modules, therefore, remains relatively constant over the entire replacement cycle. The inflation factor is having an effect, as seen in the increased total cost per intersection values in year 16 for both NCDOT in-house work and Contracted work.

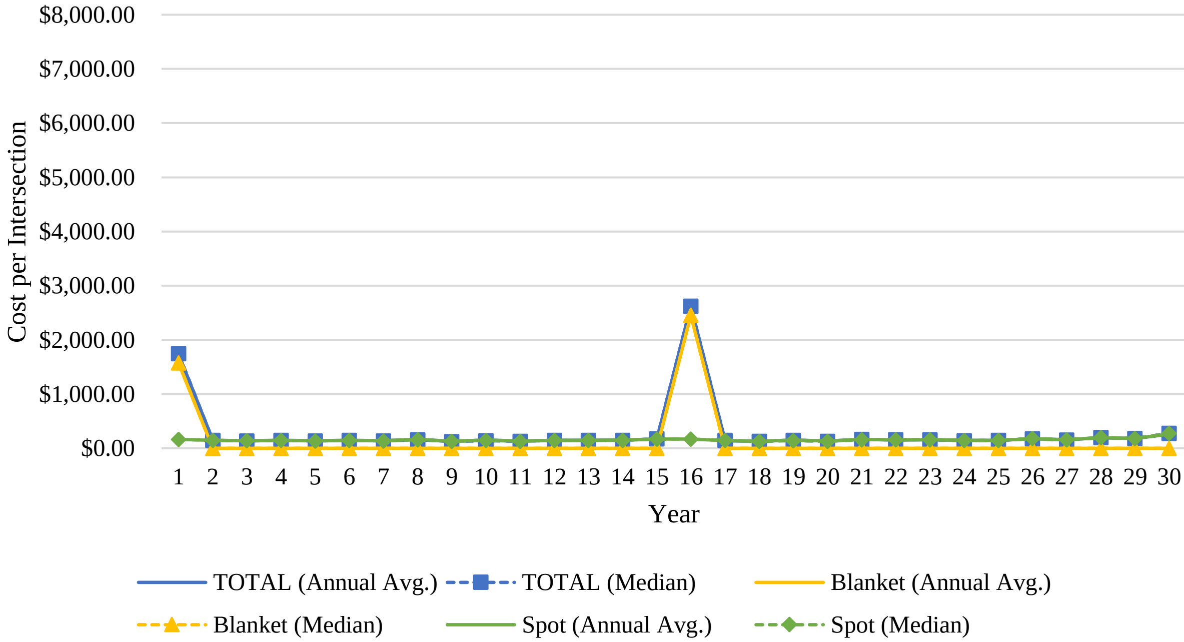


Figure 8.25 Replacement Costs to NCDOT (per Intersection) Over Time 1-year Period, Independent Replacement, 3% Inflation

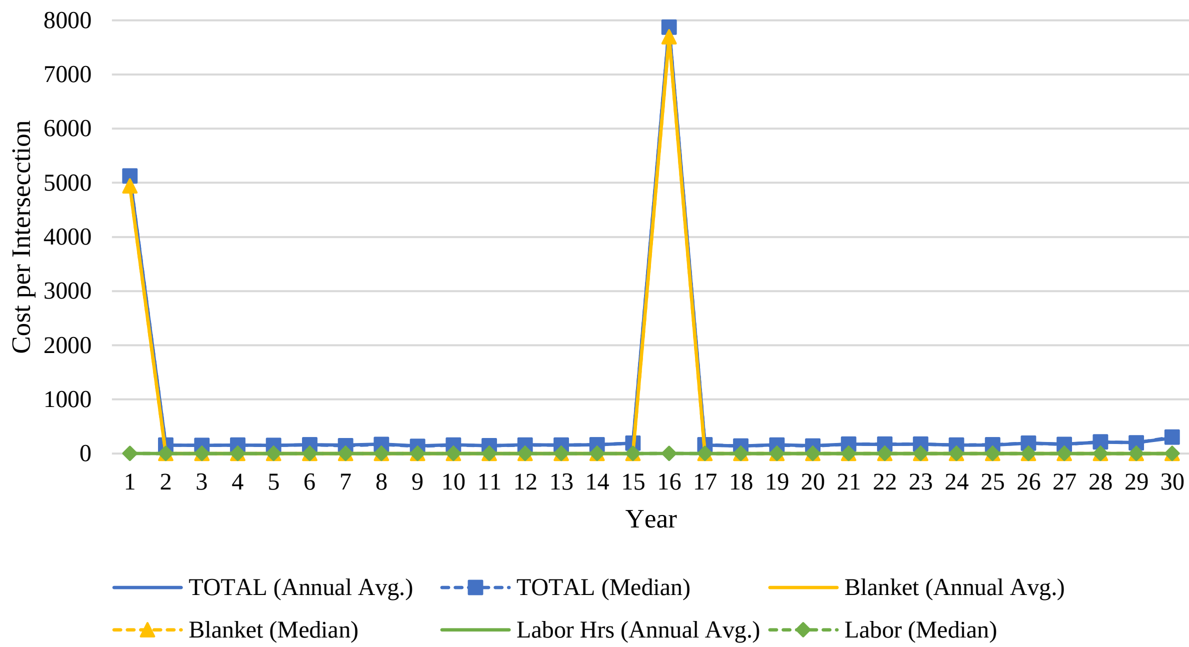


Figure 8.26 Replacement Costs for Contractor (per Intersection) Over Time
1-year Period, Independent Replacement, 3% Inflation

Table 8.33 contains an excerpt of the annual cost data, per intersection, recorded for each year of the simulation. The full tables are rather lengthy and can be found in Appendix F: Annual Cost Data for Alternative Scenarios, Tables F17 and F18.

Table 8.33 Excerpt of Annual Cost Data (per Intersection)
1-year Period, Independent Replacement, 3% Inflation

Year	NCDOT Total Cost (Average)	NCDOT Total Cost (Median)	NCDOT Total Cost (Std. Dev.)	…	Contractor Total Cost (Average)	Contractor Total Cost (Median)	Contractor Total Cost (Std. Dev.)
1	$1,736.08	$1,747.24	$36.54		$5,112.80	$5,124.18	$37.94
2	$145.39	$144.50	$22.72		$157.07	$155.95	$24.69
3	$139.27	$137.41	$17.72		$150.42	$147.96	$19.13
4	$145.77	$146.40	$25.30		$157.61	$158.26	$27.38
5	$138.57	$137.41	$10.57		$150.27	$149.05	$11.14
6	$149.01	$147.78	$19.21		$160.77	$159.55	$20.36
7	$143.27	$134.39	$23.02		$154.86	$145.70	$24.65
8	$161.83	$158.13	$20.87		$174.91	$171.09	$22.42
9	$129.81	$125.39	$29.76		$140.72	$135.66	$32.05
…	…	…	…		…	…	…
30	$260.19	$278.56	$56.77		$284.56	$304.30	$61.58

8.9.2 Replacement Quantities

Figure 8.27 shows how many Signal Heads and Modules are at each intersection to start and how many are replaced each year. The quantity of Modules and Signal Heads needed for replacement follows the same trends seen in other 1-year Period Replacement Strategy Alternatives.

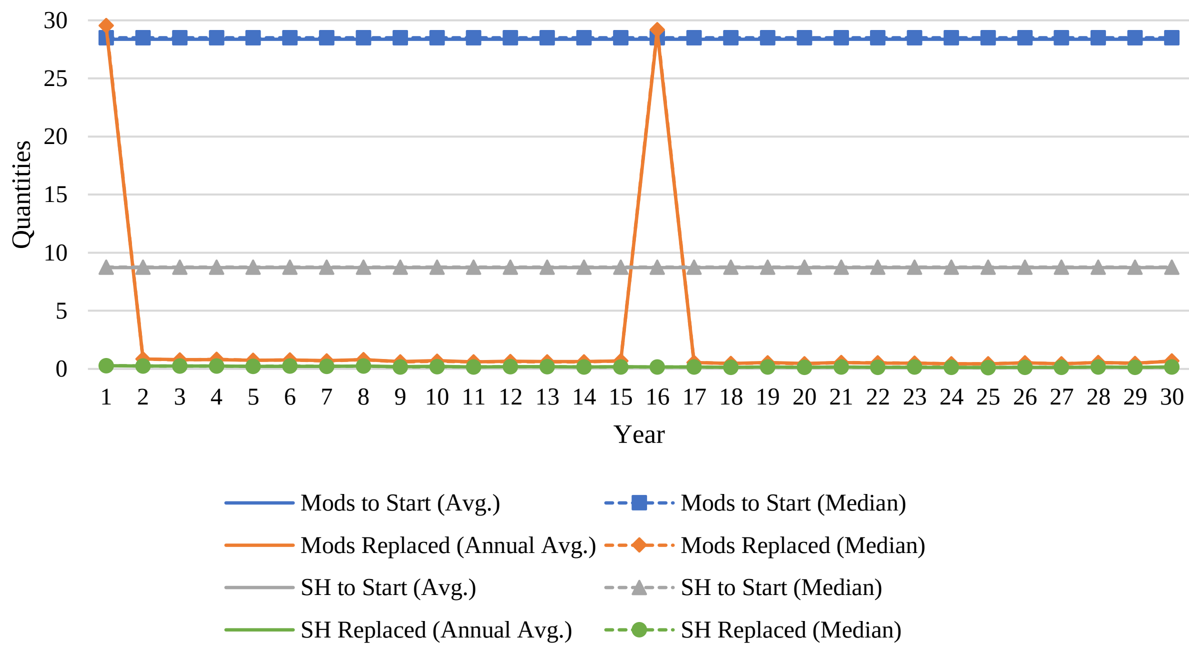


Figure 8.27 Quantities of LED Modules and Signal Heads Replaced (per Intersection) Over Time 1-year Period, Independent Replacement, 3% Inflation

Table 8.34 contains an excerpt of the annual replacement quantity data, per intersection, recorded for each year of the simulation. The full tables are rather lengthy and can be found in Appendix G: Annual Replacement Quantity Data for Alternative Scenarios, Table G9.

Table 8.34 Excerpt of Annual Replacement Quantity Data (per Intersection) 1-year Period, Independent Replacement, 3% Inflation

Year	Modules in Place (Average)	Modules in Place (Median)	Modules in Place (Std. Dev.)	…	Signal Heads Replaced (Average)	Signal Heads Replaced (Median)	Signal Heads Replaced (Std. Dev.)
1	28.37	28.50	0.61		0.28	0.29	0.03
2	28.37	28.50	0.61		0.26	0.25	0.04
3	28.37	28.50	0.61		0.24	0.24	0.03
4	28.37	28.50	0.61		0.24	0.24	0.04
5	28.37	28.50	0.61		0.22	0.22	0.02
6	28.37	28.50	0.61		0.23	0.24	0.03
…	…	…	…		…	…	…
30	28.37	28.50	0.61		0.18	0.18	0.04

8.9.3 Summary

This section provides summary information regarding the overall costs and labor hours estimated for NCDOT over the next 30 years based on a 1-year replacement period and independent replacement. This time, the summary has incorporated a rate of 3% inflation into the estimates. Table 8.35 provides a summary of all output data provided by the simulation for Alternative 8 (1-year Replacement Period, Independent Replacement, 3% Inflation). For example, NCDOT's Total Replacement Cost (for in-house work) was found to be, on average $1.79M. This is the total cost of replacement estimated for 205 intersections over 30 years. The NCDOT Total Replacement Cost per intersection, over a 30-year timespan, was found to be approximately $8,718, on average.

Table 8.35 1-year Independent Replacement (3% Inflation) Simulation Lifetime Summary Output Data (for 205 Intersections)

Metric	Scope	Average	Median	Standard Deviation
Modules in Place	Total	5,815.88	5,843.50	117.28
	Per Intersection	28.37	28.51	0.57
Signal Heads at Start	Total	1,788.25	1,795.50	29.71
	Per Intersection	8.72	8.76	0.14
Modules Replaced	Total	15,496.75	15,593.50	370.24
	Per Intersection	75.60	76.06	1.79
Signal Heads Replaced	Total	1,124.25	1,122.50	33.96
	Per Intersection	5.50	5.50	0.16
NCDOT Total Replacement Costs	Total	$1,787,244.48	$1,797,116.46	$46,784.68
	Per Intersection	$8,718.26	$8,766.42	$228.21
NCDOT Blanket Replacement Costs	Total	$825,118.28	$827,459.37	$10,625.28
	Per Intersection	$4,024.97	$4,036.38	$51.83
NCDOT Signal Head Spot Replacement Costs	Total	$898,982.70	$899,995.01	$37,481.41
	Per Intersection	$4,385.28	$4,390.20	$182.84
NCDOT Module Spot Replacement Costs	Total	$63,143.50	$64,198.40	$3,997.29
	Per Intersection	$308.02	$313.18	$19.51
NCDOT Labor Hours Required	Total	2,532.96	2,527.40	21.15
	Per Intersection	12.36	12.33	0.10
Contractor Total Replacement Costs	Total	$3,631,512.62	$3,640,970.92	$49,155.89
	Per Intersection	$17,714.70	$17,760.83	$239.78
Contractor Blanket Replacement Costs	Total	$2,588,304.75	$2,590,645.85	$10,625.28
	Per Intersection	$12,625.88	$12,637.30	$51.83
Contractor Signal Head Spot Replacement Costs	Total	$966,877.20	$967,477.23	$39,821.70
	Per Intersection	$4,716.46	$4,719.40	$194.25
Contractor Module Spot Replacement Costs	Total	$76,330.69	$77,605.90	$4,832.10
	Per Intersection	$372.33	$378.55	$23.57
NCDOT Supervisory Labor Hours Required	Total	820.00	820.00	-
	Per Intersection	4.00	4.00	-

To understand the scale of funding required for regular LED Module and Signal Heads replacement at the state level, it is necessary to scale up the costs. Multiplying each of the cost and labor hour per-intersection values found in Table 8.35 by the 8,200 intersections that NCDOT is responsible for, results in the values provided in Table 8.36. For example, NCDOT's Total Replacement Cost (for in-house work), for the whole state, was estimated to be approximately $71.5M. Contractor Total Cost estimates were approximately $145.3M.

These costs can be mixed and matched. For instance, if NCDOT were to manage all spot replacement, but contract out all blanket replacement work, the total estimated cost would be approximately $142M over the next 30 years. Note that the cost of additional NCDOT labor required when Contract work is completed has not been incorporated into these estimates. Instead, an estimate of the time required has been provided.

Table 8.36 1-year, Independent Replacement (3% Inflation) State-wide Output Summary

Metric	Scope	Average	Median	Std. Dev.
NCDOT Total Replacement Costs	State Wide	$71,489,732.00	$71,884,644.00	$1,871,346.60
NCDOT Blanket Replacement Costs	State Wide	$33,004,754.00	$33,098,316.00	$425,022.40
NCDOT Signal Head Spot Replacement Costs	State Wide	$35,959,296.00	$35,999,640.00	$1,499,247.00
NCDOT Module Spot Replacement Costs	State Wide	$2,525,764.00	$2,568,076.00	$159,957.40
NCDOT Labor Hours Required	State Wide	101,352.00	101,106.00	828.20
Contractor Total Replacement Costs	State Wide	$145,260,540.00	$145,638,806.00	$1,966,212.40
Contractor Blanket Replacement Costs	State Wide	$103,532,216.00	$103,625,860.00	$425,022.40
Contractor Signal Head Spot Replacement Costs	State Wide	$38,674,972.00	$38,699,080.00	$1,592,874.60
Contractor Module Spot Replacement Costs	State Wide	$3,053,106.00	$3,104,110.00	$193,265.80
NCDOT Supervisory Labor Hours Required	State Wide	32,800.00	32,800.00	-

8.10 Summary of Results

A summary of the results of the various alternatives that have been tested can provide additional insight into their benefits and consequences. First, Table 8.37 provides a reminder of the characteristics of each of the alternatives. Tables 8.38 and 39 each provide average cost estimates over a 30-year period. Table 8.38 shows the per-intersection average cost for each of the alternatives, while Table 8.39 shows the estimated state-wide average cost. Each of these tables includes a Total Cost, Blanket Replacement Cost, Signal Head Spot Replacement Cost, and Module Spot Replacement cost for both NCDOT in-house work and Contracted work.

Table 8.37 Characteristics of LED Module and Signal Head Replacement Strategy Alternatives

Characteristics	Alternatives								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Blanket Replacement *(Full Cycle Length)*	5	-	15	15	15	15	15	15	15
Blanket Replacement *(Replacement Period Length)*	5	-	15	15	5	5	1	1	1
Module Expected Life (years)	5	15	15	15	15	15	15	15	15
Replacement of Signal Head with Modules				X		X		X	
Inflation	0%	0%	0%	0%	0%	0%	0%	0%	3%

These results will be discussed in Chapter 9: Conclusions and Recommendations.

Table 8.38 Summary of Cost Estimate Average Values (per Intersection) Over 30 Years

Metric	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5	Alt. 6	Alt. 7	Alt. 8	Alt. 9
NCDOT Total Replacement Costs	$13,865.44	$10,049.97	$9,088.47	$11,760.70	$7,362.24	$9,596.34	$6,196.86	$8,212.18	$8,718.26
NCDOT Blanket Replacement Costs	$9,515.20	$ -	$3,148.00	$7,718.42	$3,164.54	$7,838.65	$3,156.78	$7,862.64	$4,024.97
NCDOT Signal Head Spot Replacement Costs	$2,949.16	$2,880.92	$2,898.90	$959.02	$2,846.13	$384.79	$2,844.45	$137.62	$4,385.28
NCDOT Module Spot Replacement Costs	$1,401.09	$7,169.05	$3,041.59	$3,083.28	$1,351.57	$1,372.95	$195.62	$211.98	$308.02
NCDOT Labor Hours Required	37.16	-	$12.53	12.58	$12.44	12.43	12.40	12.32	12.36
Contractor Total Replacement Costs	$34,554.37	$11,763.32	$16,667.45	$19,201.91	$14,584.91	$16,636.88	$13,177.70	$14,991.72	$17,714.70
Contractor Blanket Replacement Costs	$29,689.60	$-	$9,872.76	$14,443.22	$9,889.34	$14,563.45	$9,881.58	$14,587.44	$12,625.88
Contractor Signal Head Spot Replacement Costs	$3,171.09	$3,097.02	$3,117.86	$1,031.46	$3,061.74	$413.70	$3,059.64	$147.98	$4,716.46
Contractor Module Spot Replacement Costs	$1,693.72	$8,666.28	$3,676.84	$3,727.22	$1,633.88	$1,659.71	$236.53	$256.27	$372.33
NCDOT Supervisory Labor Hours Required	12.00	-	$4.10	4.10	$4.00	4.00	4.00	4.00	4.00
NCDOT Spot + Contractor Blanket	$34,039.85	$10,049.97	$15,813.25	$18,485.52	$14,087.04	$16,321.19	$12,921.65	$14,937.04	$17,319.18

Table 8.39 Summary of Cost Estimate Average Values (State-Wide) Over 30 Years

Metric	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5	Alt. 6	Alt. 7	Alt. 8	Alt. 9
NCDOT Total Replacement Costs	$113,696,608	$82,409,754	$74,525,454	$96,437,740	$60,370,368	$78,689,988	$50,814,252	$67,339,876	$71,489,732
NCDOT Blanket Replacement Costs	$78,024,640	$-	$25,813,600	$63,291,044	$25,949,228	$64,276,930	$25,885,596	$64,473,648	$33,004,754
NCDOT Signal Head Spot Replacement Costs	$24,183,112	$23,623,544	$23,770,980	$7,863,964	$23,338,266	$3,155,278	$23,324,490	$1,128,484	$35,959,296
NCDOT Module Spot Replacement Costs	$11,488,938	$58,786,210	$24,941,038	$25,282,896	$11,082,874	$11,258,190	$1,604,084	$1,738,236	$2,525,764
NCDOT Labor Hours Required	304,712	-	102,746	103,156	102,008	101,926	101,680	101,024	101,352
Contractor Total Replacement Costs	$283,345,834	$96,459,224	$136,673,090	$157,455,662	$119,596,262	$136,422,416	$108,057,140	$122,932,104	$145,260,540
Contractor Blanket Replacement Costs	$243,454,720	$-	$80,956,632	$118,434,404	$81,092,588	$119,420,290	$81,028,956	$119,617,008	$103,532,216
Contractor Signal Head Spot Replacement Costs	$26,002,938	$25,395,564	$25,566,452	$8,457,972	$25,106,268	$3,392,340	$25,089,048	$1,213,436	$38,674,972
Contractor Module Spot Replacement Costs	$13,888,504	$71,063,496	$30,150,088	$30,563,204	$13,397,816	$13,609,622	$1,939,546	$2,101,414	$3,053,106
NCDOT Supervisory Labor Hours Required	98,400	-	33,620	33,620	32,800	32,800	32,800	32,800	32,800
NCDOT Spot + Contractor Blanket	$279,126,770	$82,409,754	$129,668,650	$151,581,264	$115,513,728	$133,833,758	$105,957,530	$122,483,728	$142,017,276

9.0 Conclusions & Recommendations

This chapter will discuss the results presented in Chapter 8 as well as provide a set of recommendations for transportation planners based on the research conducted throughout this study.

9.1 Conclusions

Conclusions related to the simulation regarding costs and quantities have been drawn from the summary provided in Table 9.1 (a duplication of Table 8.39). For each of the eight alternative replacement strategies used with the simulation, data has been provided containing the estimated costs and quantities of Modules and Signal Heads required over a 30-year period.

Table 9.1 presents distinguishing information for each of the replacement strategy alternatives. It also contains estimated 30-year costs for all the NCDOT maintained intersections in North Carolina. For example, Replacement Strategy Alternative 2 utilized a 15-year replacement period and independent replacement (meaning that only the modules were replaced). Rows four through eight provide cost and labor estimates that assume NCDOT is doing all the work in-house. Note that the labor estimates in row eight are for blanket replacement only. Rows nine through thirteen provide cost and labor estimates assuming that all the work has been contracted out. Note that the estimated labor (row 13) in this case indicates how much time NCDOT employees should expect to be conducting inspections of contracted blanket replacement work. Finally, row fourteen shows a combined cost estimate, which assumes NCDOT will take on all spot replacement (for both modules and signal heads) while blanket replacement will be contracted out. This is a sum of rows six, seven, and ten.

9.1.1 Alternative 1: The Baseline

Alternative 1 represents the pattern of replacement identified as the past practice for NCDOT. Until recently (i.e. 2022), NCDOT was using 5-year warrantied modules at all their locations. The goal was to replace each of these modules when the warranty period ended (at 5 years). Due to the consistent nature of the replacement strategy (one fifth of the modules being replaced each year) the costs per year remain relatively consistent throughout the simulation.

The high frequency of blanket replacement required for this alternative results in the highest costs of any of the alternatives, estimating approximately $279 M in row 14 when NCDOT handles all spot replacement and a contractor is brought in to do all of the blanket replacements (for a 30-year timeframe).

Key Takeaways for the Baseline:

- Provides a baseline for comparison of alternatives 2 through 9
- Very high anticipated replacement costs due to the shorter lifespan
- Large quantity of labor hours required for blanket replacement

9.1.2 Alternative 2: Spot Replacement Only

Alternative 2 utilizes only spot replacement, representing the current practices reported by several Divisions due to lack of personnel or funding. This alternative relies on spot failure of Modules and Signal Heads to keep operations running. One issue with this is that LED Modules actually degrade over time. Thus, sudden spot failure is rare. Due to this degradation, it is possible to have Modules in the field that no longer meet the ITE minimums for safe illuminance at traffic signals.

Compared to the baseline, Alternative 2 provides a 70% decrease in anticipated total costs (compared to NCDOT spot + Contractor blanket). This cost reduction is largely due to the transition to 15-year warrantied modules and the lack of blanket replacement activities. Costs varied throughout this simulation, creating potential difficulty for effective budgeting over time.

Key Takeaways for spot replacement only:

- Mimics current practice in some divisions across NCDOT
- Very low anticipated replacement costs
- Zero labor hours required for blanket replacement
- Must replace modules which are found to fail (go dark)
- Must train technicians to recognize when LED Modules degrade below ITE Minimum Illuminance (darken unacceptably)
- No regular or uniform cost over time

Table 9.1 Summary of Cost Estimate Average Values (State-Wide) Over 30 Years

1	Replacement Strategy	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5	Alt. 6	Alt. 7	Alt. 8	Alt. 9*
2	Replacement Period	*Baseline* (5 years)	Spot Only	15-years		5-years		1-year		1-year
3	Replacement Pattern	Independent	-	Independent	Joint	Independent	Joint	Independent	Joint	Independent
4	NCDOT Total Replacement Costs	$113,696,608	$82,409,754	$74,525,454	$96,437,740	$60,370,368	$78,689,988	$50,814,252	$67,339,876	$71,489,732
5	NCDOT Blanket Replacement Costs	$78,024,640	$-	$25,813,600	$63,291,044	$25,949,228	$64,276,930	$25,885,596	$64,473,648	$33,004,754
6	NCDOT Signal Head Spot Replacement Costs	$24,183,112	$23,623,544	$23,770,980	$7,863,964	$23,338,266	$3,155,278	$23,324,490	$1,128,484	$35,959,296
7	NCDOT Module Spot Replacement Costs	$11,488,938	$58,786,210	$24,941,038	$25,282,896	$11,082,874	$11,258,190	$1,604,084	$1,738,236	$2,525,764
8	NCDOT Labor Hours Required	304,712	-	102,746	103,156	102,008	101,926	101,680	101,024	101,352
9	Contractor Total Replacement Costs	$283,345,834	$96,459,224	$136,673,090	$157,455,662	$119,596,262	$136,422,416	$108,057,140	$122,932,104	$145,260,540
10	Contractor Blanket Replacement Costs	$243,454,720	$-	$80,956,632	$118,434,404	$81,092,588	$119,420,290	$81,028,956	$119,617,008	$103,532,216
11	Contractor Signal Head Spot Replacement Costs	$26,002,938	$25,395,564	$25,566,452	$8,457,972	$25,106,268	$3,392,340	$25,089,048	$1,213,436	$38,674,972
12	Contractor Module Spot Replacement Costs	$13,888,504	$71,063,496	$30,150,088	$30,563,204	$13,397,816	$13,609,622	$1,939,546	$2,101,414	$3,053,106
13	NCDOT Supervisory Labor Hours Required	98,400	-	33,620	33,620	32,800	32,800	32,800	32,800	32,800
14	NCDOT Spot + Contractor Blanket	$279,126,770	$82,409,754	$129,668,650	$151,581,264	$115,513,728	$133,833,758	$105,957,530	$122,483,728	$142,017,276

* Alternative 9 is the only alternative to use a 3% inflation rate. All other alternatives use 0% inflation, providing estimates in today's dollars.

9.1.3 Alternatives 3 & 4: 15 Years of Blanket Replacement

The remainder of the alternative strategies adjust for the new 15-year warrantied modules. Alternatives 3 and 4 implement a 15-year replacement period. This follows the pattern identified in past practice (and the Baseline) of replacing an equal amount of LED Modules each year. By replacing 1/15th of the modules (or modules and signal heads) each year, there is a uniform level of blanket replacement always occurring.

Compared to the baseline, Alternatives 3 and 4 provide 53% and 46% decreases in anticipated costs (for NCDOT spot + Contractor blanket), respectively. This cost reduction is largely due to the transition from a 5-year warranty and replacement cycle to a 15-year warranty and replacement cycle. It is worth noting that when joint replacement of Modules and Signal Heads is implemented, the 30-year cost estimate is increased by $21.9 M, which accounts for the cost of the new Signal Heads. That is approximately a 17% increase in cost over the $129.7 M estimated for individual replacement.

Key Takeaways for a 15-year replacement period:

- High anticipated replacement costs
- Moderate quantity of labor hours required for blanket replacement
- Likely to result in many LED Modules being blanket replaced soon after spot replacement
- Uniform replacement pattern throughout cycle

9.1.4 Alternatives 5 & 6: 5 Years of Blanket Replacement

Alternatives 5 and 6 implement a 5-year replacement period. This follows the pattern identified in past practice (and the Baseline) of replacing all LED Modules within a five-year timeframe. When 1/5th of the modules (or modules and signal heads) are replaced in five years, that leaves ten years of down time when only spot replacement will occur.

Compared to the baseline, Alternatives 4 and 5 provide 59% and 56% decreases in anticipated costs (for NCDOT spot + Contractor blanket), respectively. This reduction is largely due to the transition from a 5-year warranty to a 15-year warranty. Additional decreases can be attributed to shortening the period of active blanket replacement from 15 years to 5 years. By shortening the first replacement cycle, the 5-year alternatives eliminate much of the spot replacement of existing modules that occurred when replacing 1/15th of the modules each year (alternatives 3 & 4). It is worth noting that when joint replacement of Modules and Signal Heads is implemented, the 30-year cost estimate is increased by $18.3 M. That is approximately a 16% increase in cost over the $115.5 M estimated for individual replacement, again, due to the cost of new Signal Heads. Alternatives 5 and 6 anticipate lower 30-year costs than Alternatives 3, 4, and the Baseline (Alternative 1).

Key Takeaways for a 5-year replacement period:

- Moderate anticipated replacement costs
- Low quantity of labor hours required for blanket replacement
- Replacement pattern mimics ideal current practices

9.1.5 Alternatives 7, 8, & 9: 1 Year of Blanket Replacement

9.1.5.1 Alternatives 7 & 8

Alternatives 7 and 8 implement a 1-year replacement period. With all modules (or modules and signal heads) replaced in the first year of each cycle, that leaves a fourteen-year period where only spot replacement will occur.

Compared to the baseline, Alternatives 7 and 8 provide 62% and 52% decreases in anticipated costs (for NCDOT spot + Contractor blanket), respectively. This cost reduction is largely due to the transition from a 5-year warranty and replacement cycle to a 15-year warranty and replacement cycle, but by shortening the replacement period to one year, these alternatives essentially eliminate the spot replacement of existing modules. It is worth noting that when joint replacement of Modules and Signal Heads is implemented, the 30-year cost estimate is increased by $16.5 M. That is approximately a 16% increase in cost over the $106 M estimated for individual replacement. Alternatives 7 and 8 anticipate the lowest 30-year costs of all the replacement alternatives. It should also be noted that implementing a 1-year blanket replacement strategy avoids much of the increase in cost that is likely to be seen due to inflation over time.

Key Takeaways for a 1-year replacement period:

- Low anticipated replacement costs
- Low quantity of labor hours required for blanket replacement
- Proof of replacement by documentation
- Avoid most inflation cost increases

9.1.5.2 Alternative 9

Alternatives 9 is unique in that it utilizes a 3% inflation rate over the 30-year timeframe of the simulation. This was implemented, in part, to show that the simulation is capable of such calculations. It was also implemented to remind the readers of this report that the remainder of the alternatives do not incorporate inflation into their cost estimates. Thus, all of the costs are given in today's dollars.

The reader should note that it is not a true comparison to look at Alternative 9 next to the Baseline costs, because the Baseline estimates do not account for inflation. It can only be compared to Alternative 7. However, it is worth noting that the estimated cost of Alternative 9 is still less than half of the estimated Baseline cost. That should be considered a conservative estimate of cost savings, as the estimated costs for the Baseline would increase were the scenario to be run using 3% inflation.

9.2 Recommendations

Recommendations have been divided into the following categories: replacement scenario, data tracking and management, and future work. Each of those categories discusses the recommendations resulting from this research in greater detail.

9.2.1 Replacement Scenario

Based on the results of the simulation, the research team recommends that Replacement Scenario Alternative 7 be considered as a high priority option for implementation. This alternative utilizes a 1-year replacement period and yields the lowest estimated cost over a 30-year period, also avoiding much of the anticipated inflation. Were NCDOT to implement this strategy in-house, the estimated cost is only $50.8 M over 30 years. However, that would also require 101,680 labor hours over that same time. Remember that a 40-hour employee working 50 weeks of the year is only available for 2,000 labor hours annually. If a Contractor is brought in to complete the blanket replacement portion of the work, the cost increases to $105.6 M over 30 years, resulting in only 32,800 NCDOT labor hours being required. NCDOT labor will still be required due to the NCDOT inspections of contractor work that must take place.

The distribution of these costs is important to understand. A one-year replacement period will generate a high cost in the first year of the cycle, with significantly lower costs in years two through fifteen. Figure 9.1 provides a visual representation of what the cost required throughout a thirty-year timeframe are estimated to be for Alternative 7. Years 1 and 16 require a large influx of funds (almost $42 M), however every other year is only expected to require approximately $1 M for ongoing spot replacement.

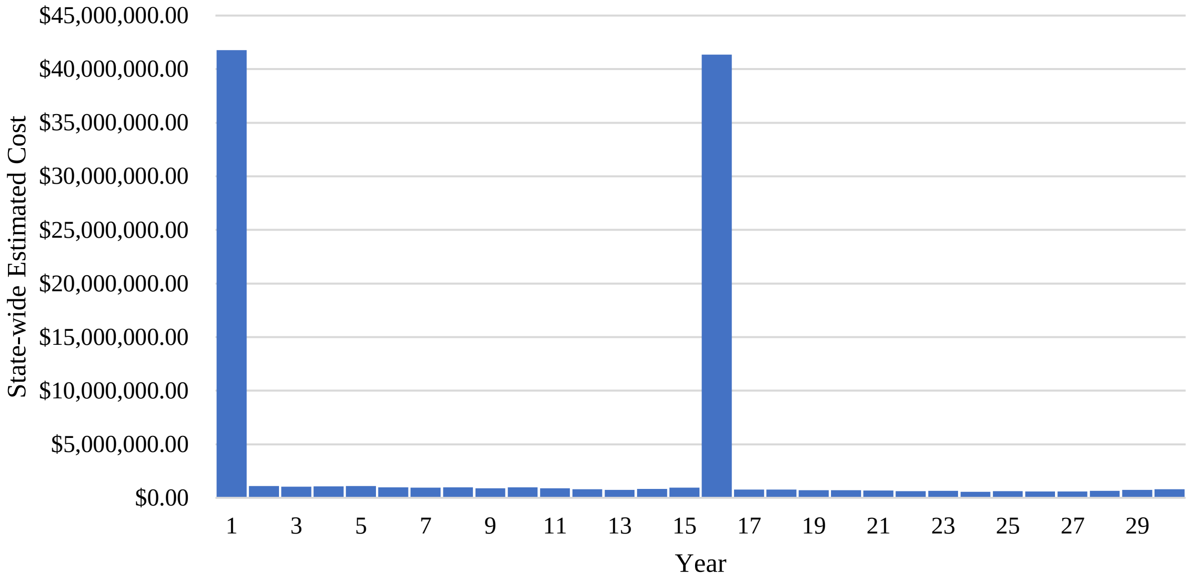


Figure 9.1 Estimated State-Wide Cost of Independent 1-year Replacement (Over 30 Years)

Additionally, NCDOT could consider the benefits of using a joint replacement strategy (Alt. 8) for the first cycle to get all new Signal Heads in the field, followed by an independent replacement strategy (Alt. 7) for the second cycle. Signal Heads are expected to last up to 30 years, making a joint replacement in each cycle redundant. However, were all Signal Heads to be replaced in year 1, it would be expected that they should not need to be replaced again, en masse, until year 31. This would increase the initial cost of replacement slightly, but long-term benefits are expected in lower costs over the full 30 years.

Our ultimate recommendation would be to achieve a 1-year total replacement completing a rapid transition to the new 15-year module technology and replacing all signal heads. This would free up NCDOT personnel to focus only on spot replacement and allow more of their time to be devoted to other critical work activities. While this option requires a large one-time funding infusion, NCDOT could be confident in providing the most up to date signal lighting at a reasonable cost for the next 15 to 20 years.

9.2.2 Data Tracking and Management

NCDOT currently has a detailed database for the tracking of intersections and activities related to traffic signal operations (DTS, see Section 3.1 for a full description of the data used from DTS for this project). However, the currently recorded Signal Head and LED data is used solely to inventory the number of items at an intersection, if it is recorded by a Division. All maintenance and operations events are recorded via Event tracking (a separate function within the database). There are two main adjustments recommended for replacement data tracking,

A. Begin recording the installation date directly on Signal Heads and/or in DTS database.
B. Reevaluate and clarify the set of Action Codes available for use in the Events data.

When it comes to data management there are, again, two main recommendations:

C. Set the level of detail expected to the Signal Head, rather than the Modules or the Intersection.
D. Utilize the large amounts of data recorded in DTS to develop the annual expenditure reports.

9.2.2.1 Record of Installation Dates

By recording the date of installation of the Signal Head and the last known blanket replacement of Modules, whether that be in a database (highly recommended) or even on the head itself, NCDOT will be able to track their failure dates, age at replacement, and deterioration rates over time. Using this record, NCDOT may be able to asses Module and Signal Head performance (see 9.2.3.1, 9.2.3.2), implement a grace period for replacements (see 9.2.3.3), and assess differences between manufacturers (see 9.2.3.2).

There will be instances in which spot replacement of a Signal Head will occur, then only a year or two later, that same Signal Head will be scheduled for blanket replacement. As the heads should last 30 years (and the LED Modules 15) replacing these items at an early age greatly undermines the life of the asset, and increases costs to NCDOT in materials and labor at the same time. A grace period solves this problem. See section 9.2.3.3 below for further discussion on implementation of a grace period.

Were Signal Head and Module installation tracking to occur within DTS, the addition of a Signal Head identifier would be required to maintain organization of data. Placing the installation dates directly on the Signal Head is another option that could be implemented in the field.

9.2.2.2 Clarify Action Codes

There is a set of eleven Action Codes used within DTS to describe events related to LED Module and Signal Head operations. Throughout this research, it has become clear that the codes are used somewhat inconsistently. After discussing the action codes with NCDOT personnel, it came to our attention that certain codes were used for a few years, then others became more standard and the former declined in use (see Section 4.2.2). That could be because the LED Modules that are in place have been in place for a long time, or it could be because the codes are not being used effectively within the database. The recommendation moving forward would be to reevaluate the codes that exist and develop a shorter set of action codes for use moving forward that match work done with these new traffic signal products. By creating a set of Action Codes that reflect the work that happens (all LED Modules replaced, a single LED Module replaced, a Signal Head replaced), NCDOT will be able to better use their data in the future to plan and compare to anticipated results of previous plans.

Once these codes have been developed, NCDOT can hold state-wide training or seminar on the proper use of these codes for future data collection.

9.2.2.3 Expecting Data for Signal Heads

Due to the large quantity of LED Modules that are located in each Division, managing data for the Signal Heads alone may be more reasonable and realistic. While there is a pervasive mindset right now that more data is better – if the data is collected inconsistently, or never ends up being used, then a more prudent use of everyone’s time would be to reduce the amount of data collected and spend some of that ‘saved’ time on other tasks. Much of this research was completed using data at the intersection level. However, to accurately assess whether the replacement strategy put in place is effective, a greater level of detail will be required.

9.2.2.4 Utilize DTS for Expenditure Reports

DTS currently tracks the labor hours and activities completed by technicians to inspect, service, and replace Signal Heads and Modules at every intersection across the state. That data is already available and could be used to generate more detailed annual expense reports by assigning each activity an appropriate cost. The expense reports currently provided to the main office report expenditures at a high level and do not evaluate the quantity of spot replacements, or the overall cost of material or labor needed for one year of replacement work. Because this data is already available, it is recommended that NCDOT utilize it to better understand how their funds are being prioritized and what areas may need additional support.

9.2.3 Future Work

Moving forward from this research, there are eight areas of work which are recommended for additional, future research to aid NCDOT in future decision-making regarding traffic signals.

A. Collection of Illuminance data over time.
B. Collection of Spot Replacement rates over time.
C. Further development of the simulation to incorporate the effects of a grace period.
D. Further development of the simulation to incorporate joint replacement in the first cycle and independent replacement in the following cycle.
E. Determining the impact of Cleaning the LED Modules throughout their life.
F. Further analysis of NCDOT traffic signal contracts across the Divisions.
G. Application of research methods on other types of NCDOT lighting.
H. Application of research methods on other high-volume assets.

9.2.3.1 Illuminance Data

One of the original goals of this research when it was proposed to NCDOT was to determine the actual field-life of an LED Module. Due to industry changes (from a 5-year warranty to a 15-year warranty), the scope of this research evolved to focus on efficiency of field replacement operations rather than on field lifespan. However, as 15-year warrantied modules are being installed, NCDOT has the opportunity to track illuminance data in-house, thus enabling the determination of a true field lifespan. This is a long-term project, as the new LED Modules are not anticipated to fail for over a decade.

Sample testing of the luminosity of a subset of NCDOT's LED Modules throughout their useful life could provide valuable information regarding their true lifespan. For instance, if a sample of LED Modules is tested every two years from their installation date, by year 14 the luminosity curve produced by that data will indicate whether the module is truly expected to fail in year 15. If the measured luminosity of the sampled LED Modules is well above ITE minimums in year 14, the service life of those modules could be extended beyond the 15-year warrantied lifespan. If an extension of service is found to be suitable, frequency of luminosity measurements should be increased to occur at least annually until the LED Modules are found to fall below ITE minimum thresholds. The year in which these modules fall below acceptable illuminance levels will indicate the true service lifespan of the 15-year warrantied LED Modules. The advantage of such testing is twofold: to discover the true lifespan and to delay the next replacement cycle based on that lifespan if it is longer than 15 years.

9.2.3.2 Spot Replacement Data.

Because the failure curves utilized within the simulation were based on information provided by LED Module manufacturers and on anecdotal data from NCDOT personnel, improvements to the simulation could be made if spot replacement data is collected over time.

Spot data collection would be simple if the 1-year replacement strategy is used in the field, however, data could be collected no matter which strategy is implemented. Simply put, the age of each LED Module and Signal Head that are found to need spot replacement should be recorded. Over time, this data will provide NCDOT with spot failure curves which are accurate to the state and thus, enhance model predictions. These curves can be used to further improve and validate the simulation.

If LED Modules are being purchased from multiple vendors, spot replacement rates for each vendor may be useful in assessing future purchases. Vendors are providing warranties for 15-years (see Section 6.3.2), however, if the LED Modules do not all last 15-years and NCDOT has record of this, there may be standing to negotiate an improved purchasing agreement.

9.2.3.3 Grace Period

Currently within the model, there are cases in which the blanket replacement process replaces 'new' Signal Heads and Modules (installed within the last year or two) due to program logic. Informational interviews suggested that this can occur in the field. At this time, NCDOT data recording and tracking does not occur at a level granular enough to prevent this from happening. However, dating heads and modules and implementing a grace period would do so.

With further development of the model logic, a grace period could be implemented both in field operations and in the model, allowing the user to input their own threshold, or to identify an optimal grace period. For example, if the grace period (or replacement threshold) were three years – if an LED Module or Signal Head were spot replaced in year 2, then scheduled for blanket replacement in year 4, that LED Module of Signal Head would be left in place and not replaced during the blanket replacement cycle. It would then be two years older than others in the blanket replacement group but it would still be within the 18 to 20-year lifespan of satisfactory performance the researchers expect. In fact, our recommendation is to utilize a grace period in the field even if one is not incorporated into the model.

Implementing a grace period could further the efficiency of NCDOT's replacement strategy by reducing the quantity of assets that are replaced within their first few years of service life.

9.2.3.4 Combination Joint and Independent Replacement

Briefly mentioned in Section 9.2.1, it is recommended that NCDOT consider the benefit that may result from utilizing a joint replacement plan during the first blanket replacement cycle, then following it with an independent replacement cycle. The initial joint replacement cycle will ensure that all Signal Heads and Modules in the field are new. However, anecdotal data suggests that Signal Heads last 30 years, double that of the replacement cycles used when modeling the scenarios. Therefore, there would be no need to replacement Signal Heads at the start of the second replacement cycle, only having aged 15 years. Instead, utilizing an independent blanket replacement strategy in the following cycle would let them spend their full 30-years of useful life in the field.

9.2.3.5 Cleaning the LED Modules

New LED Modules will be in-service in the field for approximately 15-years. After several years in the field, there is the possibility that build up on the lens of the module may impact the illuminance experienced by the driver (Urbanik 2008) effectively shortening the service life of the module. Cleaning of the LED Modules periodically during their life may lead to a longer service life. A study of doing so could be completed along with the previously recommended gathering of illuminance data over time and using a subset of the same sample.

9.2.3.6 Further Analysis of Contracts

Contracts between NCDOT and outside companies were discussed in detail in Section 4.1.4.2. The results of analyzing these contracts show they vary widely across the Divisions. There does not appear to be consistency in pricing among the contracts for which NCDOT provides materials, nor for the contracts where materials are provided by the contractor. If NCDOT is able to perform future research into the finer points of these contracts, the department may be able to standardize prices of contracted work across the state. That examination was beyond the scope of this research, but is recommended in order to ensure that LED Module and Signal Head maintenance is occurring with optimal financial efficiency for NCDOT.

9.2.3.7 Other Types of Lighting

Knowing that NCDOT utilizes many types of lighting across the department (not only in signals) it is recommended that additional research be conducted into the efficiency of replacement operations for those additional types of lighting. These might include highway lighting and even vehicles lights utilized in NCDOT's fleet vehicles.

9.2.3.8 Other High-Volume Assets

LED Modules and Signal Heads are two of many high-volume assets found in a transportation system. At many intersections one can also find cameras, sensors of many kinds, and signal cabinets and their components. By understanding the optimal replacement strategies for each of these asset types, NCDOT could improve the efficiency of their signal systems even more. Similar research as that presented here could be conducted on any of these high-volume assets.

9.3 Closure

With the recommendations provided comes an opportunity to initiate an impactful, but simple, LED Module and Signal Head management process. Implementation of which will enable NCDOT to serve as a national model in dealing with safety critical assets.

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Appendices

Appendix A: LED Degradation Models Available in Literature

Table A.1 LED Degradation Models Available in Literature

Model ID	Color	Brand	Source ID	Data Source	Data Year	Intersections Studied	(n) for total project	Collection Method	Regression Model	Units	Used for Lifespan Estimation?
1	GC	GE	Schmidt, Long 2011	MoDOT	2009	20	328	Collect illuminance intensity from a research vehicle	$y = -28.139x + 386.6$	Age vs Candelas	Yes
2	GC	Dialight	Schmidt, Long 2011	MoDOT	2009	20	328	Collect illuminance intensity from a research vehicle	$y = -32.415x + 531.07$	Age vs Candelas	Yes
3	GA	GE	Schmidt, Long 2011	MoDOT	2009	20	328	Collect illuminance intensity from a research vehicle	$y = -9.8846x + 116.46$	Age vs Candelas	Yes
4	GA	Dialight	Schmidt, Long 2011	MoDOT	2009	20	328	Collect illuminance intensity from a research vehicle	$y = -12.681x + 154.61$	Age vs Candelas	Yes
5	RC	GE	Schmidt, Long 2011	MoDOT	2009	20	328	Collect illuminance intensity from a research vehicle	$y = -6.8846x + 507.27$	Age vs Candelas	Not Enough Data
6	RC	Dialight	Schmidt, Long 2011	MoDOT	2009	20	328	Collect illuminance intensity from a research vehicle	$y = -10.932x + 298.37$	Age vs Candelas	Not Enough Data
7	YC	Dialight	Schmidt, Long 2011	MoDOT	2009	20	328	Collect illuminance intensity from a research vehicle	$y = -22.332x + 298.37$	Age vs Candelas	Not Enough Data

Model ID	Color	Brand	Source ID	Data Source	Data Year	Intersections Studied	(n) for total project	Collection Method	Regression Model	Units	Used for Lifespan Estimation?
8	YA	GE	Schmidt, Long 2011	MoDOT	2009	20	328	Collect illuminance intensity from a research vehicle	$y = 33.366x + 274.37$	Age vs Candelas	Yes
9	YA	Dialight	Schmidt, Long 2011	MoDOT	2009	20	328	Collect illuminance intensity from a research vehicle	$y = -5.9974x + 115.56$	Age vs Candelas	Yes
10	GC	GE	Schmidt	MoDOT	2011	21	4400	Collect illuminance intensity from a research vehicle	$y = -1.0791x + 36.757$	Age vs Lux	Yes
11	YC	GE	Schmidt	MoDOT	2011	21	4400	Collect illuminance intensity from a research vehicle	$y = -4.0331x + 64.453$	Age vs Lux	Yes
12	YC	Dialight	Schmidt	MoDOT	2011	21	4400	Collect illuminance intensity from a research vehicle	$y = -1.9093x + 48.38$	Age vs Lux	Not Enough Data
13	RC	Dialight	Schmidt	MoDOT	2011	21	4400	Collect illuminance intensity from a research vehicle	$y = -1.1815x + 34.878$	Age vs Lux	Yes
14	GA	GE	Schmidt	MoDOT	2011	21	4400	Collect illuminance intensity from a research vehicle	$y = -1.7137x + 18.389$	Age vs Lux	Yes
15	GA	Dialight	Schmidt	MoDOT	2011	21	4400	Collect illuminance intensity from a research vehicle	$y = -0.8045x + 16.53$	Age vs Lux	Yes

Model ID	Color	Brand	Source ID	Data Source	Data Year	Intersections Studied	(n) for total project	Collection Method	Regression Model	Units	Used for Lifespan Estimation?
16	YA	GE	Schmidt	MoDOT	2011	21	4400	Collect illuminance intensity from a research vehicle	$y = -0.2469x + 12.515$	Age vs Lux	Yes
17	YA	Dialight	Schmidt	MoDOT	2011	21	4400	Collect illuminance intensity from a research vehicle	$y = -1.1325x + 19.831$	Age vs Lux	Yes
18	RC	GE	Arhin	DDOT, Sammat Engineering	2011	30	120	Used Spectra Candela III Traffic Signal Light Tester to mimic lab conditions	-11.98 candelas / year; no intercept or equation provided. Found std dev to be 3.29	N/A	Yes
19	GC	GE	Arhin	DDOT; Sammat Engineering	2011	30	120	Used Spectra Candela III Traffic Signal Light Tester to mimic lab conditions	-25.78 candelas / year; no intercept or equation provided. Found std dev to be 3.22	N/A	Yes
20	YC	GE	Arhin	DDOT; Sammat Engineering	2011	30	120	Used Spectra Candela III Traffic Signal Light Tester to mimic lab conditions	-90.31 candelas / year; no intercept or equation provided. Found std dev to be 13.50	N/A	Yes

Appendix B: LED Module Product Specifications Summary

Manufacturer	Product #/ID	Size	Style	Color	Dominate Wavelength	Wattage	Lumosity/ maintained intensity	Warranty (yrs)	Certifications
Dialight	433-1110-003XL15	8"	Circular	Red	625	7	165	15	ITE Compliant
Dialight	433-1170-003XL15	8"	Circular	Red	625	7	165	15	ITE Compliant
Dialight	433-3130-901XL15	8"	Circular	Yellow	590	7	410	15	ITE Compliant
Dialight	433-3170-901XL15	8"	Circular	Yellow	590	7	410	15	ITE Compliant
Dialight	433-2120-001XL15	8"	Circular	Green	500	7	215	15	ITE Compliant
Dialight	433-2170-001XL15	8"	Circular	Green	500	7	215	15	ITE Compliant
Dialight	433-1210-003XL15	12"	Circular	Red	625	7	365	15	ITE Compliant
Dialight	433-1270-003XL15	12"	Circular	Red	625	7	365	15	ITE Compliant
Dialight	433-3230-901XL15	12"	Circular	Yellow	590	13	910	15	ITE Compliant
Dialight	433-3270-901XL15	12"	Circular	Yellow	590	13	910	15	ITE Compliant
Dialight	433-2220-001XL15	12"	Circular	Green	500	7	475	15	ITE Compliant
Dialight	433-2270-001XL15	12"	Circular	Green	500	7	475	15	ITE Compliant
Dialight	432-1314-001X0D15	12"	Arrow	Red	625	7	58.4	15	ITE Compliant
Dialight	432-1374-001X0D15	12"	Arrow	Red	625	7	58.4	15	ITE Compliant
Dialight	431-3334-901X0D15	12"	Arrow	Yellow	590	14	145.6	15	ITE Compliant
Dialight	431-3374-901X0D15	12"	Arrow	Yellow	590	14	145.6	15	ITE Compliant
Dialight	432-2324-001X0D15	12"	Arrow	Green	500	8	76	15	ITE Compliant
Dialight	432-2374-001X0D15	12"	Arrow	Green	500	8	76	15	ITE Compliant
GE	DR4-RTFB-71C	200mm	Circular	Red	n/a	8.9	400 - 800	n/a	interek ETL Verified compliant
GE	DR4-YTFB-71C	200mm	Circular	Yellow	n/a	7.8	400 - 800	n/a	interek ETL Verified compliant
GE	DR4-GTFB-71C	200mm	Circular	Green	n/a	9.4	400 - 800	n/a	interek ETL Verified compliant
GE	DR6-RTFB-71C	300mm	Circular	Red	n/a	9.6	400 - 800	n/a	interek ETL Verified compliant

Manufacturer	Product #/ID	Size	Style	Color	Dominate Wavelength	Wattage	Lumosity/ maintained intensity	Warranty (yrs)	Certifications
GE	DR6-YTFB-71C	300mm	Circular	Yellow	n/a	7.8	400 - 800	n/a	interek ETL Verified compliant
GE	DR6-GTFB-71C	300mm	Circular	Green	n/a	8.1	400 - 800	n/a	interek ETL Verified compliant
GE	DR2 Series	100mm	Circular	n/a	n/a	n/a	100	n/a	interek ETL Verified compliant
GE	DR4-RTFB-71C-016	200mm	Circular	Red	n/a	14	400 - 800	n/a	interek ETL Verified compliant
GE	DR4-YTFB-71C-016	200mm	Circular	Yellow	n/a	14	400 - 800	n/a	interek ETL Verified compliant
GE	DR4-GTFB-71C-016	200mm	Circular	Green	n/a	14	400 - 800	n/a	interek ETL Verified compliant
GE	DR2-RCFB-40U	100mm	Circular	Red	618-633	3	100	5	interek ETL Verified compliant
GE	DR2-YCFB-40U	100mm	Circular	Yellow	586-596	3	100	5	interek ETL Verified compliant
GE	DR2-GCFB-40U	100mm	Circular	Green	495-512	3	100	5	interek ETL Verified compliant
GE	DR6-RTAAN-17A	12"	Arrow	Red	626	5	58	n/a	interek ETL Verified compliant
GE	DR6-YTAAN-17A	12"	Arrow	Yellow	589	9	146	n/a	*not interek ETL Verified compliant
GE	DR6-YTAAN-17A-YX	12"	Arrow	Yellow	589	6	146	n/a	interek ETL Verified compliant
GE	DR6-GTAAN-17A	12"	Arrow	Green	500	5	76	n/a	interek ETL Verified compliant
GE	DR6-GCAAN-17A	12"	Arrow	Green	500	5	76	n/a	interek ETL Verified compliant
GE	DR6-RTAAN-17A	12"	Arrow	Red	625	6.5	59	n/a	interek ETL Verified compliant
GE	DR6-RTAAN-VLA	12"	Arrow	Red	625	6.5	59	n/a	interek ETL Verified compliant
GE	DR6-YTAAN-VLA	12"	Arrow	Yellow	589	6.5	146	n/a	interek ETL Verified compliant

Manufacturer	Product #/ID	Size	Style	Color	Dominate Wavelength	Wattage	Lumosity/ maintained intensity	Warranty (yrs)	Certifications
GE	DR6-YCAAN-VLA	12"	Arrow	Yellow	589	6.5	146	n/a	interek ETL Verified compliant
GE	DR6-GTAAN-VLA	12"	Arrow	Green	500	6.5	76	n/a	interek ETL Verified compliant
GE	DR6-GCAAN-VLA	12"	Arrow	Green	500	6.5	76	n/a	interek ETL Verified compliant
GE	DR4-RTFB-VLA	8"	Circular	Red	628	6.4	165	n/a	interek ETL Verified compliant
GE	DR4-RCFB-VLA	8"	Circular	Red	628	6.4	165	n/a	interek ETL Verified compliant
GE	DR4-YZFB-VLA	8"	Circular	Yellow	588	10.9	410	n/a	interek ETL Verified compliant
GE	DR4-YTFB-VLA	8"	Circular	Yellow	589	7.9	410	n/a	interek ETL Verified compliant
GE	DR4-YTFB-VLA	8"	Circular	Yellow	589	7.9	410	n/a	interek ETL Verified compliant
GE	DR4-GTFB-VLA	8"	Circular	Green	499	7.3	215	n/a	interek ETL Verified compliant
GE	DR4-GCFB-VLA	8"	Circular	Green	499	7.3	215	n/a	interek ETL Verified compliant
GE	DR6-RTFB-VLA	12"	Circular	Red	625	6.7	365	n/a	interek ETL Verified compliant
GE	DR6-RCFB-VLA	12"	Circular	Red	625	6.7	365	n/a	interek ETL Verified compliant
GE	DR6-YZFB-VLA	12"	Circular	Yellow	588	10.9	910	n/a	interek ETL Verified compliant
GE	DR6-YTFB-VLA	12"	Circular	Yellow	589	9.9	910	n/a	interek ETL Verified compliant
GE	DR6-YCFB-VLA	12"	Circular	Yellow	589	9.9	910	n/a	interek ETL Verified compliant
GE	DR6-GTFB-VLA	12"	Circular	Green	501	9.5	475	n/a	interek ETL Verified compliant
GE	DR6-GCFB-VLA	12"	Circular	Green	501	9.5	475	n/a	interek ETL Verified compliant

Manufacturer	Product #/ID	Size	Style	Color	Dominate Wavelength	Wattage	Lumosity/ maintained intensity	Warranty (yrs)	Certifications
GE	DR4-RTFB-77A	8"	Circular	Red	626	6.3	626	n/a	interek ETL Verified compliant
GE	DR4-RCFB-77A	8"	Circular	Red	626	6.3	626	n/a	interek ETL Verified compliant
GE	DR4-YTFB-77A	8"	Circular	Yellow	589	9.5	589	n/a	interek ETL Verified compliant
GE	DR4-YCFB-77A	8"	Circular	Yellow	589	9.5	589	n/a	interek ETL Verified compliant
GE	DR4-GTFB-77A	8"	Circular	Green	503	6.5	503	n/a	interek ETL Verified compliant
GE	DR4-GCFB-77A	8"	Circular	Green	503	6.5	503	n/a	interek ETL Verified compliant
GE	DR6-RTFB-77A	12"	Circular	Red	625	6.7	625	n/a	interek ETL Verified compliant
GE	DR6-RCFB-77A	12"	Circular	Red	625	6.7	625	n/a	interek ETL Verified compliant
GE	DR6-YTFB-77A	12"	Circular	Yellow	589	10.5	589	n/a	interek ETL Verified compliant
GE	DR6-YCFB-77A	12"	Circular	Yellow	589	10.5	589	n/a	interek ETL Verified compliant
GE	DR6-GTFB-77A	12"	Circular	Green	502	9.1	502	n/a	interek ETL Verified compliant
GE	DR6-GCFB-77A	12"	Circular	Green	502	9.1	502	n/a	interek ETL Verified compliant
Leotek	TSL-12BM-LD-A1	12"	Arrow	Yellow	589	7	146	5	*ITE VTCSH Compliance
Leotek	TSL-12BM-LD-A1	12"	Arrow	Green	500	6.2	76	5	*ITE VTCSH Compliance
Leotek	TSL-12YYBM-LD-A1	12"	Arrow	Yellow	589	6.2	130	5	*ITE VTCSH Compliance
Leotek	TSL-12RA-IL6-L1-P3	12"	Arrow	Red	626	3.6	58.4	5	*ITE VTCSH Compliance
Leotek	TSL-12YA-IL6-L1-P3	12"	Arrow	Yellow	589	7.2	145.6	5	*ITE VTCSH Compliance

Manufacturer	Product #/ID	Size	Style	Color	Dominate Wavelength	Wattage	Lumosity/ maintained intensity	Warranty (yrs)	Certifications
Leotek	TSL-12GA-IL6-L1-P3	12"	Arrow	Green	500	4.8	76	5	*ITE VTCSH Compliance
Leotek	TSL-08RA-IL6-B1-P3	8"	Arrow	Red	626	2.4	n/a	5	*ITE VTCSH Compliance
Leotek	TSL-08YA-IL6-B1-P3	8"	Arrow	Yellow	589	4.3	n/a	5	*ITE VTCSH Compliance
Leotek	TSL-08GA-IL6-B1-P3	8"	Arrow	Green	500	2.2	n/a	5	*ITE VTCSH Compliance
Leotek	T05W-A-6100	5"	Circular	White	n/a	7	n/a	5	*ITE VTCSH Compliance
Leotek	T05R-A-6100	5"	Circular	Red	626	7	n/a	5	*ITE VTCSH Compliance
Leotek	T05Y-A-6100	5"	Circular	Yellow	589	12	n/a	5	*ITE VTCSH Compliance
Leotek	T05G-A-CA01	5"	Circular	Green	500	7	n/a	5	*ITE VTCSH Compliance
Leotek	TSL-EV08R-HPE-A1	8"	Circular	Red	626	7	165	5	*ITE VTCSH Compliance
Leotek	TSL-EV08Y-HPE-A1	8"	Circular	Yellow	589	11	410	5	*ITE VTCSH Compliance
Leotek	TSL-EV08G-HPE-A1	8"	Circular	Green	500	10	215	5	*ITE VTCSH Compliance
Leotek	TSL-EV12R-HPE-A1	12"	Circular	Red	626	7	365	5	*ITE VTCSH Compliance
Leotek	TSL-EV12Y-HPE-A1	12"	Circular	Yellow	589	21	910	5	*ITE VTCSH Compliance
Leotek	TSL-EV12G-HPE-A1	12"	Circular	Green	500	8	475	5	*ITE VTCSH Compliance
Leotek	TSL-12Y-LX-IL6-B1-P3-ULP	12"	Circular	Yellow	589	4.5	410	5	*ITE VTCSH Compliance
Leotek	TSL-08R-LX-IL6-L1-P3	8"	Circular	Red	626	2.8	165	5	*ITE VTCSH Compliance
Leotek	TSL-08Y-LX-IL6-L1-P3	8"	Circular	Yellow	589	4.8	410	5	*ITE VTCSH Compliance

Manufacturer	**Product #/ID**	**Size**	**Style**	**Color**	**Dominate Wavelength**	**Wattage**	**Lumosity/ maintained intensity**	**Warranty (yrs)**	**Certifications**
Leotek	TSL-08G-LX-IL6-L1-P3	8"	Circular	Green	500	3.3	215	5	*ITE VTCSH Compliance
Leotek	TSL-12R-LX-IL6-L1-P3	12"	Circular	Red	626	5	365	5	*ITE VTCSH Compliance
Leotek	TSL-12Y-LX-IL6-L1-P3	12"	Circular	Yellow	589	8.9	910	5	*ITE VTCSH Compliance
Leotek	TSL-12G-LX-IL6-L1-P3	12"	Circular	Green	500	6.7	475	5	*ITE VTCSH Compliance
Leotek	TSL-08R-LX-IL6-B1-P3	8"	Circular	Red	626	2.4	165	5	*ITE VTCSH Compliance
Leotek	TSL-08Y-LX-IL6-B1-P3	8"	Circular	Yellow	589	4.3	410	5	*ITE VTCSH Compliance
Leotek	TSL-08G-LX-IL6-B1-P3	8"	Circular	Green	500	3.4	215	5	*ITE VTCSH Compliance
Leotek	TSL-12R-LX-IL6-B1-P3	12"	Circular	Red	626	4.4	365	5	*ITE VTCSH Compliance
Leotek	TSL-12Y-LX-IL6-B1-P3	12"	Circular	Yellow	589	10	910	5	*ITE VTCSH Compliance
Leotek	TSL-12Y-LX-IL6-B1-P3-ULP	12"	Circular	Yellow	589	4.5	410	5	*ITE VTCSH Compliance
Leotek	TSL-12G-LX-IL6-B1-P3	12"	Circular	Green	500	6.6	475	5	*ITE VTCSH Compliance
Leotek	TSL-08R-LX-IL6-A1-P3	8"	Circular	Red	626	6	165	5	*ITE VTCSH Compliance
Leotek	TSL-08Y-LX-IL6-A1-P3	8"	Circular	Yellow	589	6	410	5	*ITE VTCSH Compliance
Leotek	TSL-08G-LX-IL6-A1-P3	8"	Circular	Green	500	6	215	5	*ITE VTCSH Compliance
Leotek	TSL-12R-LX-IL6-A1-P3	12"	Circular	Red	626	6.2	365	5	*ITE VTCSH Compliance
Leotek	TSL-12Y-LX-IL6-A1-P3	12"	Circular	Yellow	589	9.7	910	5	*ITE VTCSH Compliance
Leotek	TSL-12G-LX-IL6-A1-P3	12"	Circular	Green	500	6.7	475	5	*ITE VTCSH Compliance

Manufacturer	Product #/ID	Size	Style	Color	Dominate Wavelength	Wattage	Lumosity/ maintained intensity	Warranty (yrs)	Certifications
Leotek	TSL-12RA-DT-A1	12"	Arrow	Red	626	6	58.4	15	*ITE VTCSH Compliance
Leotek	TSL-12YA-DT-A1	12"	Arrow	Yellow	589	10	145.6	15	*ITE VTCSH Compliance
Leotek	TSL-12GA-DT-A1	12"	Arrow	Green	500	6.8	76	15	*ITE VTCSH Compliance
Leotek	TSL-08R-DT-A1	8"	Circular	Red	626	6.1	165	15	*ITE VTCSH Compliance
Leotek	TSL-08Y-DT-A1	8"	Circular	Yellow	589	6.1	410	15	*ITE VTCSH Compliance
Leotek	TSL-08G-DT-A1	8"	Circular	Green	500	6.2	215	15	*ITE VTCSH Compliance
Leotek	TSL-12R-DT-A1	12"	Circular	Red	626	6.2	365	15	*ITE VTCSH Compliance
Leotek	TSL-12Y-DT-A1	12"	Circular	Yellow	589	7.9	910	15	*ITE VTCSH Compliance
Leotek	TSL-12G-DT-A1	12"	Circular	Green	500	6.1	475	15	*ITE VTCSH Compliance

Appendix C: Current Division Replacement Contract Excerpts

This document contains individual evaluation of the available On-Call Signals Replacement Contracts for NCDOT Divisions. Each division is evaluated independently, with notes on the specifics of the contracts and the line-item prices included (Sections 1 – 9).

Division 1

This document is from Matt Carlisle

- The contract provided is not executed and there is no bid shown, only the outline for what the bid should look like.
- No costs/prices are provided in this document.

Division 3

These two documents are from Matt Carlisle

- The contracts provided is not executed and there is no bid shown, only the outline for what the bid should look like.
- No costs/prices are provided in the documents.

Division 5

3.1 D5POC130 – Contract – Carolina Power and Signalization

SIGNALS AND INTELLIGENT TRANSPORTATION SYSTEMS pg. 84

- The section where I expect to find the information we are looking for.

2. Signal Heads

2.1 Materials

- Specs provided here, no quantities or prices.

Purchase Order Contract Bid Form

Table C.1: Division 5 Contract Bid Excerpts (Carolina Power)

Item	Sect	Description	Qty	Unit	Unit Price ($)	Amount Bid ($)
1	SP	72 HOUR EMERGENCY RESPONSE	4	EA	3,000.00	12,000.00
4	SP	VEHICLE SIGNAL HEAD (12", 3 SECTION)	25	EA	750.00	18,750.00
5	SP	VEHICLE SIGNAL HEAD (12", 4 SECTION)	10	EA	950.00	9,500.00
6	SP	VEHICLE SIGNAL HEAD (12", 5 SECTION)	5	EA	1,100.00	5,500.00

3.2 D5POC130 – Contract – Fulcher Electric

SIGNALS AND INTELLIGENT TRANSPORTATION SYSTEMS pg. 84

- The section where I expect to find the information we are looking for.

2. Signal Heads

2.1 Materials

- Specs provided here, no quantities or prices.

Purchase Order Contract Bid Form

Table C.2: Division 5 Contract Bid Excerpts (Fulcher Electric)

Item	Sect	Description	Qty	Unit	Unit Price ($)	Amount Bid ($)
1	SP	72 HOUR EMERGENCY RESPONSE	4	EA	3,500.00	14,000.00
4	SP	VEHICLE SIGNAL HEAD (12", 3 SECTION)	25	EA	850.00	21,250.00
5	SP	VEHICLE SIGNAL HEAD (12", 4 SECTION)	10	EA	1,175.00	11,750.00
6	SP	VEHICLE SIGNAL HEAD (12", 5 SECTION)	5	EA	1,299.00	6,495.00

Division 6

D6TSPOC004 – Contract – Fulcher Electric

PROJECT SPECIAL PROVISIONS – ROADWAY pg. 23

3. LED/Bulb Replacements

3.1 Materials

- "Furnishing and install" – the contractor is also responsible for materials in Division 6

Contract Bid Form

Table C.3: Division 6 Contract Bid Excerpts

Item	Sect	Description	Qty	Unit	Unit Price ($)	Amount Bid ($)
1	SP	Mobilization for Emergency Response	5	EA	1,500.00	7,500.00
3	SP	Vehicle Signal Head (12", 3 Section)	75	EA	625.00	46,875.00
4	SP	Vehicle Signal Head (12", 4 Section)	50	EA	748.00	37,400.00
5	SP	Vehicle Signal Head (12", 5 Section)	20	EA	1,025.00	20,500.00
7	SP	8" or 12" LED Single Bulb Replacements (Burn-out replacements)	25	EA	105.00	2,625.00

Division 7

D7POC388 – Contract – Garrett James Company, LLC

DEPARTMENT FURNISHED MATERIAL AND EQUIPMENT pg. 38

Signal Heads

- Signal Heads and Modules will be furnished by NCDOT
- How are the Department Furnished items' costs factored in to the calculations?

Purchase Order Contract Bid Form

Table C.4: Division 7 Contract Bid Excerpts

Item	Sect	Description	Qty	Unit	Unit Price ($)	Amount Bid ($)
10	SP	VEHICLE SIGNAL HEAD (12", 3 SECTION)	40	EA	875.00	35,000.00
11	SP	VEHICLE SIGNAL HEAD (12", 4 SECTION)	8	EA	990.00	7,920.00
12	SP	VEHICLE SIGNAL HEAD (12", 5 SECTION)	4	EA	1,500.00	6,000.00
62	SP	Department Furnished Signal Heads	50	EA	400.00	20,000.00
64	SP	Department Furnished Replacement Vehicle Signal LED Module	10	EA	30.00	300.00
80	SP	Removal of Existing Vehicular Traffic Signal Head	45	EA	10.00	450.00

Division 9

D9-Wire Fiber 22 – Draft – Contract Proposal

Section 1705 (Signal Heads) – p 50

- No specific information found related to prices within this draft contract.
- Note that Division 9 does not include Material costs in their contracted rates (all materials are NCDOT provided).
- ***the file provided by Matt Carlisle for Division 9 does not match the one sent to me directly. The file provided by Matt does not contain an executed bid, only the space where one should be.

2.2 PO3600047495-WireFiber-Brentwood-Yr1

Purchase Order 3600047495

Table C.5: Division 9 Contract Bid Excerpts

Item	QTY	UNT	Description	Unit Price ($)	Net Price ($)
190	250	EA	Assemble & Ints. Of Signal, Ped. Signal (Head) and LED Blankout Sign	250.00	62,500.00
200	150	EA	Removal of Signal, Ped. Signal (Head) and LED Blankout Sign	100.00	15,000.00
210	10	EA	Relocation of Signal, Ped. Signal (Head) and LED Blankout sign	80.00	800.00
220	50	EA	Modify or Replace Vehicle Signal or Pedestrian Signal Head Indication	40.00	2,000.00

Division 10

This document is from Matt Carlisle

- The contracts provided is not executed and there is no bid shown, only the outline for what the bid should look like.
- No costs/prices are provided in the documents.

Division 11

D11-11-00-155

R-5 Traffic Signal Heads -p 38

- Note that Division 11 does not include Material costs in their contracted rates (all materials are NCDOT provided).

Bid Form

Table C.6: Division 10 Contract Bid Excerpts

Item	QTY	UNT	Description	Unit Price ($)	Net Price ($)
21	50	EA	Install State-Furnished Traffic Signal Head	250.00	12,500.00
22	5	EA	Relocate Existing Traffic Signal Head	115.00	575.00
23	1,700	EA	Install State-Furnished LED in Existing Traffic Signal Head	30.00	51,000.00

Division 12

D12-12005819

Contract Special Provisions – Signals/ITS – p80

- "Contractor furnished equipment and material shall be new unless otherwise directed by the Engineer"

- The prices shown below are similar to prices in other divisions where the materials are not being provided. This raises some additional questions.

Purchase Order 3600047458

Table C.7: Division 12 Contract Bid Excerpts

Item	QTY	UNT	Description	Unit Price ($)	Net Price ($)
20	75	EA	Vehicle Signal Head (12” – 3 Section)	750.00	56,250.00
30	20	EA	Vehicle Signal Head (12” – 4 Section)	900.00	18,000.00
40	3	EA	Vehicle Signal Head (12” – 5 Section)	1,150.00	3,450.00
50	20	EA	Modify Exst. Signal Head	50.00	1,000.00
60	60	EA	Removal of Vehicle Signal Head	50.00	3,000.00
70	100	EA	Remove & Replace Vehicle Signal LED L	85.00	8,500.00

Appendix D: Single-Parameter Sensitivity Analysis of Joint Replacement

This appendix contains discussion of the single-parameter sensitivity analysis performed on the joint replacement function of the simulation. Joint replacement means that, during blanket replacement, the Signal Heads at each intersection are replaced along with all of the Modules.

D.1 Signal Head Estimated Lifespan

This discussion of the Signal Head Estimated Lifespan evaluates the effect that changing this variable has on the annual cost of replacement for both NCDOT and contracted work. It also evaluates the effects over the whole 30-year span of the simulation. Within the simulation, it is possible to input the expected life of the signal heads used by a transportation agency. As described in Chapter 6, a standard value of 30 years is used for running the simulation for strategy alternative evaluation. However, it is important to understand how a change in the expected lifespan of the Signal Heads may influence simulation results.

To understand this influence, runs of the simulation have been conducted using a range of signal head estimated lifespans. The output variables observed include Average Total Cost per Intersection. Cost refers to the cost of both Module and Signal Head replacements. Figure D.1 illustrates the anticipated change in cost per intersection to NCDOT annually for the next 30 years. Each line within the chart represents a different assumed Signal Head expected lifespan. No matter the expected lifespan of the Signal Head, estimated costs remain the same. This is due to the joint replacement of Signal Heads with Modules that is occurring during blanket replacement – the longest a Signal Head is in the field is 15 years following this replacement strategy.

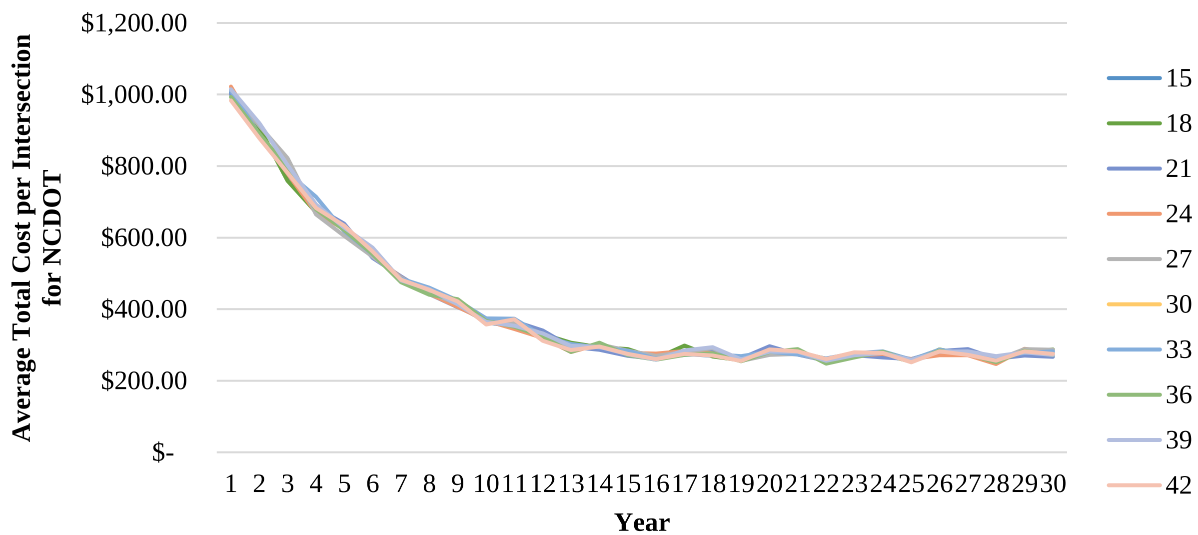

Figure D.1 Average Total Cost per Intersection for NCDOT Over Time with Varying Signal Head Life Expectancies

As the simulation runs over a 30-year span, Figure D.2 shows Average Total Cost of Signal Head and Module Replacement per Intersection for the full period. Change in expected lifespan of Signal Heads has minimal influence on the overall cost of the replacement work, for both NCDOT and contracted work. The trendlines shown in Figure D.2 follow a horizontal line, reinforcing this finding.

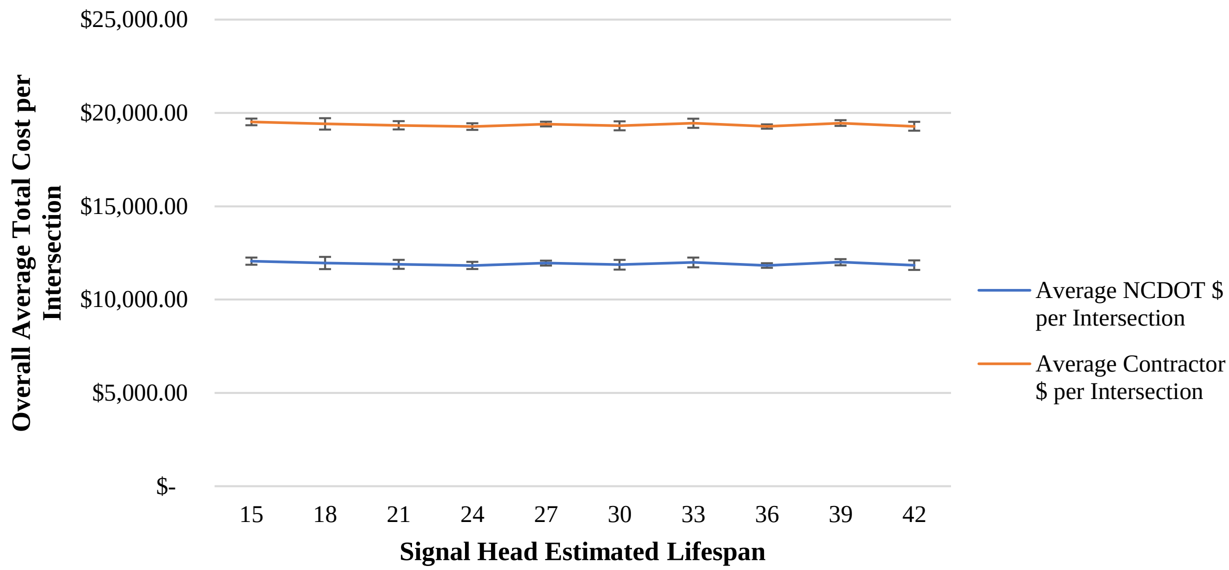

Figure D.2 Average 30-year Cost per Intersection (over 30-years) with Varying Signal Head Estimated Lifespans

D.2 Module Failure Rate

This discussion of the Module Failure Rate evaluates the effect that changing this variable has on the annual cost of replacement for both NCDOT and contracted work. It also evaluates the effects over the whole 30-year span of the simulation. Each module created in the simulation contains an inherent failure rate (see Section 6.3.2 for additional details). The default values for this failure rate are assumed, therefore, sensitivity testing of the rates is required to know whether additional research should be conducted to verify failure rates. As the failure rate is incremented in this analysis, the assumption is that each section of the failure curve is increased by the same proportion. For example, a relative increase of 1% would raise each section of the failure curve by 1% of its original value.

To understand the influence of the failure rate, runs of the simulation have been conducted using increased rates of failure for the Modules. Output observed includes Average Total Cost per Intersection. Cost here refers to replacement cost for both Modules and Signal Heads. Figure D.3 illustrates the anticipated change in cost per intersection to NCDOT annually for a 30-year period. Each line within the chart represents a different rate of failure for the modules. Due to the minimal impact that a relative increase to the failure rate provides, the lines for every set of runs are practically on top of one another. This shows that the overall cost per intersection will not change significantly with a relative increase in the Module failure rate.

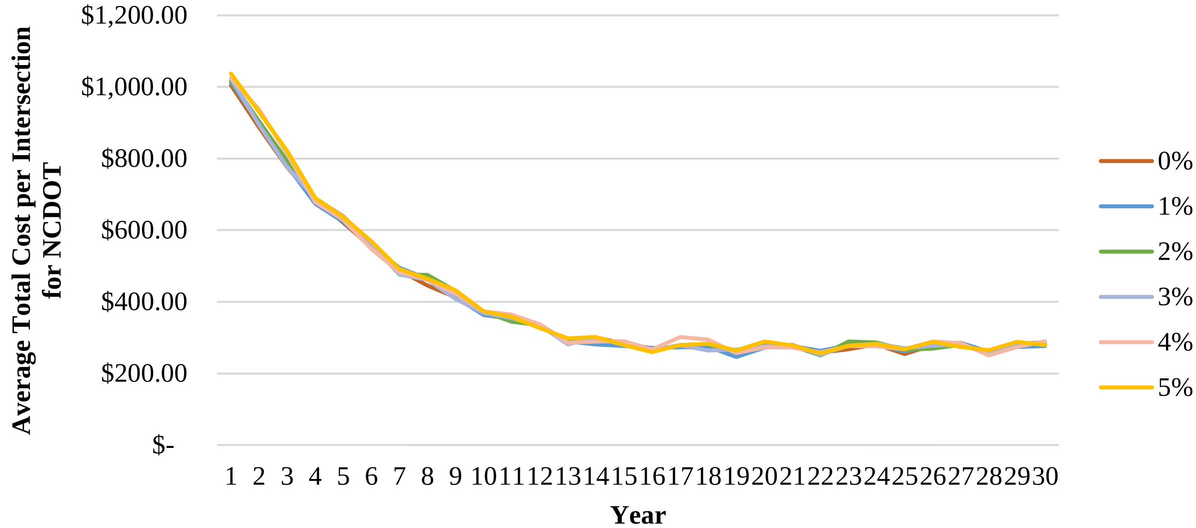

Figure D.3 Average Total Cost per Intersection for NCDOT Over Time with Varying Relative Increases to Module Failure Rate

A relative increase in Module failure rate was found to have minimal impact on the overall cost of replacement work for both NCDOT and contracted work. Figure D.4 provides additional insight by displaying the estimated costs for the whole 30-year period. The cost per intersection appears to follow a straight horizontal line, indicating that there is no significant change as relative failure rates increase.

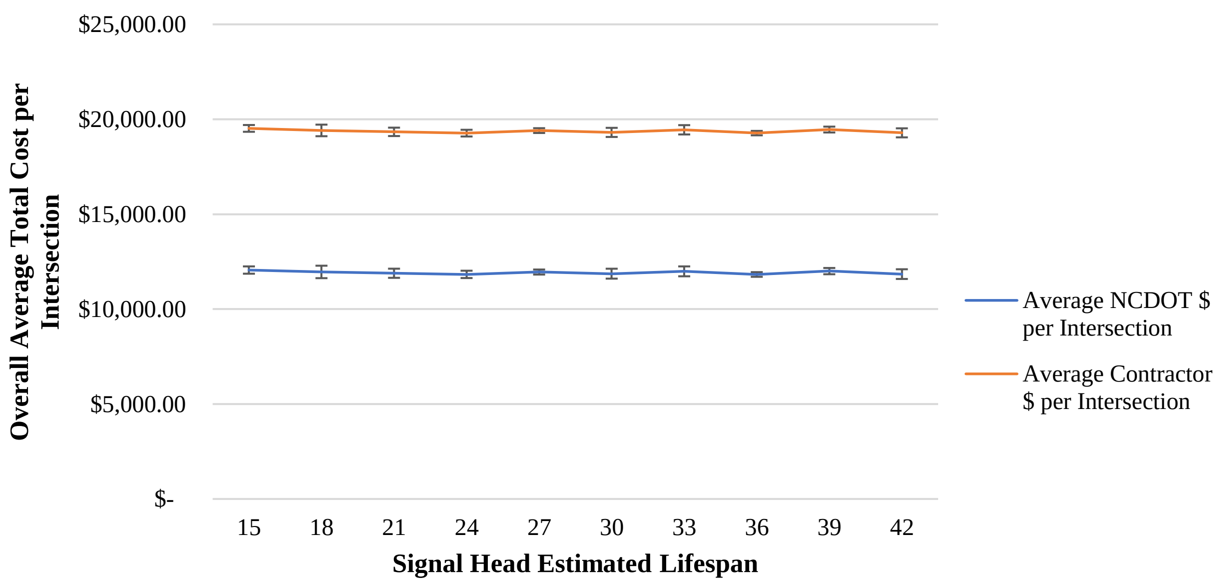

Figure D.4 Average Total Cost per Intersection (over 30-years) with Varying Module Failure Rates

<u>D.3 Signal Head Failure Rate</u>

This discussion of the Signal Head Failure Rate evaluates the effect that changing this variable has on the annual cost of replacement for both NCDOT and contracted work. It also evaluates the effects over the whole 30-year span of the simulation. Each Signal Head created within the simulation contains an inherent failure curve (see Section 6.3.2 for additional details). It is important to note that the default assumed lifespan of the Signal Heads is 30-years. The default values for the failure rate are assumed, therefore, sensitivity testing of the rates is required to know whether additional research should be conducted to verify failure rates. The curve utilized is based on the equation below. For each increment to the failure curve, it is assumed that the intersection point will increase by that percentage of the original value.

$$Failure\ Rate = \left(\frac{Current\ Age - 0.8 * Anticipated\ Life}{2}\right)^2 + (0.05 * (1 + increase))$$

To understand Signal Head failure rate influence, runs of the simulation have been conducted using increased rates of failure. Output observed includes Average Total Cost per Intersection. Cost refers to replacement costs for both Modules and Signal Heads. Figure D.5 illustrates the anticipated change in cost per intersection to NCDOT annually over a 30-year period. Each line within the chart represents a different rate of failure for the Signal Heads. Each of the lines plotted is practically on top of the others, indicating that a relative change to the Signal Head failure rate will have minimal impact on the overall cost per year for replacement of Modules and Signal Heads.

Figure D.6 reinforces this finding by showing the estimated 30-year cost per intersection at various rates of failure. The data shown in the figure follows a straight horizontal line, indicating that no significant impact on cost is made by a relative change to the failure rate.

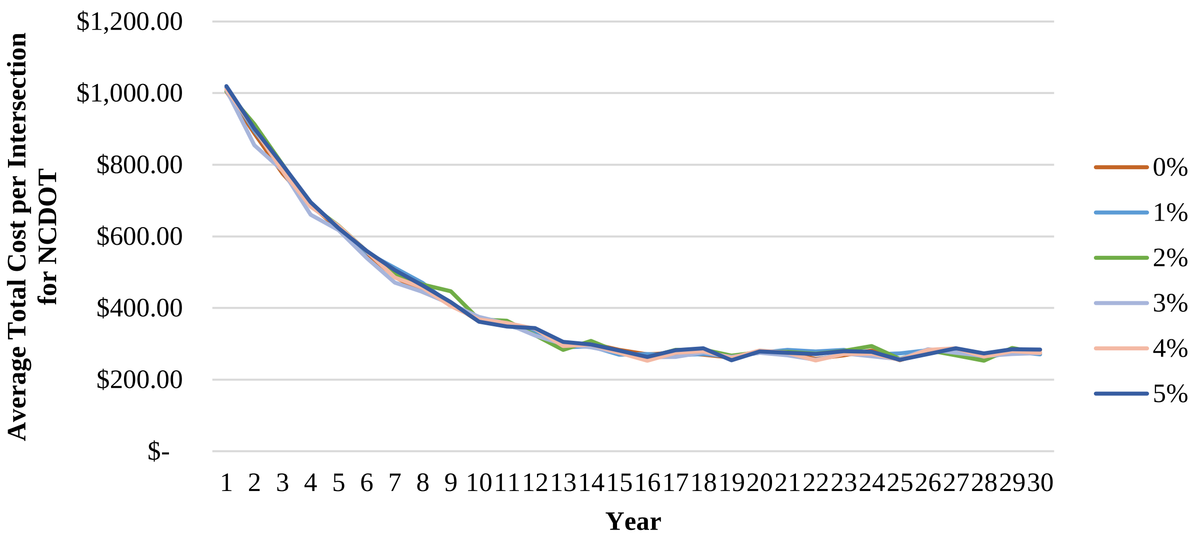

Figure D.5 Average Total Cost per Intersection for NCDOT Over Time with Varying Increases to Signal Head Failure Rate

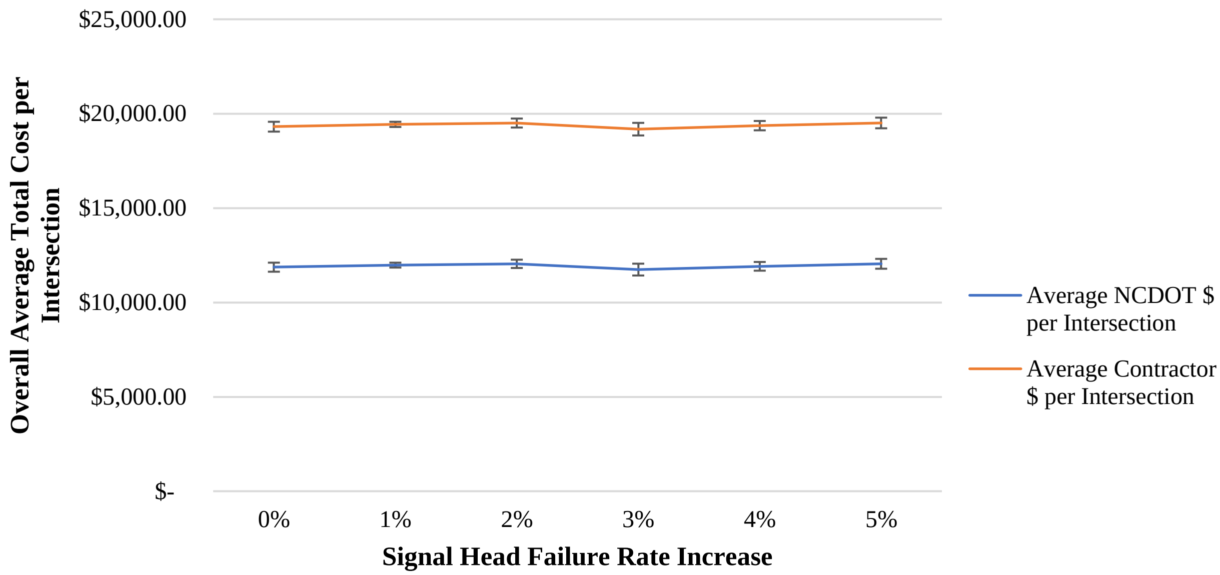

Figure D.6 Average Total Cost per Intersection (over 30 years) with Varying Increases to Signal Head Failure Rate

D.4 Cost of Labor and Equipment (Crew Costs)

This discussion of the cost of labor and equipment (Crew Costs) evaluates the effect that changing this variable has on the annual cost of replacement for both NCDOT and contracted work. It also evaluates the effects over a the whole 30-year span of the simulation. Within the simulation, there are both NCDOT replacement crews and Contractor replacement crews. Each crew's costs are considered with each spot and blanket replacement. The default values have been set (as described in Section 6.3.5 & 6.3.6), based on NCDOT data. Due to the structure of the available data, labor and equipment have been combined in to one unit and are considered as 'crew costs.' To understand the influence of crew costs, runs of the simulation were conducted using varied costs. Output observed includes Average Total Cost per Intersection). Cost refers to the replacement cost for Modules and Signal Heads. Figure D.7 illustrates the anticipated change in cost per intersection to NCDOT annually over a 30-year period as crew costs change. Each line in the chart represents a different change to the base crew costs. During the first 15-year replacement cycle there are visible differences in the overall cost. This is the period when more spot replacements are anticipated due to existing 5-year warrantied modules. During the second 15-year replacement cycle, changes in cost are less distinct.

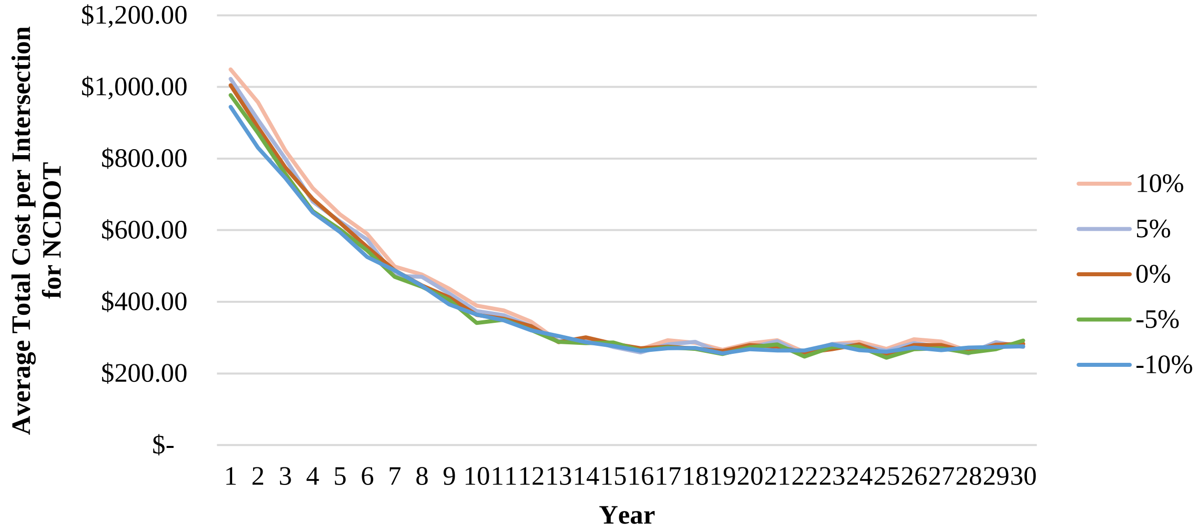

Figure D.7 Average Total Cost per Intersection for NCDOT Over Time with Varying Labor and Equipment Costs

While changes to the Crew Costs do not appear to have a large impact on the overall cost of replacement work, there is a slight impact. Figure D.8 shows this impact using the 30-year costs for both NCDOT and Contracted work. Each of the trendlines shown increases as the crew cost is increased.

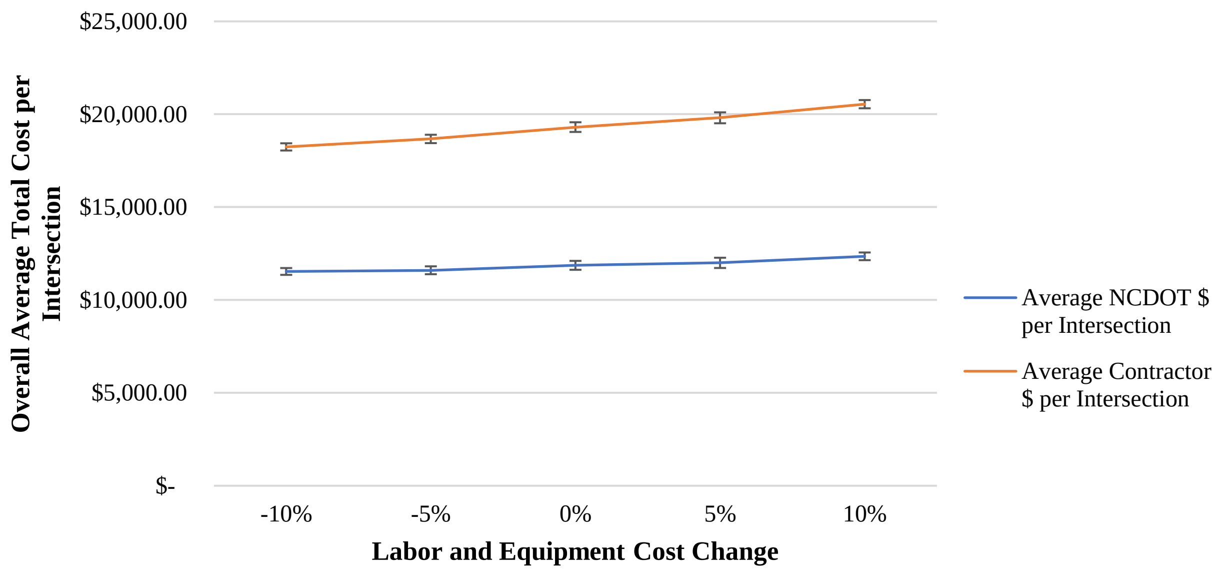

Figure D.8 Average Total Cost per Intersection with Varying Labor and Equipment Costs

Table D.1 provides the percent change in Average Total Cost that can be expected based on changing the crew costs while using this simulation. For instance, if an agency raises their base crew costs for replacement by 5%, they can expect total costs per intersection to increase by 4.5%. Note that Contractor percent change in costs is higher than that of in-house work. This is due to the Contractor cost per replacement being higher than in-house costs for every type of activity. Note that the increases seen in Table D.1 are less than the increases found when Crew Costs were changed during independent replacement. This is likely due to the higher cost of joint replacement overall.

Table D.1 Percent Change in Average Total Cost per Intersection as Crew Costs Change

Increase to Crew Cost (%)	% Change in Average 30-year Costs	
	NCDOT	Contractor
-10	-2.77 %	-5.52 %
-5	-2.23 %	-3.30 %
0	0.0 %	0.0 %
+5	1.13 %	2.60 %
+10	4.10 %	6.40 %

D.5 Cost of Materials

This discussion of the cost of materials (Modules and Signal Heads) evaluates the effect that changing these variables has on the annual cost of replacement for both NCDOT and contracted work. It also evaluates the effects over the whole 30-year span of the simulation. Within the simulation, each asset (module or signal head) is assigned an inherent material cost based on their type (see Section 6.3.3 for additional details). With every replacement, material costs are incurred. To understand the influence that changing material costs may have, runs of the simulation have been conducted using varied material costs. Output observed includes Average Total Cost per Intersection. Cost refers to the replacement cost of Modules and Signal Heads. Figure D.9 shows that overall cost per intersection is impacted by an increase in material cost. This differs slightly from the results of the independent replacement sensitivity analysis because there the impact is greater. This is likely due to the increased quantity of Signal Heads required when conducting joint replacement strategies.

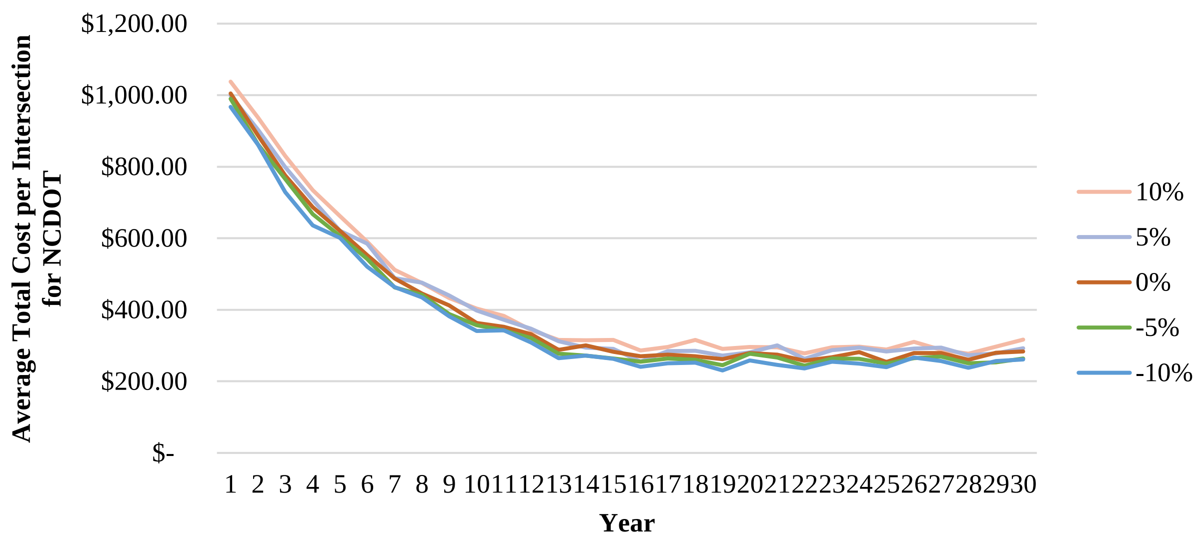

Figure D.9 Average Total Cost per Intersection for NCDOT Over Time with Varying Material Costs

Changes to material cost do appear to have an impact on the overall cost, which is shown again in Figure D.10. Each data point represents the anticipated cost per intersection for the entire 30-year span. Both trendlines are seen to go up as the cost of materials increases.

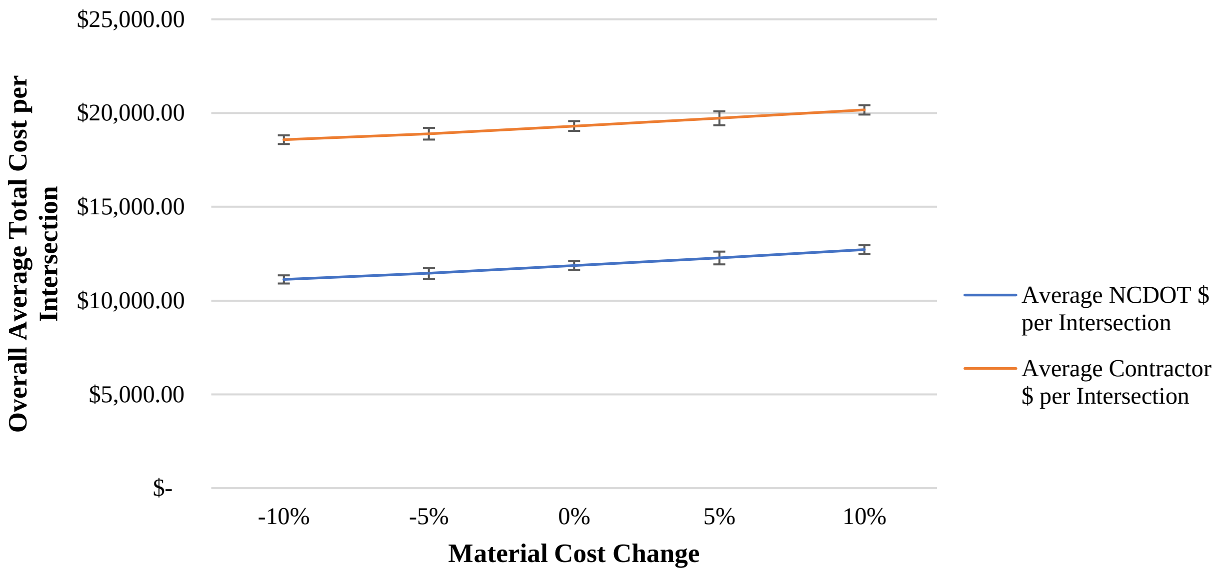

Figure D.10 Average Total Cost per Intersection (over 30 years) with Varying Material Costs

Table D.2 provides the percent change in average total cost that can be expected based on changing the material costs while using this simulation. For instance, if a manufacturer raises their base material costs by 5%, a transportation agency can expect total costs per intersection to increase by 3.41%.

Table D.2: Percent Change in Average Total Cost per Intersection as Material Costs Change

Increase to Material Cost (%)	% Change in Average 30-year Costs	
	NCDOT	Contractor
-10	-6.22 %	-3.78 %
-5	-3.49 %	-2.13 %
0	0.0 %	0.0 %
+5	3.41 %	2.13 %
+10	7.17 %	4.45 %

D.6 Inflation

This discussion of the rate of inflation evaluates the effect that changing this variable has on the annual cost of replacement for both NCDOT and contracted work. It also evaluates the effect over the whole 30-year span of the simulation. While inflation is not a parameter that any transportation agency can control, it is important to understand the impacts that it may have on the estimates provided with this simulation. Within the simulation the user can input an anticipated rate of inflation. At the end of each year, both material costs and crew costs are increased based on this rate. This occurs every year, for all 30 years observed. Cost values are reset at the start of each model iteration, allowing for comparison across iterations. To understand the impact of inflation, runs of the simulation have been conducted using varied rates. Output observed includes Average Total Cost per Intersection. Cost refers to replacement costs of Modules and Signal Heads. Figure D.11 shows that inflation has an exponential impact on the cost for each intersection, as would be expected.

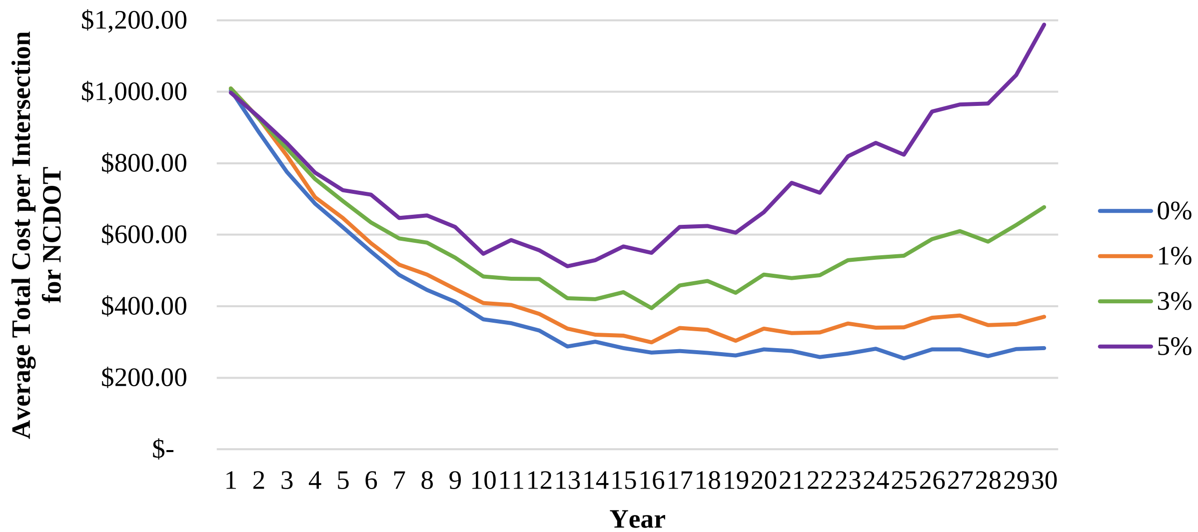

Figure D.11 Average Total Cost per Intersection for NCDOT Over Time with Varying Inflation Rates

Changing the rate of inflation has a major impact on the overall cost of replacement work, for both NCDOT and Contracted work. Figure D.12 shows this impact, the trend lines for both NCDOT and Contractor work quickly increase as inflation rates increase. The scale of this figure has not been standardized to match the other 30-year figures, as the total costs exceed the $25,000 cap that was identified with other parameter changes.

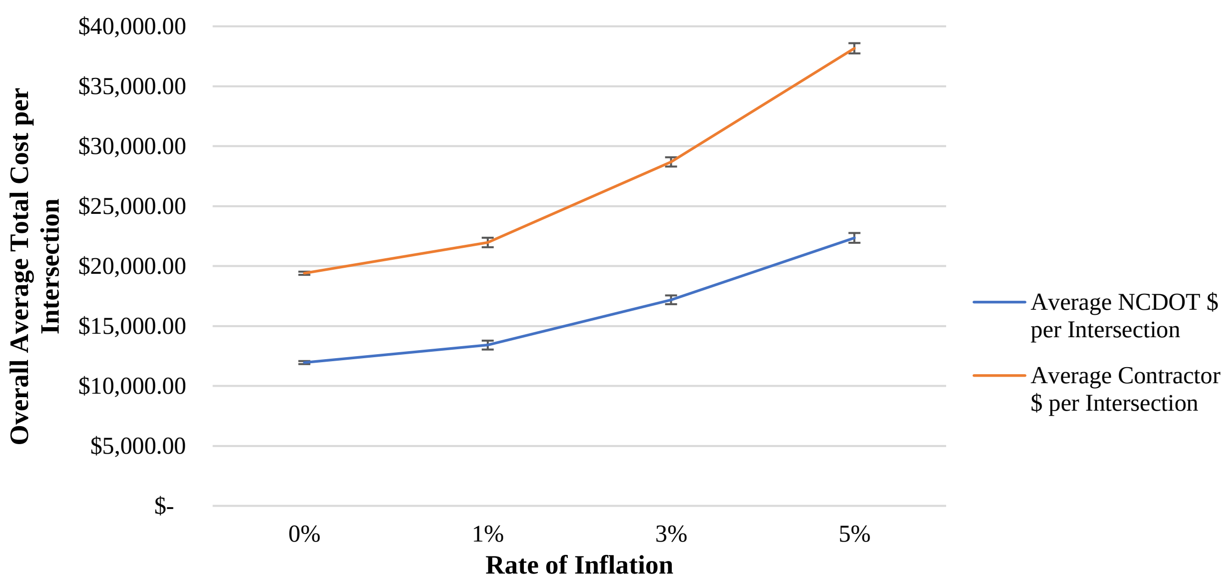

Figure D.12 Average Cost per Intersection (over 30 years) with Varying Inflation Rates

Table D.3 provides the percent change in average total cost that can be expected based on changing the inflation rate while using this simulation. For instance, if an agency anticipates an inflation rate of 3%, they can expect 30-year costs per intersection to increase by 45%. Note that Contractor percent change is higher than that of in-house work due to the higher base cost of contracted work.

Table D.3: Percent Change in Average Total Cost per Intersection as Inflation Rate Changes

Increase to Inflation Rate (%)	% Change in Average 30-year Costs	
	NCDOT	Contractor
0	0.0 %	0.0 %
1	13.01 %	13.78 %
3	44.84 %	48.59 %
5	88.36 %	97.67 %

Appendix E: Validation Calculations of Expected Simulation Output

Table E.1 Calculated LED Module Replacement Quantities for 1-year Period, Independent Replacement Strategy

Year	# Blanket	Failure Rate	Modules in Field															# Spot	Annual Total
		Failure Rate	0.3%	0.1%	0.05%	0.05%	0.05%	0.05%	0.05%	0.05%	0.05%	0.05%	0.05%	0.05%	0.05%	0.1%	0.3%		
		Age	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15		
1	5,846		5,846	-	-	-	-	-	-	-	-	-	-	-	-	-	-	18	5,864
2	-		18	5,828	-	-	-	-	-	-	-	-	-	-	-	-	-	6	6
3	-		6	18	5,823	-	-	-	-	-	-	-	-	-	-	-	-	3	3
4	-		3	6	18	5,820	-	-	-	-	-	-	-	-	-	-	-	3	3
5	-		3	3	6	18	5,817	-	-	-	-	-	-	-	-	-	-	3	3
6	-		3	3	3	6	18	5,814	-	-	-	-	-	-	-	-	-	3	3
7	-		3	3	3	3	6	18	5,811	-	-	-	-	-	-	-	-	3	3
8	-		3	3	3	3	3	6	18	5,808	-	-	-	-	-	-	-	3	3
9	-		3	3	3	3	3	3	6	18	5,805	-	-	-	-	-	-	3	3
10	-		3	3	3	3	3	3	3	6	18	5,802	-	-	-	-	-	3	3
11	-		3	3	3	3	3	3	3	3	6	18	5,799	-	-	-	-	3	3
12	-		3	3	3	3	3	3	3	3	3	6	18	5,796	-	-	-	3	3
13	-		3	3	3	3	3	3	3	3	3	3	6	18	5,793	-	-	3	3
14	-		3	3	3	3	3	3	3	3	3	3	3	6	18	5,790	-	6	6
15	-		6	3	3	3	3	3	3	3	3	3	3	3	6	18	5,784	17	17
16	5,846		5,846	-	-	-	-	-	-	-	-	-	-	-	-	-	-	18	5,864
17	-		18	5,828	-	-	-	-	-	-	-	-	-	-	-	-	-	6	6
18	-		6	18	5,823	-	-	-	-	-	-	-	-	-	-	-	-	3	3
19	-		3	6	18	5,820	-	-	-	-	-	-	-	-	-	-	-	3	3
20	-		3	3	6	18	5,817	-	-	-	-	-	-	-	-	-	-	3	3
21	-		3	3	3	6	18	5,814	-	-	-	-	-	-	-	-	-	3	3
22	-		3	3	3	3	6	18	5,811	-	-	-	-	-	-	-	-	3	3
23	-		3	3	3	3	3	6	18	5,808	-	-	-	-	-	-	-	3	3
24	-		3	3	3	3	3	3	6	18	5,805	-	-	-	-	-	-	3	3
25	-		3	3	3	3	3	3	3	6	18	5,802	-	-	-	-	-	3	3
26	-		3	3	3	3	3	3	3	3	6	18	5,799	-	-	-	-	3	3
27	-		3	3	3	3	3	3	3	3	3	6	18	5,796	-	-	-	3	3
28	-		3	3	3	3	3	3	3	3	3	3	6	18	5,793	-	-	3	3
29	-		3	3	3	3	3	3	3	3	3	3	3	6	18	5,790	-	6	6
30	-		6	3	3	3	3	3	3	3	3	3	3	3	6	18	5,784	17	17

Table E.2 Calculated Signal Head Replacement Quantities for 1-year Period, Independent Replacement Strategy (SH Ages 1 to 15)

Year	Modules in Field																
	Failure Rate	3%	0.05%														
	Age	Ex.*	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1		1,796	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2		1,796	54	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3		1,742	52	54	-	-	-	-	-	-	-	-	-	-	-	-	-
4		1,690	51	52	54	-	-	-	-	-	-	-	-	-	-	-	-
5		1,639	49	51	52	54	-	-	-	-	-	-	-	-	-	-	-
6		1,590	48	49	51	52	54	-	-	-	-	-	-	-	-	-	-
7		1,542	46	48	49	51	52	54	-	-	-	-	-	-	-	-	-
8		1,496	45	46	48	49	51	52	54	-	-	-	-	-	-	-	-
9		1,451	44	45	46	48	49	51	52	54	-	-	-	-	-	-	-
10		1,407	42	44	45	46	48	49	51	52	54	-	-	-	-	-	-
11		1,365	41	42	44	45	46	48	49	51	52	54	-	-	-	-	-
12		1,323	40	41	42	44	45	46	48	49	51	52	54	-	-	-	-
13		1,283	39	40	41	42	44	45	46	48	49	51	52	54	-	-	-
14		1,245	38	39	40	41	42	44	45	46	48	49	51	52	54	-	-
15		1,207	37	38	39	40	41	42	44	45	46	48	49	51	52	54	-
16		1,171	35	37	38	39	40	41	42	44	45	46	48	49	51	52	54
17		1,135	34	35	37	38	39	40	41	42	44	45	46	48	49	51	52
18		1,101	33	34	35	37	38	39	40	41	42	44	45	46	48	49	51
19		1,067	32	33	34	35	37	38	39	40	41	42	44	45	46	48	49
20		1,035	31	32	33	34	35	37	38	39	40	41	42	44	45	46	48
21		1,004	31	31	32	33	34	35	37	38	39	40	41	42	44	45	46
22		973	30	31	31	32	33	34	35	37	38	39	40	41	42	44	45
23		943	29	30	31	31	32	33	34	35	37	38	39	40	41	42	44
24		915	28	29	30	31	31	32	33	34	35	37	38	39	40	41	42
25		887	27	28	29	30	31	31	32	33	34	35	37	38	39	40	41
26		860	26	27	28	29	30	31	31	32	33	34	35	37	38	39	40
27			1	26	27	28	29	30	31	31	32	33	34	35	37	38	39
28			1	1	26	27	28	29	30	31	31	32	33	34	35	37	38
29			2	1	1	26	27	28	29	30	31	31	32	33	34	35	37
30			4	2	1	1	26	27	28	29	30	31	31	32	33	34	35

*this is the quantity of Signal Heads designated as ‘Existing’

Table E.3 Calculated Signal Head Replacement Quantities for 1-year Period, Independent Replacement Strategy (SH Ages 16 to 30)

Year	Modules in Field																	# Spot	Annual Total
	Failure Rate	3%	0.05%									0.26%	1.01%	2.26%	4.01%	6.26%	9.01%		
	Age	Ex.*	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30		
1		1,796	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	54	54
2		1,796	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	52	52
3		1,742	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	51	51
4		1,690	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	49	49
5		1,639	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	48	48
6		1,590	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	46	46
7		1,542	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	45	45
8		1,496	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	44	44
9		1,451	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	42	42
10		1,407	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	41	41
11		1,365	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	40	40
12		1,323	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	39	39
13		1,283	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	38	38
14		1,245	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	37	37
15		1,207	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	35	35
16		1,171	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	34	34
17		1,135	54	-	-	-	-	-	-	-	-	-	-	-	-	-	-	33	33
18		1,101	52	54	-	-	-	-	-	-	-	-	-	-	-	-	-	32	32
19		1,067	51	52	54	-	-	-	-	-	-	-	-	-	-	-	-	31	31
20		1,035	49	51	52	54	-	-	-	-	-	-	-	-	-	-	-	31	31
21		1,004	48	49	51	52	54	-	-	-	-	-	-	-	-	-	-	30	30
22		973	46	48	49	51	52	54	-	-	-	-	-	-	-	-	-	29	29
23		943	45	46	48	49	51	52	54	-	-	-	-	-	-	-	-	28	28
24		915	44	45	46	48	49	51	52	54	-	-	-	-	-	-	-	27	27
25		887	42	44	45	46	48	49	51	52	54	-	-	-	-	-	-	26	26
26		860	41	42	44	45	46	48	49	51	52	54	-	-	-	-	-	1	1
27			40	41	42	44	45	46	48	49	51	52	54	-	-	-	-	1	1
28			39	40	41	42	44	45	46	48	49	51	52	54	-	-	-	2	2
29			38	39	40	41	42	44	45	46	48	49	51	52	54	-	-	4	4
30			37	38	39	40	41	42	44	45	46	48	49	51	52	54	-	8	8

*this is the quantity of Signal Heads designated as ‘Existing’

Appendix F: Annual Cost Data (per Intersection) for Alternative Scenarios

Table F.1 NCDOT Costs for In-House Work (5-year Period; 5-year Cycle; Independent Replacement)

Year	Total (Avg.)	Total (Med.)	Total (St. Dev.)	Blanket (Avg.)	Blanket (Med.)	Blanket (St. Dev.)	Signal Head Spot (Avg.)	Signal Head Spot (Med.)	Signal Head Spot (St. Dev.)	Module Spot (Avg.)	Module Spot (Med.)	Module Spot (St. Dev.)
1	$987.19	$989.30	$35.36	$315.22	$315.88	$6.10	$135.45	$135.33	$20.60	$536.52	$541.89	$24.73
2	$809.87	$812.20	$15.98	$318.31	$318.06	$11.36	$128.12	$130.90	$9.28	$363.44	$361.10	$16.85
3	$676.51	$680.98	$18.15	$319.78	$316.29	$10.88	$143.94	$146.16	$10.77	$212.79	$213.48	$9.76
4	$543.76	$542.16	$17.12	$314.23	$312.33	$6.67	$137.27	$141.38	$17.75	$92.26	$93.43	$9.63
5	$454.98	$449.20	$30.15	$318.33	$317.90	$4.90	$129.76	$124.16	$30.68	$6.89	$6.54	$2.59
6	$442.09	$436.90	$28.70	$315.22	$315.88	$6.10	$118.58	$110.64	$24.99	$8.29	$7.47	$2.47
7	$435.61	$437.80	$23.14	$318.31	$318.06	$11.36	$110.65	$116.15	$17.60	$6.66	$6.54	$2.80
8	$441.70	$444.62	$35.92	$319.78	$316.29	$10.88	$114.44	$117.22	$27.13	$7.47	$7.00	$1.73
9	$430.90	$429.06	$10.85	$314.23	$312.33	$6.67	$109.31	$107.76	$12.25	$7.36	$7.01	$2.26
10	$437.76	$428.36	$19.69	$318.33	$317.90	$4.90	$112.54	$106.65	$18.60	$6.89	$6.54	$2.29
11	$428.52	$431.70	$17.82	$315.22	$315.88	$6.10	$105.47	$105.78	$14.00	$7.82	$7.94	$2.91
12	$431.31	$432.38	$20.02	$318.31	$318.06	$11.36	$105.30	$109.56	$16.80	$7.71	$7.94	$2.53
13	$422.94	$426.45	$22.70	$319.78	$316.29	$10.88	$94.40	$89.04	$21.94	$8.76	$7.94	$2.34
14	$412.16	$409.54	$15.77	$314.23	$312.33	$6.67	$89.98	$89.26	$17.23	$7.94	$7.48	$2.34
15	$422.26	$419.18	$20.10	$318.33	$317.90	$4.90	$95.40	$89.99	$17.24	$8.52	$8.40	$2.71
16	$425.61	$425.79	$11.82	$315.22	$315.88	$6.10	$101.28	$101.56	$10.70	$9.11	$9.34	$3.15
17	$411.88	$410.99	$17.25	$318.31	$318.06	$11.36	$87.38	$83.80	$19.23	$6.19	$6.08	$2.06
18	$415.59	$422.83	$22.21	$319.78	$316.29	$10.88	$89.38	$93.90	$18.39	$6.42	$5.14	$3.10
19	$400.81	$395.65	$15.85	$314.23	$312.33	$6.67	$79.11	$77.66	$13.36	$7.48	$7.00	$1.73
20	$405.47	$407.80	$15.97	$318.33	$317.90	$4.90	$78.97	$85.10	$17.60	$8.18	$8.88	$2.77
21	$395.84	$398.56	$15.37	$315.22	$315.88	$6.10	$73.61	$72.88	$12.09	$7.00	$7.00	$1.32
22	$403.28	$402.79	$14.68	$318.31	$318.06	$11.36	$79.14	$82.90	$15.95	$5.84	$6.08	$2.33
23	$404.28	$407.66	$20.32	$319.78	$316.29	$10.88	$77.72	$83.02	$14.53	$6.77	$6.54	$2.22
24	$403.97	$402.08	$11.11	$314.23	$312.33	$6.67	$82.86	$83.54	$6.77	$6.89	$6.08	$4.18
25	$390.17	$389.90	$12.59	$318.33	$317.90	$4.90	$65.53	$65.56	$9.18	$6.31	$5.60	$2.63
26	$392.80	$390.80	$17.77	$315.22	$315.88	$6.10	$69.64	$66.54	$13.13	$7.94	$7.47	$2.23
27	$407.50	$415.34	$19.70	$318.31	$318.06	$11.36	$81.60	$84.48	$14.36	$7.59	$8.40	$2.31
28	$406.38	$402.50	$23.33	$319.78	$316.29	$10.88	$76.91	$76.68	$14.99	$9.69	$9.81	$3.12
29	$403.52	$402.40	$17.99	$314.23	$312.33	$6.67	$82.29	$77.94	$15.81	$7.01	$7.00	$2.06
30	$420.78	$419.96	$21.52	$318.33	$317.90	$4.90	$93.11	$96.40	$16.70	$9.34	$8.88	$3.00

Table F.2 Costs for Contracted Work (5-year Period; 5-year Cycle; Independent Replacement)

Year	Total (Avg.)	Total (Med.)	Total (St. Dev.)	Blanket (Avg.)	Blanket (Med.)	Blanket (St. Dev.)	Signal Head Spot (Avg.)	Signal Head Spot (Med.)	Signal Head Spot (St. Dev.)	Module Spot (Avg.)	Module Spot (Med.)	Module Spot (St. Dev.)
1	$1,781.89	$1,785.00	$40.14	$987.70	$988.36	$6.10	$145.62	$145.38	$21.97	$648.57	$655.07	$29.90
2	$1,567.96	$1,570.64	$19.14	$990.79	$990.54	$11.36	$137.83	$140.56	$9.84	$439.34	$436.52	$20.37
3	$1,404.36	$1,410.47	$19.68	$992.27	$988.77	$10.88	$154.87	$157.28	$11.61	$257.23	$258.08	$11.79
4	$1,245.92	$1,243.42	$17.41	$986.71	$984.81	$6.67	$147.68	$152.30	$18.90	$111.53	$112.94	$11.64
5	$1,138.83	$1,133.00	$32.00	$990.81	$990.38	$4.90	$139.69	$133.82	$32.77	$8.33	$7.91	$3.13
6	$1,125.18	$1,119.24	$30.39	$987.70	$988.36	$6.10	$127.46	$118.93	$26.63	$10.02	$9.04	$2.98
7	$1,117.77	$1,120.45	$24.09	$990.79	$990.54	$11.36	$118.94	$124.82	$18.83	$8.05	$7.91	$3.38
8	$1,124.21	$1,127.74	$37.72	$992.27	$988.77	$10.88	$122.91	$125.90	$28.98	$9.04	$8.48	$2.09
9	$1,113.16	$1,111.30	$11.52	$986.71	$984.81	$6.67	$117.56	$115.85	$13.02	$8.89	$8.47	$2.73
10	$1,120.12	$1,110.10	$21.17	$990.81	$990.38	$4.90	$120.98	$114.74	$19.96	$8.33	$7.91	$2.76
11	$1,110.63	$1,114.23	$19.01	$987.70	$988.36	$6.10	$113.47	$114.07	$15.09	$9.46	$9.60	$3.51
12	$1,113.35	$1,115.40	$21.00	$990.79	$990.54	$11.36	$113.25	$117.85	$18.14	$9.32	$9.60	$3.06
13	$1,104.42	$1,107.70	$24.29	$992.27	$988.77	$10.88	$101.57	$95.97	$23.58	$10.59	$9.60	$2.82
14	$1,093.10	$1,090.30	$16.91	$986.71	$984.81	$6.67	$96.79	$95.90	$18.53	$9.60	$9.04	$2.83
15	$1,103.68	$1,100.44	$21.75	$990.81	$990.38	$4.90	$102.57	$96.82	$18.66	$10.31	$10.16	$3.27
16	$1,107.58	$1,108.03	$12.25	$987.70	$988.36	$6.10	$108.86	$109.17	$11.37	$11.01	$11.29	$3.80
17	$1,092.24	$1,090.49	$18.53	$990.79	$990.54	$11.36	$93.97	$89.84	$20.59	$7.48	$7.35	$2.48
18	$1,096.17	$1,103.86	$23.37	$992.27	$988.77	$10.88	$96.14	$101.12	$19.70	$7.76	$6.22	$3.74
19	$1,080.78	$1,075.45	$16.67	$986.71	$984.81	$6.67	$85.04	$83.22	$14.28	$9.04	$8.48	$2.09
20	$1,085.66	$1,088.88	$16.73	$990.81	$990.38	$4.90	$84.97	$91.64	$18.75	$9.88	$10.72	$3.34
21	$1,075.34	$1,078.19	$16.07	$987.70	$988.36	$6.10	$79.17	$78.24	$12.94	$8.47	$8.48	$1.60
22	$1,082.93	$1,082.12	$15.77	$990.79	$990.54	$11.36	$85.09	$88.84	$17.12	$7.06	$7.35	$2.81
23	$1,084.01	$1,087.66	$21.04	$992.27	$988.77	$10.88	$83.56	$89.07	$15.60	$8.19	$7.91	$2.68
24	$1,084.19	$1,081.59	$11.53	$986.71	$984.81	$6.67	$89.15	$89.60	$7.23	$8.33	$7.35	$5.05
25	$1,068.94	$1,068.62	$13.32	$990.81	$990.38	$4.90	$70.51	$70.63	$9.81	$7.62	$6.78	$3.18
26	$1,072.03	$1,069.53	$18.76	$987.70	$988.36	$6.10	$74.74	$71.22	$14.18	$9.60	$9.04	$2.70
27	$1,087.76	$1,096.80	$20.71	$990.79	$990.54	$11.36	$87.79	$90.92	$15.57	$9.18	$10.16	$2.79
28	$1,086.45	$1,083.01	$23.90	$992.27	$988.77	$10.88	$82.47	$82.34	$15.75	$11.72	$11.86	$3.77
29	$1,083.62	$1,082.34	$19.32	$986.71	$984.81	$6.67	$88.44	$83.79	$17.12	$8.47	$8.48	$2.49
30	$1,102.11	$1,101.51	$23.14	$990.81	$990.38	$4.90	$100.01	$103.42	$17.92	$11.29	$10.72	$3.62

Table F.3 NCDOT Costs for In-House Work (Spot Replacement Only, 15-year Modules)

Year	Total (Avg.)	Total (Med.)	Total (St. Dev.)	Blanket (Avg.)	Blanket (Med.)	Blanket (St. Dev.)	Signal Head Spot (Avg.)	Signal Head Spot (Med.)	Signal Head Spot (St. Dev.)	Module Spot (Avg.)	Module Spot (Med.)	Module Spot (St. Dev.)
1	$797.22	$806.56	$37.69	$-	$-	$-	$132.35	$138.51	$18.06	$664.87	$663.82	$36.43
2	$720.30	$711.96	$32.07	$-	$-	$-	$139.05	$144.81	$20.84	$581.25	$573.66	$27.83
3	$655.56	$647.38	$40.47	$-	$-	$-	$132.36	$138.69	$25.64	$523.20	$524.60	$28.75
4	$568.17	$588.58	$38.03	$-	$-	$-	$118.19	$128.57	$20.76	$449.98	$453.13	$30.20
5	$540.03	$543.53	$17.47	$-	$-	$-	$133.49	$129.50	$15.22	$406.53	$408.28	$16.65
6	$472.39	$473.51	$21.61	$-	$-	$-	$117.24	$122.90	$19.92	$355.15	$352.70	$13.03
7	$427.58	$422.06	$23.29	$-	$-	$-	$119.03	$118.25	$21.93	$308.55	$308.78	$13.92
8	$404.73	$405.96	$26.50	$-	$-	$-	$123.63	$116.85	$25.49	$281.10	$274.68	$16.45
9	$362.41	$370.46	$15.94	$-	$-	$-	$109.22	$109.56	$13.23	$253.19	$249.92	$13.58
10	$332.78	$336.12	$20.08	$-	$-	$-	$116.03	$124.56	$20.93	$216.75	$213.02	$12.29
11	$305.58	$317.19	$23.98	$-	$-	$-	$117.20	$118.65	$10.50	$188.38	$195.26	$17.74
12	$262.39	$258.96	$22.13	$-	$-	$-	$88.97	$91.30	$17.02	$173.43	$175.18	$13.90
13	$243.63	$242.36	$16.59	$-	$-	$-	$87.72	$86.11	$13.41	$155.91	$155.09	$11.31
14	$233.06	$234.32	$20.98	$-	$-	$-	$90.93	$86.35	$19.41	$142.13	$142.48	$9.25
15	$211.76	$214.63	$17.73	$-	$-	$-	$90.41	$85.35	$22.30	$121.34	$121.93	$10.97
16	$195.79	$191.80	$15.30	$-	$-	$-	$86.48	$82.30	$13.34	$109.31	$110.72	$7.32
17	$186.08	$185.12	$19.22	$-	$-	$-	$81.20	$81.32	$16.37	$104.88	$104.18	$9.23
18	$179.33	$174.83	$13.61	$-	$-	$-	$84.50	$77.18	$14.99	$94.83	$93.90	$13.64
19	$172.55	$174.25	$13.45	$-	$-	$-	$78.53	$82.07	$11.47	$94.02	$92.03	$8.88
20	$176.09	$173.83	$19.17	$-	$-	$-	$80.44	$78.34	$12.76	$95.65	$94.36	$8.47
21	$192.00	$197.95	$23.60	$-	$-	$-	$84.56	$86.94	$20.55	$107.44	$105.58	$9.06
22	$188.69	$180.82	$30.26	$-	$-	$-	$75.41	$72.90	$25.52	$113.28	$114.92	$8.88
23	$217.18	$212.89	$26.34	$-	$-	$-	$77.15	$84.90	$15.97	$140.03	$136.40	$15.37
24	$231.72	$237.14	$16.41	$-	$-	$-	$72.78	$67.24	$16.61	$158.95	$152.29	$13.83
25	$249.20	$250.96	$19.53	$-	$-	$-	$67.83	$64.04	$16.89	$181.37	$184.52	$13.75
26	$280.68	$275.19	$29.05	$-	$-	$-	$68.95	$68.24	$9.88	$211.73	$206.94	$20.78
27	$302.00	$302.62	$13.62	$-	$-	$-	$75.90	$81.62	$15.89	$226.10	$228.44	$16.29
28	$298.46	$300.62	$24.07	$-	$-	$-	$70.49	$73.16	$8.71	$227.97	$230.77	$17.36
29	$325.03	$324.17	$17.50	$-	$-	$-	$80.48	$72.70	$20.42	$244.55	$242.44	$25.69
30	$317.59	$317.17	$19.93	$-	$-	$-	$80.39	$77.96	$12.54	$237.19	$234.97	$14.38

Table F.4 Costs for Contracted Work (Spot Replacement Only, 15-year Modules)

Year	Total (Avg.)	Total (Med.)	Total (St. Dev.)	Blanket (Avg.)	Blanket (Med.)	Blanket (St. Dev.)	Signal Head Spot (Avg.)	Signal Head Spot (Med.)	Signal Head Spot (St. Dev.)	Module Spot (Avg.)	Module Spot (Med.)	Module Spot (St. Dev.)
1	$946.09	$957.39	$44.99	$-	$-	$-	$142.37	$148.76	$19.35	$803.72	$802.45	$44.04
2	$852.20	$842.02	$37.13	$-	$-	$-	$149.56	$155.93	$22.32	$702.64	$693.46	$33.64
3	$774.73	$766.21	$46.48	$-	$-	$-	$142.26	$149.13	$27.46	$632.47	$634.16	$34.75
4	$670.98	$695.34	$44.25	$-	$-	$-	$127.02	$138.03	$22.22	$543.95	$547.76	$36.51
5	$634.88	$638.95	$20.26	$-	$-	$-	$143.44	$139.65	$16.32	$491.44	$493.56	$20.14
6	$555.20	$556.83	$23.91	$-	$-	$-	$125.88	$131.88	$21.25	$429.32	$426.36	$15.75
7	$501.02	$495.32	$25.95	$-	$-	$-	$128.03	$127.06	$23.62	$372.99	$373.28	$16.82
8	$472.78	$472.40	$29.26	$-	$-	$-	$132.97	$125.93	$27.29	$339.81	$332.05	$19.88
9	$423.51	$432.21	$18.33	$-	$-	$-	$117.44	$117.85	$14.20	$306.07	$302.12	$16.42
10	$386.69	$389.22	$21.96	$-	$-	$-	$124.66	$133.82	$22.45	$262.02	$257.51	$14.86
11	$353.38	$367.53	$27.87	$-	$-	$-	$125.66	$127.14	$11.30	$227.72	$236.04	$21.45
12	$305.47	$300.52	$25.09	$-	$-	$-	$95.82	$98.32	$18.37	$209.65	$211.76	$16.81
13	$282.83	$281.20	$18.72	$-	$-	$-	$94.36	$92.54	$14.35	$188.47	$187.48	$13.68
14	$269.65	$270.72	$23.11	$-	$-	$-	$97.84	$92.79	$21.00	$171.81	$172.24	$11.19
15	$243.88	$247.70	$19.00	$-	$-	$-	$97.19	$91.60	$24.19	$146.68	$147.39	$13.26
16	$225.18	$221.84	$17.10	$-	$-	$-	$93.04	$88.50	$14.47	$132.14	$133.84	$8.85
17	$213.98	$212.24	$21.27	$-	$-	$-	$87.20	$87.56	$17.56	$126.78	$125.93	$11.16
18	$205.45	$200.00	$15.51	$-	$-	$-	$90.81	$82.64	$16.21	$114.64	$113.50	$16.49
19	$197.94	$200.78	$15.16	$-	$-	$-	$84.29	$87.72	$12.25	$113.65	$111.24	$10.73
20	$202.12	$199.29	$21.51	$-	$-	$-	$86.49	$84.30	$13.61	$115.62	$114.07	$10.24
21	$220.80	$227.02	$25.86	$-	$-	$-	$90.92	$93.38	$22.01	$129.88	$127.62	$10.95
22	$218.16	$209.01	$33.18	$-	$-	$-	$81.22	$78.56	$27.33	$136.94	$138.92	$10.73
23	$252.28	$245.76	$29.98	$-	$-	$-	$83.00	$91.24	$17.07	$169.27	$164.90	$18.58
24	$270.26	$278.09	$18.62	$-	$-	$-	$78.12	$72.12	$17.93	$192.14	$184.10	$16.71
25	$292.20	$294.08	$22.01	$-	$-	$-	$72.95	$69.21	$18.05	$219.25	$223.06	$16.63
26	$330.19	$323.48	$33.94	$-	$-	$-	$74.24	$73.46	$10.59	$255.95	$250.16	$25.12
27	$354.90	$354.58	$15.68	$-	$-	$-	$81.58	$87.37	$17.01	$273.32	$276.14	$19.69
28	$351.48	$353.21	$28.13	$-	$-	$-	$75.91	$78.81	$9.34	$275.58	$278.97	$20.98
29	$382.06	$381.94	$21.04	$-	$-	$-	$86.43	$78.17	$21.78	$295.62	$293.09	$31.05
30	$373.05	$373.08	$22.93	$-	$-	$-	$86.32	$83.82	$13.39	$286.73	$284.04	$17.39

Table F.5 NCDOT Costs for In-House Work (15-year Period; Independent Replacement)

Year	Total (Avg.)	Total (Med.)	Total (St. Dev.)	Blanket (Avg.)	Blanket (Med.)	Blanket (St. Dev.)	Signal Head Spot (Avg.)	Signal Head Spot (Med.)	Signal Head Spot (St. Dev.)	Module Spot (Avg.)	Module Spot (Med.)	Module Spot (St. Dev.)
1	$879.82	$876.31	$30.04	$104.06	$102.56	$3.77	$141.85	$144.50	$19.74	$633.92	$626.44	$30.60
2	$743.53	$738.52	$43.33	$110.44	$109.37	$5.96	$137.10	$133.36	$14.87	$495.99	$494.71	$29.56
3	$644.02	$649.79	$35.93	$105.90	$105.58	$5.14	$137.19	$130.85	$16.98	$400.93	$403.62	$25.57
4	$543.18	$547.54	$36.06	$99.98	$99.98	$2.89	$119.82	$119.78	$16.60	$323.38	$327.47	$20.17
5	$492.29	$493.22	$24.51	$109.55	$110.34	$4.83	$116.24	$116.93	$8.75	$266.51	$265.80	$20.49
6	$458.64	$455.77	$32.26	$105.07	$104.04	$5.56	$142.89	$131.24	$25.26	$210.68	$213.96	$15.55
7	$381.17	$386.88	$31.39	$99.19	$99.82	$7.04	$115.44	$119.80	$20.69	$166.54	$163.97	$20.04
8	$341.71	$342.02	$18.07	$106.64	$105.33	$5.06	$107.07	$101.31	$14.15	$128.00	$124.26	$12.40
9	$320.20	$306.88	$29.14	$109.95	$109.61	$3.68	$111.44	$108.66	$22.13	$98.80	$95.76	$11.56
10	$272.89	$271.65	$19.64	$96.58	$97.47	$5.28	$99.46	$98.44	$17.62	$76.84	$76.62	$5.18
11	$274.24	$273.43	$22.86	$108.60	$107.84	$7.46	$107.48	$110.24	$17.67	$58.16	$60.26	$6.17
12	$253.38	$253.60	$14.90	$107.25	$107.51	$4.45	$111.21	$109.58	$19.10	$34.92	$35.03	$3.23
13	$225.87	$224.54	$15.67	$96.56	$93.84	$4.71	$101.05	$100.14	$14.18	$28.26	$27.56	$3.23
14	$219.03	$225.42	$24.26	$107.37	$104.60	$6.92	$97.76	$97.50	$19.24	$13.90	$13.08	$4.31
15	$205.80	$204.46	$21.12	$106.86	$105.73	$5.59	$91.22	$90.36	$15.56	$7.71	$7.00	$3.30
16	$195.18	$190.98	$14.42	$104.06	$102.56	$3.77	$85.40	$82.92	$12.36	$5.72	$6.08	$1.45
17	$202.51	$201.12	$21.63	$110.44	$109.37	$5.96	$86.00	$86.28	$18.64	$6.07	$6.08	$1.66
18	$190.16	$187.92	$5.86	$105.90	$105.58	$5.14	$77.25	$76.16	$5.60	$7.01	$7.94	$1.73
19	$189.17	$184.92	$14.51	$99.98	$99.98	$2.89	$82.07	$79.49	$12.76	$7.12	$6.54	$2.64
20	$194.82	$191.46	$10.86	$109.55	$110.34	$4.83	$80.95	$82.24	$11.37	$4.32	$4.67	$1.22
21	$192.78	$192.62	$11.47	$105.07	$104.04	$5.56	$80.47	$81.15	$13.24	$7.24	$7.47	$1.30
22	$185.17	$183.93	$17.98	$99.19	$99.82	$7.04	$78.97	$80.29	$13.74	$7.01	$7.00	$2.39
23	$193.25	$194.44	$11.25	$106.64	$105.33	$5.06	$81.12	$84.25	$10.76	$5.49	$4.67	$1.61
24	$184.88	$184.66	$14.78	$109.95	$109.61	$3.68	$69.55	$71.18	$15.28	$5.37	$3.74	$2.90
25	$171.98	$168.90	$15.00	$96.58	$97.47	$5.28	$69.22	$68.19	$11.14	$6.19	$6.08	$2.95
26	$185.06	$189.82	$11.59	$108.60	$107.84	$7.46	$67.58	$67.62	$12.28	$8.88	$7.94	$3.08
27	$179.05	$177.27	$17.74	$107.25	$107.51	$4.45	$66.20	$64.56	$14.64	$5.61	$5.61	$1.41
28	$169.51	$168.14	$17.03	$96.56	$93.84	$4.71	$66.65	$68.82	$12.73	$6.31	$7.00	$2.43
29	$189.30	$187.10	$15.45	$107.37	$104.60	$6.92	$74.10	$75.26	$10.14	$7.82	$7.47	$2.34
30	$209.89	$210.47	$14.19	$106.86	$105.73	$5.59	$96.13	$93.55	$11.49	$6.89	$7.00	$1.57

Table F.6 Costs for Contracted Work (15-year Period; Independent Replacement)

Year	Total (Avg.)	Total (Med.)	Total (St. Dev.)	Blanket (Avg.)	Blanket (Med.)	Blanket (St. Dev.)	Signal Head Spot (Avg.)	Signal Head Spot (Med.)	Signal Head Spot (St. Dev.)	Module Spot (Avg.)	Module Spot (Med.)	Module Spot (St. Dev.)
1	$1,236.12	$1,231.68	$35.09	$317.28	$315.79	$3.77	$152.53	$155.33	$20.99	$766.31	$757.27	$36.99
2	$1,087.08	$1,082.19	$50.18	$340.07	$339.00	$5.96	$147.44	$143.60	$15.92	$599.58	$598.02	$35.73
3	$967.79	$974.54	$41.74	$335.52	$335.20	$5.15	$147.61	$140.70	$18.27	$484.66	$487.91	$30.91
4	$832.92	$838.72	$41.15	$313.20	$313.20	$2.88	$128.79	$128.85	$17.78	$390.92	$395.86	$24.38
5	$786.41	$788.03	$28.79	$339.18	$339.96	$4.83	$125.07	$126.10	$9.31	$322.17	$321.32	$24.77
6	$743.12	$741.20	$36.18	$334.69	$333.66	$5.56	$153.74	$141.00	$27.09	$254.68	$258.64	$18.80
7	$637.88	$643.33	$35.92	$312.41	$313.04	$7.04	$124.15	$128.88	$22.13	$201.32	$198.22	$24.22
8	$606.17	$606.22	$20.45	$336.27	$334.96	$5.06	$115.17	$108.92	$15.10	$154.73	$150.21	$15.00
9	$579.02	$563.24	$32.70	$339.58	$339.24	$3.68	$120.00	$116.85	$23.62	$119.44	$115.76	$13.97
10	$509.87	$507.80	$21.21	$309.81	$310.70	$5.28	$107.17	$106.14	$18.89	$92.89	$92.61	$6.27
11	$524.11	$523.05	$24.23	$338.23	$337.46	$7.46	$115.57	$118.92	$18.88	$70.31	$72.84	$7.46
12	$498.69	$498.26	$15.88	$336.88	$337.14	$4.45	$119.60	$118.17	$20.50	$42.21	$42.36	$3.91
13	$452.68	$451.12	$16.70	$309.78	$307.06	$4.71	$108.74	$107.65	$15.38	$34.16	$33.32	$3.90
14	$458.92	$464.80	$26.05	$337.00	$334.22	$6.93	$105.13	$104.82	$20.60	$16.80	$15.81	$5.21
15	$443.93	$442.28	$22.58	$336.49	$335.36	$5.59	$98.13	$97.30	$16.60	$9.32	$8.48	$3.99
16	$416.09	$411.62	$15.16	$317.28	$315.79	$3.77	$91.89	$89.16	$13.10	$6.92	$7.35	$1.75
17	$439.82	$438.56	$23.30	$340.07	$339.00	$5.96	$92.41	$92.62	$20.22	$7.34	$7.35	$2.00
18	$427.08	$424.38	$6.36	$335.52	$335.20	$5.15	$83.09	$81.82	$6.16	$8.47	$9.60	$2.09
19	$410.08	$405.60	$15.92	$313.20	$313.20	$2.88	$88.27	$85.54	$13.77	$8.61	$7.91	$3.19
20	$431.38	$428.02	$11.70	$339.18	$339.96	$4.83	$86.98	$88.10	$12.32	$5.23	$5.65	$1.47
21	$430.06	$429.95	$12.53	$334.69	$333.66	$5.56	$86.62	$87.49	$14.35	$8.75	$9.04	$1.57
22	$405.78	$404.86	$19.45	$312.41	$313.04	$7.04	$84.90	$86.34	$14.83	$8.47	$8.48	$2.89
23	$429.95	$431.28	$11.87	$336.27	$334.96	$5.06	$87.04	$90.20	$11.51	$6.64	$5.65	$1.95
24	$420.78	$420.72	$15.88	$339.58	$339.24	$3.68	$74.70	$76.44	$16.33	$6.49	$4.52	$3.51
25	$391.72	$389.39	$15.91	$309.81	$310.70	$5.28	$74.43	$73.46	$12.05	$7.48	$7.35	$3.57
26	$421.69	$426.58	$12.01	$338.23	$337.46	$7.46	$72.74	$72.60	$13.25	$10.73	$9.60	$3.72
27	$414.83	$412.95	$18.58	$336.88	$337.14	$4.45	$71.18	$69.44	$15.53	$6.78	$6.78	$1.71
28	$389.00	$388.00	$18.05	$309.78	$307.06	$4.71	$71.60	$74.18	$13.47	$7.62	$8.48	$2.94
29	$426.22	$424.05	$16.25	$337.00	$334.22	$6.93	$79.76	$81.11	$10.88	$9.46	$9.04	$2.82
30	$448.25	$448.54	$14.86	$336.49	$335.36	$5.59	$103.42	$100.67	$12.18	$8.33	$8.48	$1.90

Table F.7 NCDOT Costs for In-House Work (15-year Period; Joint Replacement)

Year	Total (Avg.)	Total (Med.)	Total (St. Dev.)	Blanket (Avg.)	Blanket (Med.)	Blanket (St. Dev.)	Signal Head Spot (Avg.)	Signal Head Spot (Med.)	Signal Head Spot (St. Dev.)	Module Spot (Avg.)	Module Spot (Med.)	Module Spot (St. Dev.)
1	$989.64	$987.76	$29.30	$247.45	$247.92	$10.54	$114.58	$114.57	$10.87	$627.61	$621.30	$19.26
2	$880.34	$880.86	$38.89	$251.83	$248.28	$26.10	$120.95	$118.15	$17.17	$507.56	$507.79	$28.45
3	$770.89	$764.82	$37.15	$260.80	$263.38	$17.23	$95.61	$103.01	$16.83	$414.48	$420.43	$25.29
4	$676.50	$677.83	$40.72	$253.96	$253.91	$21.45	$101.73	$105.57	$21.65	$320.81	$321.40	$15.81
5	$620.81	$617.88	$34.32	$270.73	$266.20	$12.61	$77.97	$75.82	$18.12	$272.11	$275.15	$17.94
6	$563.36	$560.29	$39.40	$263.94	$266.20	$24.19	$80.44	$75.71	$10.23	$218.98	$219.56	$13.45
7	$473.59	$475.76	$14.20	$238.50	$236.74	$22.87	$68.08	$75.96	$17.88	$167.00	$171.91	$12.84
8	$445.31	$444.76	$20.29	$259.70	$257.19	$15.25	$54.70	$56.70	$10.82	$130.92	$128.46	$8.18
9	$409.21	$421.14	$31.07	$265.73	$268.32	$19.95	$46.20	$46.02	$11.60	$97.28	$93.42	$13.27
10	$351.19	$352.40	$23.15	$238.65	$237.28	$24.12	$38.72	$36.38	$7.79	$73.81	$72.88	$4.38
11	$352.62	$351.34	$23.68	$260.05	$260.58	$19.61	$30.90	$31.60	$7.25	$61.66	$62.60	$10.39
12	$332.89	$331.49	$16.16	$272.93	$277.24	$14.35	$20.60	$19.57	$5.39	$39.36	$38.30	$9.00
13	$289.64	$290.14	$18.95	$244.36	$245.36	$19.80	$19.82	$19.02	$8.84	$25.46	$26.16	$4.05
14	$284.95	$283.18	$22.28	$259.42	$256.15	$21.69	$10.93	$11.78	$5.21	$14.60	$14.01	$2.49
15	$281.21	$283.52	$17.98	$271.14	$274.28	$17.76	$2.94	$1.18	$3.72	$7.12	$7.00	$1.86
16	$256.80	$256.97	$10.30	$247.45	$247.92	$10.54	$3.51	$2.36	$1.72	$5.84	$6.08	$2.10
17	$263.15	$263.29	$25.03	$251.83	$248.28	$26.10	$4.78	$3.54	$4.41	$6.54	$6.08	$1.41
18	$273.72	$277.81	$19.14	$260.80	$263.38	$17.23	$5.91	$4.98	$5.39	$7.01	$7.00	$2.06
19	$265.65	$266.56	$20.12	$253.96	$253.91	$21.45	$5.28	$4.71	$2.95	$6.42	$7.00	$1.76
20	$282.00	$277.19	$11.11	$270.73	$266.20	$12.61	$4.85	$4.71	$1.80	$6.43	$6.54	$1.53
21	$275.85	$279.07	$26.34	$263.94	$266.20	$24.19	$3.51	$2.36	$2.75	$8.41	$7.94	$2.60
22	$250.51	$246.73	$23.34	$238.50	$236.74	$22.87	$5.93	$4.71	$2.52	$6.07	$7.47	$2.55
23	$271.78	$270.70	$20.28	$259.70	$257.19	$15.25	$5.54	$4.71	$4.27	$6.54	$6.54	$1.66
24	$279.92	$283.34	$21.38	$265.73	$268.32	$19.95	$6.24	$4.71	$3.96	$7.94	$7.94	$2.45
25	$253.00	$250.43	$28.02	$238.65	$237.28	$24.12	$7.81	$7.07	$4.29	$6.54	$6.54	$2.23
26	$269.50	$271.95	$19.96	$260.05	$260.58	$19.61	$2.67	$2.64	$2.58	$6.77	$7.47	$1.98
27	$286.15	$293.48	$14.94	$272.93	$277.24	$14.35	$4.46	$3.54	$3.24	$8.76	$8.88	$3.67
28	$255.76	$253.56	$21.39	$244.36	$245.36	$19.80	$5.09	$4.71	$3.01	$6.30	$5.60	$2.72
29	$272.77	$270.21	$23.52	$259.42	$256.15	$21.69	$4.12	$3.54	$2.74	$9.23	$9.34	$2.09
30	$281.98	$283.70	$19.70	$271.14	$274.28	$17.76	$5.12	$3.54	$3.77	$5.72	$5.61	$1.83

Table F.8 Costs for Contracted Work (15-year Period; Joint Replacement)

Year	Total (Avg.)	Total (Med.)	Total (St. Dev.)	Blanket (Avg.)	Blanket (Med.)	Blanket (St. Dev.)	Signal Head Spot (Avg.)	Signal Head Spot (Med.)	Signal Head Spot (St. Dev.)	Module Spot (Avg.)	Module Spot (Med.)	Module Spot (St. Dev.)
1	$1,342.68	$1,340.01	$33.21	$460.68	$461.14	$10.54	$123.31	$123.54	$11.64	$758.68	$751.06	$23.27
2	$1,225.02	$1,224.04	$42.46	$481.46	$477.90	$26.10	$130.00	$127.22	$18.23	$613.56	$613.84	$34.39
3	$1,094.32	$1,088.70	$41.87	$490.43	$493.00	$17.23	$102.85	$110.72	$18.01	$501.04	$508.24	$30.57
4	$964.40	$967.64	$43.19	$467.18	$467.13	$21.45	$109.41	$113.38	$23.25	$387.81	$388.52	$19.12
5	$913.19	$910.82	$38.62	$500.36	$495.82	$12.61	$83.89	$81.66	$19.38	$328.94	$332.61	$21.69
6	$844.69	$840.54	$41.95	$493.56	$495.82	$24.19	$86.42	$81.47	$10.97	$264.71	$265.41	$16.27
7	$726.86	$729.18	$14.12	$451.73	$449.96	$22.87	$73.25	$81.72	$19.22	$201.88	$207.81	$15.52
8	$706.40	$706.58	$21.58	$489.32	$486.82	$15.25	$58.82	$60.98	$11.68	$158.26	$155.30	$9.89
9	$662.62	$674.67	$33.03	$495.36	$497.94	$19.95	$49.66	$49.64	$12.43	$117.60	$112.94	$16.05
10	$582.78	$584.55	$23.33	$451.88	$450.50	$24.13	$41.68	$39.01	$8.47	$89.22	$88.09	$5.30
11	$597.54	$595.50	$24.42	$489.68	$490.21	$19.61	$33.32	$34.03	$7.78	$74.54	$75.67	$12.56
12	$572.29	$570.29	$17.26	$502.55	$506.86	$14.35	$22.16	$21.04	$5.76	$47.58	$46.30	$10.87
13	$509.64	$510.78	$19.07	$457.58	$458.58	$19.80	$21.28	$20.48	$9.46	$30.78	$31.62	$4.89
14	$518.43	$517.10	$22.61	$489.05	$485.78	$21.69	$11.73	$12.75	$5.58	$17.65	$16.94	$3.02
15	$512.57	$514.81	$18.10	$500.77	$503.92	$17.76	$3.19	$1.27	$4.03	$8.61	$8.48	$2.25
16	$471.52	$471.36	$10.26	$460.68	$461.14	$10.54	$3.78	$2.55	$1.82	$7.06	$7.35	$2.54
17	$494.54	$495.16	$25.01	$481.46	$477.90	$26.10	$5.17	$3.82	$4.77	$7.91	$7.35	$1.70
18	$505.25	$509.38	$19.29	$490.43	$493.00	$17.23	$6.35	$5.38	$5.77	$8.47	$8.48	$2.49
19	$480.63	$481.84	$20.14	$467.18	$467.13	$21.45	$5.69	$5.10	$3.15	$7.77	$8.48	$2.13
20	$513.36	$508.67	$10.99	$500.36	$495.82	$12.61	$5.24	$5.10	$1.94	$7.77	$7.91	$1.85
21	$507.51	$510.94	$26.64	$493.56	$495.82	$24.19	$3.78	$2.55	$2.93	$10.16	$9.60	$3.13
22	$465.47	$461.23	$23.41	$451.73	$449.96	$22.87	$6.39	$5.10	$2.69	$7.34	$9.04	$3.08
23	$503.19	$502.18	$20.86	$489.32	$486.82	$15.25	$5.96	$5.10	$4.55	$7.91	$7.91	$2.00
24	$511.65	$515.22	$21.37	$495.36	$497.94	$19.95	$6.68	$5.10	$4.24	$9.60	$9.60	$2.95
25	$468.18	$465.90	$28.49	$451.88	$450.50	$24.13	$8.40	$7.65	$4.56	$7.91	$7.91	$2.70
26	$500.71	$503.43	$19.87	$489.68	$490.21	$19.61	$2.84	$2.82	$2.74	$8.19	$9.04	$2.39
27	$517.95	$524.58	$14.94	$502.55	$506.86	$14.35	$4.80	$3.82	$3.48	$10.59	$10.72	$4.43
28	$470.66	$468.05	$21.51	$457.58	$458.58	$19.80	$5.46	$5.10	$3.16	$7.62	$6.78	$3.29
29	$504.67	$502.17	$23.77	$489.05	$485.78	$21.69	$4.46	$3.82	$2.97	$11.15	$11.29	$2.52
30	$513.20	$514.79	$19.81	$500.77	$503.92	$17.76	$5.51	$3.82	$4.04	$6.92	$6.78	$2.21

Table F.9 NCDOT Costs for In-House Work (5-year Period; Independent Replacement)

Year	Total (Avg.)	Total (Med.)	Total (St. Dev.)	Blanket (Avg.)	Blanket (Med.)	Blanket (St. Dev.)	Signal Head Spot (Avg.)	Signal Head Spot (Med.)	Signal Head Spot (St. Dev.)	Module Spot (Avg.)	Module Spot (Med.)	Module Spot (St. Dev.)
1	$986.81	$975.88	$46.74	$318.59	$319.12	$8.11	$140.58	$146.46	$18.82	$527.64	$523.20	$38.03
2	$777.47	$780.08	$26.68	$313.62	$316.53	$11.01	$112.20	$107.05	$17.09	$351.64	$347.09	$20.80
3	$658.30	$648.66	$23.87	$316.99	$318.06	$10.51	$128.87	$125.91	$16.27	$212.44	$205.54	$22.08
4	$533.06	$534.91	$17.32	$314.61	$312.90	$10.76	$124.20	$127.15	$13.20	$94.25	$91.56	$8.89
5	$454.02	$457.01	$27.92	$318.45	$317.90	$11.68	$127.51	$135.36	$20.81	$8.06	$7.94	$3.35
6	$117.36	$112.42	$15.07	$-	$-	$-	$110.94	$106.93	$14.10	$6.42	$6.08	$2.42
7	$130.35	$125.28	$15.71	$-	$-	$-	$126.26	$122.00	$15.10	$4.09	$3.27	$1.99
8	$123.67	$124.42	$12.22	$-	$-	$-	$118.53	$120.30	$13.55	$5.14	$5.14	$2.39
9	$100.44	$99.40	$10.13	$-	$-	$-	$94.72	$94.72	$11.02	$5.72	$6.08	$1.76
10	$103.96	$112.77	$15.67	$-	$-	$-	$99.63	$108.25	$15.44	$4.32	$3.74	$1.41
11	$108.89	$117.80	$16.91	$-	$-	$-	$103.98	$113.30	$17.38	$4.91	$5.14	$1.20
12	$97.55	$93.46	$12.88	$-	$-	$-	$92.99	$90.19	$12.44	$4.56	$3.74	$2.71
13	$103.56	$98.76	$12.71	$-	$-	$-	$98.66	$95.50	$11.56	$4.91	$3.74	$1.98
14	$96.38	$95.39	$6.73	$-	$-	$-	$91.24	$90.78	$6.97	$5.14	$5.14	$2.34
15	$104.11	$100.73	$15.32	$-	$-	$-	$97.57	$94.20	$15.73	$6.54	$7.01	$3.24
16	$429.01	$427.74	$17.30	$318.59	$319.12	$8.11	$100.96	$100.56	$13.00	$9.46	$8.88	$1.96
17	$405.77	$405.38	$21.49	$313.62	$316.53	$11.01	$83.62	$80.36	$12.96	$8.52	$7.94	$3.14
18	$413.93	$416.68	$24.74	$316.99	$318.06	$10.51	$87.01	$87.36	$19.29	$9.93	$9.81	$2.54
19	$403.83	$404.66	$13.63	$314.61	$312.90	$10.76	$78.01	$80.50	$12.98	$11.21	$10.28	$1.66
20	$413.24	$413.15	$28.49	$318.45	$317.90	$11.68	$86.62	$89.36	$17.32	$8.17	$8.40	$2.68
21	$90.45	$85.18	$18.46	$-	$-	$-	$83.33	$78.59	$16.86	$7.13	$6.08	$4.24
22	$79.81	$73.61	$19.28	$-	$-	$-	$74.21	$67.72	$19.68	$5.61	$5.61	$1.66
23	$80.69	$73.94	$13.61	$-	$-	$-	$75.44	$69.27	$14.14	$5.26	$5.61	$2.17
24	$80.11	$77.39	$11.46	$-	$-	$-	$74.73	$72.25	$9.36	$5.37	$5.14	$2.33
25	$76.91	$74.95	$9.53	$-	$-	$-	$70.13	$69.34	$10.26	$6.77	$7.00	$1.56
26	$66.35	$65.99	$8.79	$-	$-	$-	$60.51	$62.26	$9.17	$5.84	$6.08	$1.78
27	$77.72	$81.68	$12.03	$-	$-	$-	$72.46	$73.85	$11.33	$5.26	$5.14	$2.23
28	$78.49	$79.07	$12.48	$-	$-	$-	$72.30	$72.53	$10.00	$6.19	$6.54	$2.78
29	$85.61	$82.02	$20.51	$-	$-	$-	$81.41	$76.89	$20.37	$4.20	$4.67	$1.00
30	$84.40	$81.69	$12.68	$-	$-	$-	$77.50	$76.09	$12.53	$6.89	$6.08	$2.34

Table F.10 Costs for Contracted Work (5-year Period; Independent Replacement)

Year	Total (Avg.)	Total (Med.)	Total (St. Dev.)	Blanket (Avg.)	Blanket (Med.)	Blanket (St. Dev.)	Signal Head Spot (Avg.)	Signal Head Spot (Med.)	Signal Head Spot (St. Dev.)	Module Spot (Avg.)	Module Spot (Med.)	Module Spot (St. Dev.)
1	$1,780.04	$1,762.90	$54.87	$991.07	$991.60	$8.11	$151.14	$157.38	$20.11	$1,780.04	$1,762.90	$54.87
2	$1,532.02	$1,535.16	$29.78	$986.10	$989.01	$11.01	$120.84	$115.25	$18.53	$1,532.02	$1,535.16	$29.78
3	$1,384.85	$1,373.92	$27.44	$989.47	$990.54	$10.51	$138.58	$135.48	$17.61	$1,384.85	$1,373.92	$27.44
4	$1,234.66	$1,235.76	$19.04	$987.09	$985.38	$10.76	$133.64	$137.10	$14.24	$1,234.66	$1,235.76	$19.04
5	$1,137.89	$1,141.01	$29.27	$990.93	$990.38	$11.68	$137.22	$145.70	$22.29	$1,137.89	$1,141.01	$29.27
6	$127.17	$121.98	$16.22	$-	$-	$-	$119.40	$115.02	$15.04	$127.17	$121.98	$16.22
7	$140.62	$134.83	$16.60	$-	$-	$-	$135.68	$130.88	$15.88	$140.62	$134.83	$16.60
8	$133.64	$133.69	$12.78	$-	$-	$-	$127.43	$129.08	$14.35	$133.64	$133.69	$12.78
9	$108.86	$107.60	$10.58	$-	$-	$-	$101.94	$101.94	$11.63	$108.86	$107.60	$10.58
10	$112.34	$121.45	$16.89	$-	$-	$-	$107.12	$116.35	$16.59	$112.34	$121.45	$16.89
11	$117.84	$127.36	$18.19	$-	$-	$-	$111.91	$122.08	$18.75	$117.84	$127.36	$18.19
12	$105.60	$101.09	$13.97	$-	$-	$-	$100.09	$96.92	$13.35	$105.60	$101.09	$13.97
13	$111.90	$106.38	$13.67	$-	$-	$-	$105.97	$102.43	$12.27	$111.90	$106.38	$13.67
14	$104.45	$103.88	$7.19	$-	$-	$-	$98.24	$98.09	$7.41	$104.45	$103.88	$7.19
15	$112.79	$108.83	$16.42	$-	$-	$-	$104.89	$100.92	$16.86	$112.79	$108.83	$16.42
16	$1,111.00	$1,109.00	$17.96	$991.07	$991.60	$8.11	108.50	$107.97	$13.96	$1,111.00	$1,109.00	$17.96
17	$1,086.23	$1,085.96	$22.11	$986.10	$989.01	$11.01	$89.82	$86.22	$13.69	$1,086.23	$1,085.96	$22.11
18	$1,095.02	$1,097.65	$25.76	$989.47	$990.54	$10.51	$93.54	$93.99	$20.68	$1,095.02	$1,097.65	$25.76
19	$1,084.63	$1,085.82	$14.39	$987.09	$985.38	$10.76	$83.99	$86.74	$14.09	$1,084.63	$1,085.82	$14.39
20	$1,094.11	$1,094.12	$29.99	$990.93	$990.38	$11.68	$93.30	$96.10	$18.56	$1,094.11	$1,094.12	$29.99
21	$98.23	$92.30	$19.99	$-	$-	$-	$89.62	$84.54	$18.00	$98.23	$92.30	$19.99
22	$86.59	$80.06	$20.82	$-	$-	$-	$79.82	$72.79	$21.28	$86.59	$80.06	$20.82
23	$87.43	$80.28	$14.44	$-	$-	$-	$81.07	$74.54	$15.05	$87.43	$80.28	$14.44
24	$87.03	$83.74	$12.78	$-	$-	$-	$80.54	$77.52	$10.23	$87.03	$83.74	$12.78
25	$83.66	$81.49	$10.05	$-	$-	$-	$75.47	$74.71	$10.93	$83.66	$81.49	$10.05
26	$72.13	$71.26	$9.42	$-	$-	$-	$65.07	$66.74	$9.84	$72.13	$71.26	$9.42
27	$84.37	$88.60	$12.95	$-	$-	$-	$78.02	$79.41	$12.11	$84.37	$88.60	$12.95
28	$85.32	$86.00	$13.79	$-	$-	$-	$77.84	$78.09	$10.77	$85.32	$86.00	$13.79
29	$92.68	$89.25	$21.86	$-	$-	$-	$87.60	$83.04	$21.68	$92.68	$89.25	$21.86
30	$91.79	$89.02	$13.70	$-	$-	$-	$83.46	$82.24	$13.51	$91.79	$89.02	$13.70

Table F.11 NCDOT Costs for In-House Work (5-year Period; Independent Replacement)

Year	Total (Avg.)	Total (Med.)	Total (St. Dev.)	Blanket (Avg.)	Blanket (Med.)	Blanket (St. Dev.)	Signal Head Spot (Avg.)	Signal Head Spot (Med.)	Signal Head Spot (St. Dev.)	Module Spot (Avg.)	Module Spot (Med.)	Module Spot (St. Dev.)
1	$1,426.87	$1,421.62	$23.84	$793.33	$788.77	$28.69	$100.05	$96.46	$21.25	$533.48	$536.29	$16.81
2	$1,214.28	$1,200.15	$53.26	$775.34	$763.66	$30.10	$75.15	$73.98	$8.71	$363.79	$356.90	$25.57
3	$1,043.31	$1,040.85	$26.75	$772.91	$769.18	$19.89	$57.15	$60.86	$15.66	$213.25	$215.36	$19.92
4	$925.96	$917.30	$40.42	$797.04	$789.98	$37.70	$31.75	$31.72	$4.16	$97.17	$93.90	$7.71
5	$793.52	$790.66	$44.88	$780.70	$775.70	$42.57	$5.35	$4.71	$4.29	$7.47	$6.54	$3.96
6	$9.28	$9.60	$3.44	$-	$-	$-	$3.22	$2.36	$2.10	$6.07	$5.60	$2.55
7	$9.46	$9.14	$3.04	$-	$-	$-	$4.44	$4.61	$2.57	$5.02	$5.14	$1.93
8	$9.53	$9.19	$3.81	$-	$-	$-	$2.99	$3.54	$2.76	$6.54	$5.14	$2.73
9	$12.36	$11.39	$5.69	$-	$-	$-	$5.59	$5.79	$4.72	$6.77	$6.54	$2.77
10	$9.90	$7.98	$4.61	$-	$-	$-	$5.93	$4.72	$4.05	$3.97	$3.74	$1.56
11	$10.93	$10.10	$4.95	$-	$-	$-	$5.09	$2.64	$4.82	$5.84	$5.60	$2.53
12	$9.25	$8.44	$3.68	$-	$-	$-	$4.46	$3.54	$3.22	$4.79	$4.67	$2.36
13	$12.24	$11.39	$5.36	$-	$-	$-	$6.51	$5.78	$4.63	$5.72	$5.61	$1.16
14	$8.10	$7.98	$3.37	$-	$-	$-	$3.90	$4.71	$3.10	$4.20	$4.20	$1.12
15	$11.25	$10.54	$3.37	$-	$-	$-	$3.31	$3.54	$2.55	$7.94	$7.94	$2.55
16	$806.20	$798.60	$27.96	$793.33	$788.77	$28.69	$3.87	$3.43	$3.93	$8.99	$9.34	$2.49
17	$787.43	$773.71	$31.44	$775.34	$763.66	$30.10	$3.45	$2.64	$2.33	$8.64	$9.81	$3.15
18	$786.16	$783.27	$22.01	$772.91	$769.18	$19.89	$3.67	$3.81	$2.89	$9.58	$9.81	$2.63
19	$808.81	$800.98	$38.21	$797.04	$789.98	$37.70	$3.48	$2.36	$3.25	$8.29	$7.94	$1.90
20	$793.52	$791.74	$42.50	$780.70	$775.70	$42.57	$6.27	$5.89	$4.76	$6.54	$5.60	$2.73
21	$10.98	$11.25	$3.15	$-	$-	$-	$4.10	$4.71	$2.05	$6.89	$7.00	$2.17
22	$9.86	$10.12	$2.47	$-	$-	$-	$4.49	$4.71	$3.45	$5.37	$5.14	$2.53
23	$9.53	$9.36	$3.21	$-	$-	$-	$3.58	$2.36	$3.31	$5.96	$6.54	$1.57
24	$11.62	$10.37	$4.81	$-	$-	$-	$6.36	$6.06	$3.56	$5.26	$5.61	$2.12
25	$9.19	$7.98	$3.73	$-	$-	$-	$4.17	$3.54	$3.53	$5.02	$5.14	$2.17
26	$11.12	$10.96	$3.60	$-	$-	$-	$5.16	$4.08	$3.50	$5.96	$5.60	$1.72
27	$11.46	$11.84	$4.49	$-	$-	$-	$5.27	$3.43	$4.17	$6.19	$6.08	$2.34
28	$13.72	$10.92	$5.81	$-	$-	$-	$8.12	$8.04	$4.12	$5.61	$5.61	$2.55
29	$8.41	$8.95	$4.38	$-	$-	$-	$3.15	$2.64	$2.62	$5.26	$5.14	$2.73
30	$12.11	$11.94	$3.33	$-	$-	$-	$4.76	$4.71	$2.55	$7.36	$7.00	$2.66

Table F.12 Costs for Contracted Work (5-year Period; Independent Replacement)

Year	Total (Avg.)	Total (Med.)	Total (St. Dev.)	Blanket (Avg.)	Blanket (Med.)	Blanket (St. Dev.)	Signal Head Spot (Avg.)	Signal Head Spot (Med.)	Signal Head Spot (St. Dev.)	Module Spot (Avg.)	Module Spot (Med.)	Module Spot (St. Dev.)
1	$2,218.27	$2,213.23	$25.49	$1,465.81	$1,461.25	$28.69	$107.57	$104.07	$22.68	$644.90	$648.28	$20.32
2	$1,968.42	$1,951.46	$57.98	$1,447.82	$1,436.14	$30.10	$80.84	$79.64	$9.47	$439.77	$431.44	$30.90
3	$1,764.74	$1,759.86	$29.78	$1,445.39	1,441.66	$19.89	$61.56	$65.54	$16.78	$257.79	$260.33	$24.08
4	$1,621.12	$1,611.64	$41.18	$1,469.52	1,462.46	$37.70	$34.15	$34.26	$4.43	$117.46	$113.50	$9.31
5	$1,467.98	$1,465.98	$44.99	$1,453.18	$1,448.18	$42.57	$5.76	$5.10	$4.59	$9.04	$7.91	$4.79
6	$10.80	$11.17	$3.96	$-	$-	$-	$3.46	$2.55	$2.24	$7.34	$6.78	$3.08
7	$10.82	$10.60	$3.44	$-	$-	$-	$4.75	$4.90	$2.76	$6.07	$6.22	$2.33
8	$11.11	$10.46	$4.34	$-	$-	$-	$3.21	$3.82	$2.95	$7.91	$6.22	$3.30
9	$14.17	$12.96	$6.29	$-	$-	$-	$5.98	$6.18	$5.04	$8.19	$7.91	$3.35
10	$11.20	$9.06	$5.06	$-	$-	$-	$6.40	$5.10	$4.34	$4.80	$4.52	$1.89
11	$12.52	$11.86	$5.40	$-	$-	$-	$5.46	$2.82	$5.16	$7.06	$6.78	$3.06
12	$10.59	$9.62	$4.11	$-	$-	$-	$4.80	$3.82	$3.44	$5.79	$5.65	$2.86
13	$13.87	$12.96	$5.80	$-	$-	$-	$6.95	$6.18	$4.92	$6.92	$6.78	$1.41
14	$9.30	$9.06	$3.70	$-	$-	$-	$4.21	$5.10	$3.35	$5.08	$5.08	$1.35
15	$13.18	$12.30	$3.88	$-	$-	$-	$3.58	$3.82	$2.76	$9.60	$9.60	$3.08
16	$1,480.85	$1,472.84	$28.14	$1,465.81	$1,461.25	$28.69	$4.16	$3.62	$4.23	$10.87	$11.29	$3.01
17	$1,461.98	$1,448.15	$31.48	$1,447.82	$1,436.14	$30.10	$3.71	$2.82	$2.51	$10.45	$11.86	$3.80
18	$1,460.93	$1,458.19	$22.36	$1,445.39	$1,441.66	$19.89	$3.96	$4.10	$3.12	$11.58	$11.86	$3.18
19	$1,483.27	$1,475.32	$38.19	$1,469.52	$1,462.46	$37.70	$3.72	$2.55	$3.45	$10.02	$9.60	$2.29
20	$1,467.82	$1,466.16	$42.54	$1,453.18	$1,448.18	$42.57	$6.73	$6.38	$5.03	$7.91	$6.78	$3.30
21	$12.74	$13.01	$3.59	$-	$-	$-	$4.41	$5.10	$2.18	$8.33	$8.48	$2.63
22	$11.34	$11.59	$2.71	$-	$-	$-	$4.85	$5.10	$3.73	$6.50	$6.22	$3.06
23	$11.05	$11.02	$3.49	$-	$-	$-	$3.84	$2.55	$3.54	$7.20	$7.91	$1.90
24	$13.21	$11.74	$5.39	$-	$-	$-	$6.85	$6.45	$3.83	$6.36	$6.78	$2.56
25	$10.56	$9.06	$4.11	$-	$-	$-	$4.48	$3.82	$3.78	$6.07	$6.22	$2.63
26	$12.73	$12.52	$3.93	$-	$-	$-	$5.52	$4.38	$3.76	$7.20	$6.78	$2.08
27	$13.09	$13.52	$4.87	$-	$-	$-	$5.61	$3.62	$4.39	$7.48	$7.35	$2.82
28	$15.45	$12.39	$6.54	$-	$-	$-	$8.68	$8.53	$4.42	$6.78	$6.78	$3.08
29	$9.75	$10.32	$5.02	$-	$-	$-	$3.39	$2.82	$2.82	$6.36	$6.22	$3.30
30	$14.01	$13.66	$3.82	$-	$-	$-	$5.12	$5.10	$2.70	$8.90	$8.48	$3.22

Table F.13 NCDOT Costs for In-House Work (1-year Period; Independent Replacement, 0% Inflation)

Year	Total (Avg.)	Total (Med.)	Total (St. Dev.)	Blanket (Avg.)	Blanket (Med.)	Blanket (St. Dev.)	Signal Head Spot (Avg.)	Signal Head Spot (Med.)	Signal Head Spot (St. Dev.)	Module Spot (Avg.)	Module Spot (Med.)	Module Spot (St. Dev.)
1	$1,732.78	$1,735.44	$30.26	$1,578.39	$1,577.08	$20.77	$137.10	$134.01	$10.08	$17.28	$16.82	$5.29
2	$133.90	$135.82	$10.25	$-	$-	$-	$129.24	$129.74	$10.42	$4.67	$4.67	$1.58
3	$125.72	$135.36	$23.65	$-	$-	$-	$121.17	$129.74	$21.97	$4.55	$4.67	$2.26
4	$130.29	$121.65	$24.21	$-	$-	$-	$124.56	$113.72	$25.07	$5.72	$5.61	$2.26
5	$134.03	$134.00	$22.26	$-	$-	$-	$129.13	$130.72	$21.68	$4.91	$3.74	$2.22
6	$118.33	$116.33	$13.79	$-	$-	$-	$113.90	$111.66	$13.96	$4.44	$4.67	$1.92
7	$117.29	$116.29	$24.10	$-	$-	$-	$112.85	$113.50	$23.78	$4.44	$4.20	$2.04
8	$119.07	$121.12	$13.31	$-	$-	$-	$112.99	$114.26	$13.84	$6.07	$5.61	$1.80
9	$108.17	$108.26	$17.60	$-	$-	$-	$103.38	$103.60	$18.25	$4.79	$4.68	$2.14
10	$117.90	$112.04	$14.83	$-	$-	$-	$114.05	$109.23	$15.65	$3.85	$4.20	$2.57
11	$108.49	$102.40	$16.73	$-	$-	$-	$101.95	$94.93	$18.23	$6.54	$7.47	$2.83
12	$98.94	$95.60	$18.99	$-	$-	$-	$93.45	$90.47	$19.85	$5.49	$5.14	$2.52
13	$92.04	$93.64	$8.48	$-	$-	$-	$86.08	$84.97	$7.49	$5.96	$5.61	$2.82
14	$101.07	$96.34	$26.10	$-	$-	$-	$95.81	$91.20	$27.30	$5.26	$5.14	$2.44
15	$117.20	$114.09	$17.84	$-	$-	$-	$100.97	$100.54	$17.83	$16.24	$16.35	$4.55
16	$1,681.91	$1,688.39	$27.21	$1,578.39	$1,577.08	$20.77	$88.58	$94.43	$16.60	$14.95	$15.88	$3.77
17	$94.91	$100.38	$18.29	$-	$-	$-	$89.66	$94.98	$19.53	$5.25	$6.07	$2.87
18	$93.88	$95.82	$15.17	$-	$-	$-	$88.86	$89.74	$14.47	$5.02	$4.67	$1.65
19	$85.89	$89.60	$14.32	$-	$-	$-	$81.10	$84.93	$15.32	$4.79	$5.14	$2.03
20	$85.49	$85.88	$11.38	$-	$-	$-	$80.58	$81.68	$11.25	$4.91	$4.68	$1.92
21	$83.89	$84.72	$20.60	$-	$-	$-	$79.45	$80.04	$19.87	$4.44	$4.67	$1.92
22	$76.50	$79.37	$18.12	$-	$-	$-	$70.19	$74.23	$18.04	$6.31	$5.61	$1.30
23	$80.23	$84.80	$11.59	$-	$-	$-	$74.98	$78.07	$11.39	$5.26	$5.14	$1.99
24	$68.04	$64.21	$16.53	$-	$-	$-	$62.90	$59.96	$17.51	$5.14	$5.14	$2.60
25	$76.50	$78.27	$17.54	$-	$-	$-	$72.88	$75.93	$17.19	$3.62	$3.74	$1.05
26	$72.79	$76.96	$13.12	$-	$-	$-	$67.76	$72.78	$13.75	$5.02	$5.14	$1.86
27	$72.99	$71.02	$12.69	$-	$-	$-	$67.15	$65.19	$13.35	$5.84	$6.08	$2.04
28	$80.15	$79.64	$12.40	$-	$-	$-	$75.94	$75.44	$12.76	$4.20	$3.74	$2.06
29	$89.67	$86.92	$10.37	$-	$-	$-	$85.47	$82.25	$10.41	$4.21	$3.74	$1.00
30	$98.78	$96.74	$9.78	$-	$-	$-	$82.32	$81.64	$11.02	$16.47	$15.88	$2.64

Table F.14 Costs for Contracted Work (1-year Period; Independent Replacement, 0% Inflation)

Year	Total (Avg.)	Total (Med.)	Total (St. Dev.)	Blanket (Avg.)	Blanket (Med.)	Blanket (St. Dev.)	Signal Head Spot (Avg.)	Signal Head Spot (Med.)	Signal Head Spot (St. Dev.)	Module Spot (Avg.)	Module Spot (Med.)	Module Spot (St. Dev.)
1	$5,109.15	$5,111.88	$31.34	$4,940.79	$4,939.48	$20.77	$147.47	$144.06	$10.66	$20.89	$20.33	$6.39
2	$144.91	$147.24	$10.92	$-	$-	$-	$139.26	$139.89	$11.09	$5.65	$5.65	$1.91
3	$135.99	$146.38	$25.62	$-	$-	$-	$130.49	$139.61	$23.57	$5.51	$5.65	$2.73
4	$140.87	$131.89	$25.91	$-	$-	$-	$133.95	$122.40	$26.94	$6.92	$6.78	$2.73
5	$144.69	$144.43	$23.97	$-	$-	$-	$138.76	$140.48	$23.24	$5.93	$4.52	$2.68
6	$127.84	$125.80	$14.82	$-	$-	$-	$122.48	$120.15	$14.97	$5.37	$5.65	$2.32
7	$126.61	$125.56	$25.91	$-	$-	$-	$121.24	$122.18	$25.52	$5.37	$5.08	$2.47
8	$128.68	$131.17	$14.15	$-	$-	$-	$121.34	$122.66	$14.75	$7.34	$6.78	$2.17
9	$116.95	$117.24	$19.00	$-	$-	$-	$111.16	$111.60	$19.77	$5.79	$5.65	$2.59
10	$127.44	$121.11	$15.69	$-	$-	$-	$122.78	$117.72	$16.62	$4.66	$5.08	$3.10
11	$117.64	$111.38	$17.69	$-	$-	$-	$109.73	$102.34	$19.49	$7.91	$9.04	$3.41
12	$107.14	$103.71	$20.29	$-	$-	$-	$100.50	$97.49	$21.33	$6.64	$6.22	$3.04
13	$99.72	$102.13	$9.38	$-	$-	$-	$92.52	$91.12	$8.08	$7.20	$6.78	$3.41
14	$109.29	$104.62	$27.81	$-	$-	$-	$102.93	$98.41	$29.25	$6.36	$6.22	$2.95
15	$128.37	$124.82	$19.28	$-	$-	$-	$108.75	$108.44	$19.23	$19.62	$19.76	$5.50
16	$5,054.19	$5,059.93	$28.18	$4,940.79	$4,939.48	$20.77	$95.33	$101.65	$17.95	$18.07	$19.20	$4.56
17	$102.77	$108.58	$19.48	$-	$-	$-	$96.41	$101.90	$20.98	$6.36	$7.34	$3.46
18	$101.64	$103.44	$16.34	$-	$-	$-	$95.57	$96.57	$15.46	$6.07	$5.65	$2.00
19	$93.14	$97.21	$15.27	$-	$-	$-	$87.35	$91.56	$16.46	$5.79	$6.22	$2.45
20	$92.63	$92.80	$12.22	$-	$-	$-	$86.70	$87.72	$12.00	$5.93	$5.65	$2.32
21	$90.82	$91.74	$22.05	$-	$-	$-	$85.45	$86.10	$21.16	$5.37	$5.65	$2.32
22	$83.13	$86.10	$19.50	$-	$-	$-	$75.51	$79.88	$19.39	$7.63	$6.78	$1.57
23	$86.99	$91.83	$12.46	$-	$-	$-	$80.63	$84.31	$12.17	$6.36	$6.22	$2.41
24	$73.90	$70.06	$17.56	$-	$-	$-	$67.68	$64.54	$18.72	$6.21	$6.22	$3.14
25	$82.77	$84.22	$18.90	$-	$-	$-	$78.39	$81.40	$18.46	$4.38	$4.52	$1.27
26	$79.08	$83.20	$14.02	$-	$-	$-	$73.01	$78.34	$14.73	$6.07	$6.22	$2.25
27	$79.19	$76.87	$13.65	$-	$-	$-	$72.13	$70.16	$14.41	$7.06	$7.35	$2.47
28	$86.76	$86.28	$13.03	$-	$-	$-	$81.67	$81.19	$13.46	$5.08	$4.52	$2.49
29	$96.96	$94.24	$11.22	$-	$-	$-	$91.88	$88.60	$11.25	$5.08	$4.52	$1.21
30	$108.47	$106.30	$10.30	$-	$-	$-	$88.56	$87.70	$11.77	$19.91	$19.20	$3.19

Table F.15 NCDOT Costs for In-House Work (1-year Period; Joint Replacement, 0% Inflation)

Year	Total (Avg.)	Total (Med.)	Total (St. Dev.)	Blanket (Avg.)	Blanket (Med.)	Blanket (St. Dev.)	Signal Head Spot (Avg.)	Signal Head Spot (Med.)	Signal Head Spot (St. Dev.)	Module Spot (Avg.)	Module Spot (Med.)	Module Spot (St. Dev.)
1	$3,951.68	$3,909.24	$97.12	$3,931.32	$3,890.05	$98.54	$3.78	$3.54	$2.42	$16.58	$15.42	$4.76
2	$10.31	$8.90	$3.02	$-	$-	$-	$4.12	$3.54	$2.09	$6.19	$5.60	$3.83
3	$9.10	$9.88	$3.65	$-	$-	$-	$4.08	$3.54	$2.81	$5.02	$4.67	$2.11
4	$10.01	$9.28	$6.62	$-	$-	$-	$3.35	$3.43	$2.66	$6.66	$5.14	$5.00
5	$8.68	$11.02	$5.32	$-	$-	$-	$3.31	$3.54	$2.55	$5.37	$5.14	$3.52
6	$12.61	$12.31	$3.84	$-	$-	$-	$5.03	$3.43	$3.93	$7.59	$7.94	$1.69
7	$9.41	$8.20	$4.35	$-	$-	$-	$4.39	$4.61	$2.93	$5.02	$5.14	$2.59
8	$11.21	$11.58	$4.84	$-	$-	$-	$6.07	$6.16	$2.89	$5.14	$5.14	$2.29
9	$11.43	$12.14	$3.50	$-	$-	$-	$6.18	$7.07	$3.03	$5.26	$5.61	$1.11
10	$13.13	$12.18	$6.97	$-	$-	$-	$6.24	$4.71	$5.74	$6.89	$7.48	$2.44
11	$8.38	$9.36	$3.59	$-	$-	$-	$3.02	$2.36	$2.25	$5.37	$4.68	$2.90
12	$11.16	$11.17	$3.79	$-	$-	$-	$5.55	$6.34	$3.09	$5.61	$6.08	$1.80
13	$11.03	$11.70	$4.98	$-	$-	$-	$5.54	$4.71	$4.09	$5.49	$4.68	$3.21
14	$8.27	$8.45	$3.04	$-	$-	$-	$3.83	$4.71	$2.16	$4.44	$5.14	$2.63
15	$20.70	$21.49	$5.27	$-	$-	$-	$4.94	$3.71	$4.42	$15.77	$15.42	$4.28
16	$3,953.60	$3,913.83	$98.64	$3,931.32	$3,890.05	$98.54	$5.59	$5.78	$2.50	$16.70	$15.88	$3.10
17	$9.08	$9.26	$4.24	$-	$-	$-	$2.90	$2.36	$2.37	$6.19	$5.14	$3.08
18	$10.56	$11.47	$3.83	$-	$-	$-	$5.19	$3.54	$4.33	$5.37	$6.07	$2.72
19	$10.94	$10.32	$4.72	$-	$-	$-	$5.57	$4.71	$4.14	$5.37	$5.60	$1.98
20	$9.80	$10.54	$4.21	$-	$-	$-	$4.19	$3.54	$3.68	$5.60	$5.60	$2.23
21	$8.91	$8.43	$4.24	$-	$-	$-	$3.31	$3.54	$3.46	$5.61	$5.61	$2.69
22	$11.69	$11.74	$4.37	$-	$-	$-	$5.73	$6.16	$3.28	$5.96	$5.60	$1.80
23	$11.59	$11.94	$3.92	$-	$-	$-	$3.65	$3.54	$3.67	$7.94	$7.94	$1.87
24	$9.40	$9.38	$3.74	$-	$-	$-	$3.21	$3.54	$2.45	$6.19	$6.08	$2.82
25	$9.11	$9.41	$4.26	$-	$-	$-	$4.56	$4.72	$3.83	$4.56	$4.67	$2.66
26	$9.00	$10.46	$3.73	$-	$-	$-	$4.10	$4.72	$3.89	$4.91	$5.14	$1.64
27	$6.68	$7.27	$3.56	$-	$-	$-	$2.36	$2.36	$1.78	$4.32	$3.74	$2.64
28	$10.37	$7.77	$4.83	$-	$-	$-	$5.12	$2.91	$4.98	$5.26	$5.14	$2.28
29	$13.75	$13.07	$4.80	$-	$-	$-	$7.68	$8.14	$4.33	$6.07	$5.14	$2.54
30	$20.58	$23.16	$9.08	$-	$-	$-	$5.05	$3.54	$5.07	$15.53	$17.28	$5.17

Table F.16 Costs for Contracted Work (1-year Period; Joint Replacement, 0% Inflation)

Year	Total (Avg.)	Total (Med.)	Total (St. Dev.)	Blanket (Avg.)	Blanket (Med.)	Blanket (St. Dev.)	Signal Head Spot (Avg.)	Signal Head Spot (Med.)	Signal Head Spot (St. Dev.)	Module Spot (Avg.)	Module Spot (Med.)	Module Spot (St. Dev.)
1	$7,317.81	$7,275.00	$96.98	$7,293.72	$7,252.45	$98.54	$4.04	$3.82	$2.56	$20.05	$18.63	$5.75
2	$11.95	$10.46	$3.69	$-	$-	$-	$4.46	$3.82	$2.26	$7.48	$6.78	$4.63
3	$10.44	$11.44	$4.08	$-	$-	$-	$4.37	$3.82	$2.98	$6.07	$5.65	$2.56
4	$11.64	$10.55	$7.75	$-	$-	$-	$3.59	$3.62	$2.85	$8.05	$6.22	$6.05
5	$10.07	$12.59	$6.16	$-	$-	$-	$3.58	$3.82	$2.76	$6.49	$6.22	$4.26
6	$14.57	$14.36	$4.17	$-	$-	$-	$5.39	$3.62	$4.23	$9.18	$9.60	$2.04
7	$10.80	$9.48	$4.99	$-	$-	$-	$4.73	$4.90	$3.18	$6.07	$6.22	$3.13
8	$12.75	$13.14	$5.45	$-	$-	$-	$6.53	$6.65	$3.08	$6.21	$6.22	$2.77
9	$12.97	$13.80	$3.81	$-	$-	$-	$6.61	$7.65	$3.21	$6.36	$6.78	$1.34
10	$15.02	$14.14	$7.65	$-	$-	$-	$6.68	$5.10	$6.09	$8.33	$9.04	$2.95
11	$9.75	$11.02	$4.17	$-	$-	$-	$3.26	$2.55	$2.42	$6.50	$5.65	$3.51
12	$12.74	$12.54	$4.23	$-	$-	$-	$5.96	$6.72	$3.33	$6.78	$7.35	$2.18
13	$12.59	$13.72	$5.57	$-	$-	$-	$5.96	$5.10	$4.37	$6.64	$5.65	$3.88
14	$9.51	$9.62	$3.53	$-	$-	$-	$4.14	$5.10	$2.34	$5.37	$6.22	$3.18
15	$24.34	$25.85	$6.03	$-	$-	$-	$5.28	$3.90	$4.74	$19.06	$18.63	$5.18
16	$7,319.88	$7,280.61	$98.83	$7,293.72	$7,252.45	$98.54	$5.98	$6.18	$2.67	$20.19	$19.20	$3.74
17	$10.57	$10.55	$4.88	$-	$-	$-	$3.09	$2.55	$2.50	$7.48	$6.22	$3.72
18	$12.07	$13.37	$4.19	$-	$-	$-	$5.58	$3.82	$4.62	$6.50	$7.34	$3.29
19	$12.50	$11.88	$5.24	$-	$-	$-	$6.01	$5.10	$4.46	$6.50	$6.78	$2.39
20	$11.31	$12.30	$4.69	$-	$-	$-	$4.53	$3.82	$3.97	$6.78	$6.78	$2.70
21	$10.35	$9.89	$4.78	$-	$-	$-	$3.58	$3.82	$3.74	$6.78	$6.78	$3.25
22	$13.40	$13.30	$4.91	$-	$-	$-	$6.19	$6.65	$3.56	$7.20	$6.78	$2.17
23	$13.52	$13.99	$4.30	$-	$-	$-	$3.91	$3.82	$3.92	$9.60	$9.60	$2.26
24	$10.94	$10.75	$4.29	$-	$-	$-	$3.46	$3.82	$2.62	$7.48	$7.35	$3.41
25	$10.43	$10.88	$4.77	$-	$-	$-	$4.92	$5.10	$4.13	$5.51	$5.65	$3.22
26	$10.34	$11.82	$4.06	$-	$-	$-	$4.41	$5.10	$4.18	$5.93	$6.22	$1.98
27	$7.78	$8.34	$4.15	$-	$-	$-	$2.55	$2.55	$1.93	$5.22	$4.52	$3.19
28	$11.86	$9.18	$5.25	$-	$-	$-	$5.51	$3.10	$5.35	$6.36	$6.22	$2.76
29	$15.60	$14.92	$5.32	$-	$-	$-	$8.26	$8.73	$4.66	$7.34	$6.22	$3.07
30	$24.22	$27.54	$10.39	$-	$-	$-	$5.44	$3.82	$5.45	$18.78	$20.90	$6.24

Table F.17 NCDOT Costs for In-House Work (1-year Period; Independent Replacement, 3% Inflation)

Year	Total (Avg.)	Total (Med.)	Total (St. Dev.)	Blanket (Avg.)	Blanket (Med.)	Blanket (St. Dev.)	Signal Head Spot (Avg.)	Signal Head Spot (Med.)	Signal Head Spot (St. Dev.)	Module Spot (Avg.)	Module Spot (Med.)	Module Spot (St. Dev.)
1	$1,736.08	$1,747.24	$36.54	$1,573.50	$1,577.96	$20.26	$147.63	$147.92	$17.53	$14.95	$14.02	$2.73
2	$145.39	$144.50	$22.72	$-	$-	$-	$139.50	$138.72	$21.41	$5.89	$5.29	$2.27
3	$139.27	$137.41	$17.72	$-	$-	$-	$134.56	$133.44	$16.78	$4.71	$4.96	$2.04
4	$145.77	$146.40	$25.30	$-	$-	$-	$139.27	$140.27	$24.29	$6.51	$6.64	$2.78
5	$138.57	$137.41	$10.57	$-	$-	$-	$130.43	$128.84	$11.79	$8.15	$8.41	$2.08
6	$149.01	$147.78	$19.21	$-	$-	$-	$144.67	$143.99	$20.86	$4.33	$3.79	$2.32
7	$143.27	$134.39	$23.02	$-	$-	$-	$136.99	$128.82	$23.38	$6.27	$6.69	$2.30
8	$161.83	$158.13	$20.87	$-	$-	$-	$155.66	$151.26	$20.76	$6.18	$6.32	$3.07
9	$129.81	$125.39	$29.76	$-	$-	$-	$122.42	$118.88	$29.49	$7.40	$7.69	$2.35
10	$152.02	$143.53	$31.54	$-	$-	$-	$144.40	$139.88	$30.31	$7.62	$6.70	$3.78
11	$132.10	$131.70	$18.39	$-	$-	$-	$126.30	$125.12	$16.08	$5.81	$5.03	$3.07
12	$149.24	$144.87	$23.34	$-	$-	$-	$143.74	$140.34	$24.45	$5.50	$5.17	$2.37
13	$147.72	$144.09	$20.76	$-	$-	$-	$142.06	$140.10	$20.49	$5.66	$6.00	$2.54
14	$152.67	$147.81	$21.04	$-	$-	$-	$144.60	$140.95	$20.23	$8.06	$6.86	$2.59
15	$173.18	$176.27	$18.37	$-	$-	$-	$150.93	$149.42	$19.74	$22.26	$19.78	$7.62
16	$2,620.35	$2,622.46	$40.33	$2,451.46	$2,458.42	$31.57	$143.22	$144.02	$25.28	$25.66	$24.74	$7.70
17	$142.28	$148.76	$22.99	$-	$-	$-	$133.85	$140.51	$24.30	$8.44	$8.25	$1.78
18	$130.67	$130.18	$24.60	$-	$-	$-	$124.68	$126.12	$24.86	$5.98	$5.40	$3.64
19	$151.62	$145.05	$33.11	$-	$-	$-	$143.47	$135.58	$33.37	$8.15	$7.16	$3.34
20	$132.24	$127.96	$23.95	$-	$-	$-	$124.87	$123.18	$22.58	$7.37	$5.73	$4.11
21	$162.74	$161.91	$12.57	$-	$-	$-	$155.15	$152.62	$11.82	$7.59	$8.44	$2.99
22	$153.36	$160.02	$26.47	$-	$-	$-	$143.37	$146.99	$23.80	$9.99	$9.56	$4.13
23	$158.53	$158.60	$20.57	$-	$-	$-	$147.12	$150.44	$19.80	$11.41	$10.74	$5.32
24	$145.64	$142.64	$37.98	$-	$-	$-	$133.66	$134.34	$36.68	$11.99	$12.91	$6.08
25	$146.42	$149.51	$26.92	$-	$-	$-	$137.16	$138.57	$26.69	$9.26	$8.55	$3.58
26	$179.06	$178.18	$28.66	$-	$-	$-	$167.08	$171.74	$28.71	$11.98	$11.74	$5.27
27	$158.26	$155.38	$31.80	$-	$-	$-	$147.43	$147.82	$29.48	$10.83	$9.07	$7.46
28	$195.87	$200.37	$30.88	$-	$-	$-	$186.01	$193.11	$32.70	$9.86	$9.34	$3.96
29	$185.08	$184.64	$34.55	$-	$-	$-	$170.92	$167.54	$36.01	$14.16	$14.96	$4.56
30	$260.19	$278.56	$56.77	$-	$-	$-	$224.14	$238.92	$52.40	$36.05	$35.22	$9.04

Table F.18 Costs for Contracted Work (1-year Period; Independent Replacement, 3% Inflation)

Year	Total (Avg.)	Total (Med.)	Total (St. Dev.)	Blanket (Avg.)	Blanket (Med.)	Blanket (St. Dev.)	Signal Head Spot (Avg.)	Signal Head Spot (Med.)	Signal Head Spot (St. Dev.)	Module Spot (Avg.)	Module Spot (Med.)	Module Spot (St. Dev.)
1	$5,112.80	$5,124.18	$37.94	$4,935.90	$4,940.36	$20.26	$158.83	$159.43	$18.84	$18.07	$16.94	$3.31
2	$157.07	$155.95	$24.69	$-	$-	$-	$149.95	$148.97	$23.13	$7.13	$6.40	$2.74
3	$150.42	$147.96	$19.13	$-	$-	$-	$144.73	$143.18	$18.00	$5.69	$5.99	$2.46
4	$157.61	$158.26	$27.38	$-	$-	$-	$149.74	$150.72	$26.14	$7.87	$8.02	$3.36
5	$150.27	$149.05	$11.14	$-	$-	$-	$140.42	$138.82	$12.59	$9.85	$10.17	$2.52
6	$160.77	$159.55	$20.36	$-	$-	$-	$155.53	$154.96	$22.34	$5.24	$4.58	$2.80
7	$154.86	$145.70	$24.65	$-	$-	$-	$147.27	$138.95	$25.09	$7.58	$8.09	$2.79
8	$174.91	$171.09	$22.42	$-	$-	$-	$167.45	$163.02	$22.25	$7.47	$7.64	$3.71
9	$140.72	$135.66	$32.05	$-	$-	$-	$131.78	$127.65	$31.70	$8.94	$9.30	$2.84
10	$164.30	$154.48	$34.27	$-	$-	$-	$155.09	$150.06	$32.76	$9.21	$8.10	$4.57
11	$143.02	$142.32	$20.07	$-	$-	$-	$136.00	$134.43	$17.28	$7.02	$6.07	$3.71
12	$161.06	$156.08	$24.98	$-	$-	$-	$154.41	$150.61	$26.30	$6.64	$6.25	$2.86
13	$159.41	$155.64	$22.15	$-	$-	$-	$152.56	$150.80	$21.79	$6.84	$7.25	$3.07
14	$165.24	$160.12	$22.68	$-	$-	$-	$155.49	$151.83	$21.68	$9.74	$8.29	$3.13
15	$189.16	$192.81	$19.83	$-	$-	$-	$162.25	$160.78	$21.19	$26.91	$23.92	$9.21
16	$7,875.01	$7,874.95	$41.51	$7,689.98	$7,696.93	$31.57	$154.02	$154.67	$27.22	$31.01	$29.91	$9.31
17	$154.37	$160.96	$24.43	$-	$-	$-	$144.18	$151.00	$26.00	$10.19	$9.96	$2.15
18	$141.31	$140.50	$26.35	$-	$-	$-	$134.07	$135.32	$26.68	$7.23	$6.53	$4.40
19	$164.16	$157.50	$35.21	$-	$-	$-	$154.30	$145.96	$35.49	$9.85	$8.65	$4.04
20	$143.36	$138.40	$26.01	$-	$-	$-	$134.45	$132.45	$24.28	$8.91	$6.93	$4.96
21	$176.31	$176.00	$13.85	$-	$-	$-	$167.13	$164.78	$12.84	$9.18	$10.20	$3.62
22	$166.20	$173.64	$28.84	$-	$-	$-	$154.12	$157.88	$25.59	$12.08	$11.56	$4.99
23	$172.08	$172.06	$22.49	$-	$-	$-	$158.29	$162.22	$21.48	$13.80	$12.98	$6.43
24	$158.30	$154.57	$40.79	$-	$-	$-	$143.82	$144.54	$39.17	$14.49	$15.60	$7.34
25	$158.56	$161.61	$29.06	$-	$-	$-	$147.37	$148.68	$28.70	$11.19	$10.33	$4.33
26	$194.13	$192.27	$30.95	$-	$-	$-	$179.65	$184.60	$30.93	$14.48	$14.18	$6.38
27	$171.83	$169.06	$34.75	$-	$-	$-	$158.74	$159.39	$31.89	$13.09	$10.96	$9.02
28	$212.07	$216.84	$32.77	$-	$-	$-	$200.15	$208.06	$34.97	$11.92	$11.29	$4.79
29	$200.82	$200.71	$36.44	$-	$-	$-	$183.70	$180.04	$38.17	$17.12	$18.09	$5.51
30	$284.56	$304.30	$61.58	$-	$-	$-	$240.98	$256.40	$56.17	$43.58	$42.58	$10.92

Appendix G: Annual Replacement Quantity Data (per Intersection) for Alternative Scenarios

Table G.1 Quantities of Modules and Signal Heads Required Annually (5-year Period; 5-year Cycle; Independent Replacement)

Year	Modules in Place (Avg.)	Modules in Place (Med.)	Modules in Place (St. Dev.)	Modules Replaced (Avg.)	Modules Replaced (Med.)	Modules Replaced (St. Dev.)	Signal Heads in Place (Avg.)	Signal Heads in Place (Med.)	Signal Heads in Place (St. Dev.)	Signal Heads Replaced (Avg.)	Signal Heads Replaced (Med.)	Signal Heads Replaced (St. Dev.)
1	28.74	28.64	0.76	9.32	9.34	0.31	8.82	8.80	0.22	0.25	0.25	0.03
2	28.74	28.64	0.76	8.47	8.46	0.30	8.82	8.80	0.22	0.24	0.24	0.02
3	28.74	28.64	0.76	7.83	7.76	0.34	8.82	8.80	0.22	0.27	0.28	0.02
4	28.74	28.64	0.76	6.99	6.96	0.24	8.82	8.80	0.22	0.26	0.27	0.03
5	28.74	28.64	0.76	6.62	6.60	0.24	8.82	8.80	0.22	0.25	0.24	0.05
6	28.74	28.64	0.76	6.46	6.46	0.29	8.82	8.80	0.22	0.22	0.20	0.04
7	28.74	28.64	0.76	6.50	6.50	0.38	8.82	8.80	0.22	0.21	0.22	0.03
8	28.74	28.64	0.76	6.57	6.45	0.46	8.82	8.80	0.22	0.21	0.22	0.05
9	28.74	28.64	0.76	6.37	6.28	0.17	8.82	8.80	0.22	0.21	0.21	0.02
10	28.74	28.64	0.76	6.51	6.46	0.19	8.82	8.80	0.22	0.21	0.20	0.03
11	28.74	28.64	0.76	6.38	6.44	0.23	8.82	8.80	0.22	0.20	0.20	0.03
12	28.74	28.64	0.76	6.47	6.41	0.36	8.82	8.80	0.22	0.20	0.20	0.03
13	28.74	28.64	0.76	6.45	6.42	0.34	8.82	8.80	0.22	0.18	0.18	0.04
14	28.74	28.64	0.76	6.26	6.20	0.19	8.82	8.80	0.22	0.17	0.17	0.03
15	28.74	28.64	0.76	6.41	6.40	0.22	8.82	8.80	0.22	0.18	0.17	0.04
16	28.74	28.64	0.76	6.36	6.34	0.19	8.82	8.80	0.22	0.19	0.20	0.02
17	28.74	28.64	0.76	6.35	6.30	0.30	8.82	8.80	0.22	0.16	0.16	0.03
18	28.74	28.64	0.76	6.41	6.32	0.36	8.82	8.80	0.22	0.17	0.18	0.03
19	28.74	28.64	0.76	6.18	6.14	0.23	8.82	8.80	0.22	0.15	0.14	0.02
20	28.74	28.64	0.76	6.31	6.24	0.16	8.82	8.80	0.22	0.15	0.16	0.03
21	28.74	28.64	0.76	6.18	6.25	0.22	8.82	8.80	0.22	0.14	0.14	0.02
22	28.74	28.64	0.76	6.30	6.31	0.30	8.82	8.80	0.22	0.15	0.15	0.03
23	28.74	28.64	0.76	6.34	6.29	0.37	8.82	8.80	0.22	0.15	0.15	0.03
24	28.74	28.64	0.76	6.21	6.16	0.23	8.82	8.80	0.22	0.16	0.15	0.01
25	28.74	28.64	0.76	6.22	6.24	0.18	8.82	8.80	0.22	0.13	0.12	0.02
26	28.74	28.64	0.76	6.16	6.20	0.24	8.82	8.80	0.22	0.13	0.12	0.03
27	28.74	28.64	0.76	6.32	6.37	0.37	8.82	8.80	0.22	0.16	0.16	0.03
28	28.74	28.64	0.76	6.35	6.20	0.39	8.82	8.80	0.22	0.14	0.14	0.02
29	28.74	28.64	0.76	6.20	6.12	0.24	8.82	8.80	0.22	0.15	0.15	0.03
30	28.74	28.64	0.76	6.40	6.34	0.23	8.82	8.80	0.22	0.17	0.18	0.03

Table G.2 Quantities of Modules and Signal Heads Required Annually (Spot Replacement Only, 15-year Modules)

Year	Modules in Place (Avg.)	Modules in Place (Med.)	Modules in Place (St. Dev.)	Modules Replaced (Avg.)	Modules Replaced (Med.)	Modules Replaced (St. Dev.)	Signal Heads in Place (Avg.)	Signal Heads in Place (Med.)	Signal Heads in Place (St. Dev.)	Signal Heads Replaced (Avg.)	Signal Heads Replaced (Med.)	Signal Heads Replaced (St. Dev.)
1	28.57	28.51	0.54	4.28	4.33	0.21	8.76	8.72	0.15	0.25	0.26	0.03
2	28.57	28.51	0.54	3.89	3.84	0.17	8.76	8.72	0.15	0.26	0.27	0.04
3	28.57	28.51	0.54	3.54	3.49	0.23	8.76	8.72	0.15	0.25	0.26	0.04
4	28.57	28.51	0.54	3.07	3.18	0.21	8.76	8.72	0.15	0.22	0.24	0.03
5	28.57	28.51	0.54	2.94	2.96	0.10	8.76	8.72	0.15	0.25	0.24	0.03
6	28.57	28.51	0.54	2.57	2.58	0.13	8.76	8.72	0.15	0.22	0.22	0.03
7	28.57	28.51	0.54	2.34	2.32	0.14	8.76	8.72	0.15	0.22	0.22	0.04
8	28.57	28.51	0.54	2.23	2.24	0.16	8.76	8.72	0.15	0.23	0.22	0.05
9	28.57	28.51	0.54	1.99	2.04	0.09	8.76	8.72	0.15	0.21	0.20	0.02
10	28.57	28.51	0.54	1.84	1.86	0.12	8.76	8.72	0.15	0.22	0.23	0.04
11	28.57	28.51	0.54	1.70	1.74	0.13	8.76	8.72	0.15	0.21	0.21	0.02
12	28.57	28.51	0.54	1.46	1.44	0.13	8.76	8.72	0.15	0.17	0.18	0.03
13	28.57	28.51	0.54	1.35	1.34	0.10	8.76	8.72	0.15	0.17	0.16	0.02
14	28.57	28.51	0.54	1.30	1.30	0.13	8.76	8.72	0.15	0.17	0.16	0.04
15	28.57	28.51	0.54	1.19	1.20	0.11	8.76	8.72	0.15	0.17	0.16	0.05
16	28.57	28.51	0.54	1.10	1.06	0.10	8.76	8.72	0.15	0.17	0.16	0.03
17	28.57	28.51	0.54	1.04	1.05	0.12	8.76	8.72	0.15	0.15	0.16	0.03
18	28.57	28.51	0.54	1.01	0.99	0.08	8.76	8.72	0.15	0.16	0.15	0.03
19	28.57	28.51	0.54	0.97	0.98	0.08	8.76	8.72	0.15	0.15	0.15	0.02
20	28.57	28.51	0.54	0.99	0.98	0.11	8.76	8.72	0.15	0.15	0.15	0.02
21	28.57	28.51	0.54	1.08	1.12	0.14	8.76	8.72	0.15	0.16	0.16	0.04
22	28.57	28.51	0.54	1.06	1.02	0.18	8.76	8.72	0.15	0.15	0.14	0.05
23	28.57	28.51	0.54	1.21	1.19	0.15	8.76	8.72	0.15	0.15	0.16	0.03
24	28.57	28.51	0.54	1.27	1.30	0.10	8.76	8.72	0.15	0.14	0.12	0.03
25	28.57	28.51	0.54	1.36	1.38	0.11	8.76	8.72	0.15	0.13	0.13	0.03
26	28.57	28.51	0.54	1.53	1.50	0.16	8.76	8.72	0.15	0.13	0.13	0.02
27	28.57	28.51	0.54	1.65	1.66	0.08	8.76	8.72	0.15	0.14	0.15	0.03
28	28.57	28.51	0.54	1.62	1.64	0.13	8.76	8.72	0.15	0.14	0.15	0.02
29	28.57	28.51	0.54	1.77	1.76	0.09	8.76	8.72	0.15	0.15	0.14	0.03
30	28.57	28.51	0.54	1.73	1.73	0.11	8.76	8.72	0.15	0.15	0.15	0.02

Table G.3 Quantities of Modules and Signal Heads Required Annually (15-year Period; Independent Replacement)

Year	Modules in Place (Avg.)	Modules in Place (Med.)	Modules in Place (St. Dev.)	Modules Replaced (Avg.)	Modules Replaced (Med.)	Modules Replaced (St. Dev.)	Signal Heads in Place (Avg.)	Signal Heads in Place (Med.)	Signal Heads in Place (St. Dev.)	Signal Heads Replaced (Avg.)	Signal Heads Replaced (Med.)	Signal Heads Replaced (St. Dev.)
1	28.38	28	0.93	6.11	6.04	0.24	8.74	8.64	0.26	0.27	0.27	0.03
2	28.38	28	0.93	5.46	5.47	0.33	8.74	8.64	0.26	0.26	0.26	0.03
3	28.38	28	0.93	4.83	4.78	0.26	8.74	8.64	0.26	0.26	0.24	0.04
4	28.38	28	0.93	4.23	4.22	0.25	8.74	8.64	0.26	0.22	0.22	0.03
5	28.38	28	0.93	4.11	4.16	0.21	8.74	8.64	0.26	0.22	0.22	0.02
6	28.38	28	0.93	3.84	3.91	0.23	8.74	8.64	0.26	0.27	0.24	0.05
7	28.38	28	0.93	3.36	3.38	0.24	8.74	8.64	0.26	0.22	0.22	0.04
8	28.38	28	0.93	3.24	3.20	0.19	8.74	8.64	0.26	0.20	0.20	0.02
9	28.38	28	0.93	3.21	3.20	0.14	8.74	8.64	0.26	0.21	0.20	0.04
10	28.38	28	0.93	2.72	2.65	0.20	8.74	8.64	0.26	0.19	0.20	0.03
11	28.38	28	0.93	2.94	2.89	0.31	8.74	8.64	0.26	0.20	0.20	0.03
12	28.38	28	0.93	2.80	2.78	0.11	8.74	8.64	0.26	0.21	0.21	0.04
13	28.38	28	0.93	2.47	2.4	0.19	8.74	8.64	0.26	0.19	0.20	0.03
14	28.38	28	0.93	2.61	2.62	0.27	8.74	8.64	0.26	0.18	0.18	0.03
15	28.38	28	0.93	2.52	2.49	0.24	8.74	8.64	0.26	0.17	0.18	0.03
16	28.38	28	0.93	2.48	2.45	0.16	8.74	8.64	0.26	0.16	0.16	0.02
17	28.38	28	0.93	2.58	2.54	0.24	8.74	8.64	0.26	0.16	0.16	0.04
18	28.38	28	0.93	2.40	2.39	0.14	8.74	8.64	0.26	0.15	0.14	0.02
19	28.38	28	0.93	2.35	2.34	0.11	8.74	8.64	0.26	0.16	0.16	0.03
20	28.38	28	0.93	2.52	2.54	0.15	8.74	8.64	0.26	0.15	0.15	0.03
21	28.38	28	0.93	2.40	2.38	0.14	8.74	8.64	0.26	0.16	0.16	0.03
22	28.38	28	0.93	2.30	2.28	0.24	8.74	8.64	0.26	0.15	0.16	0.03
23	28.38	28	0.93	2.43	2.38	0.16	8.74	8.64	0.26	0.15	0.15	0.02
24	28.38	28	0.93	2.47	2.43	0.12	8.74	8.64	0.26	0.13	0.14	0.03
25	28.38	28	0.93	2.16	2.14	0.21	8.74	8.64	0.26	0.13	0.13	0.02
26	28.38	28	0.93	2.43	2.41	0.22	8.74	8.64	0.26	0.13	0.12	0.03
27	28.38	28	0.93	2.36	2.37	0.20	8.74	8.64	0.26	0.12	0.12	0.02
28	28.38	28	0.93	2.14	2.05	0.19	8.74	8.64	0.26	0.12	0.13	0.02
29	28.38	28	0.93	2.43	2.32	0.25	8.74	8.64	0.26	0.14	0.15	0.02
30	28.38	28	0.93	2.55	2.5	0.20	8.74	8.64	0.26	0.18	0.18	0.02

Table G.4 Quantities of Modules and Signal Heads Required Annually (15-year Period; Joint Replacement)

Year	Modules in Place (Avg.)	Modules in Place (Med.)	Modules in Place (St. Dev.)	Modules Replaced (Avg.)	Modules Replaced (Med.)	Modules Replaced (St. Dev.)	Signal Heads in Place (Avg.)	Signal Heads in Place (Med.)	Signal Heads in Place (St. Dev.)	Signal Heads Replaced (Avg.)	Signal Heads Replaced (Med.)	Signal Heads Replaced (St. Dev.)
1	28.27	28.12	0.63	5.79	5.79	0.20	8.71	8.68	0.16	0.77	0.78	0.04
2	28.27	28.12	0.63	5.22	5.21	0.27	8.71	8.68	0.16	0.79	0.79	0.08
3	28.27	28.12	0.63	4.65	4.61	0.23	8.71	8.68	0.16	0.77	0.76	0.04
4	28.27	28.12	0.63	4.18	4.19	0.28	8.71	8.68	0.16	0.77	0.79	0.08
5	28.27	28.12	0.63	3.90	3.86	0.20	8.71	8.68	0.16	0.77	0.76	0.03
6	28.27	28.12	0.63	3.57	3.56	0.28	8.71	8.68	0.16	0.75	0.75	0.07
7	28.27	28.12	0.63	3.03	3.06	0.14	8.71	8.68	0.16	0.67	0.66	0.05
8	28.27	28.12	0.63	2.93	2.93	0.15	8.71	8.68	0.16	0.69	0.68	0.05
9	28.27	28.12	0.63	2.75	2.84	0.22	8.71	8.68	0.16	0.69	0.70	0.06
10	28.27	28.12	0.63	2.35	2.35	0.20	8.71	8.68	0.16	0.60	0.60	0.06
11	28.27	28.12	0.63	2.40	2.40	0.18	8.71	8.68	0.16	0.64	0.64	0.05
12	28.27	28.12	0.63	2.35	2.37	0.13	8.71	8.68	0.16	0.66	0.68	0.05
13	28.27	28.12	0.63	2.04	2.04	0.15	8.71	8.68	0.16	0.59	0.58	0.05
14	28.27	28.12	0.63	2.04	2.02	0.17	8.71	8.68	0.16	0.61	0.60	0.04
15	28.27	28.12	0.63	2.03	2.05	0.15	8.71	8.68	0.16	0.61	0.60	0.05
16	28.27	28.12	0.63	1.86	1.84	0.10	8.71	8.68	0.16	0.56	0.56	0.04
17	28.27	28.12	0.63	1.89	1.89	0.20	8.71	8.68	0.16	0.57	0.57	0.06
18	28.27	28.12	0.63	1.98	2.01	0.17	8.71	8.68	0.16	0.60	0.61	0.05
19	28.27	28.12	0.63	1.94	1.94	0.17	8.71	8.68	0.16	0.59	0.59	0.05
20	28.27	28.12	0.63	2.06	2.03	0.08	8.71	8.68	0.16	0.63	0.62	0.02
21	28.27	28.12	0.63	2.00	2.04	0.22	8.71	8.68	0.16	0.60	0.62	0.06
22	28.27	28.12	0.63	1.81	1.79	0.20	8.71	8.68	0.16	0.55	0.54	0.06
23	28.27	28.12	0.63	1.97	1.97	0.16	8.71	8.68	0.16	0.60	0.60	0.05
24	28.27	28.12	0.63	2.04	2.08	0.17	8.71	8.68	0.16	0.62	0.62	0.05
25	28.27	28.12	0.63	1.81	1.78	0.23	8.71	8.68	0.16	0.54	0.54	0.06
26	28.27	28.12	0.63	1.94	1.96	0.16	8.71	8.68	0.16	0.58	0.58	0.04
27	28.27	28.12	0.63	2.09	2.16	0.14	8.71	8.68	0.16	0.63	0.65	0.05
28	28.27	28.12	0.63	1.85	1.82	0.17	8.71	8.68	0.16	0.56	0.54	0.05
29	28.27	28.12	0.63	1.97	1.96	0.18	8.71	8.68	0.16	0.60	0.60	0.04
30	28.27	28.12	0.63	2.04	2.06	0.16	8.71	8.68	0.16	0.62	0.62	0.05

Table G.5 Quantities of Modules and Signal Heads Required Annually (5-year Period; Independent Replacement)

Year	Modules in Place (Avg.)	Modules in Place (Med.)	Modules in Place (St. Dev.)	Modules Replaced (Avg.)	Modules Replaced (Med.)	Modules Replaced (St. Dev.)	Signal Heads in Place (Avg.)	Signal Heads in Place (Med.)	Signal Heads in Place (St. Dev.)	Signal Heads Replaced (Avg.)	Signal Heads Replaced (Med.)	Signal Heads Replaced (St. Dev.)
1	28.64	28.66	0.36	9.41	9.56	0.29	8.80	8.81	0.12	0.26	0.27	0.03
2	28.64	28.66	0.36	8.17	8.14	0.37	8.80	8.81	0.12	0.22	0.20	0.03
3	28.64	28.66	0.36	7.65	7.62	0.3	8.80	8.81	0.12	0.24	0.24	0.03
4	28.64	28.66	0.36	6.93	6.85	0.31	8.80	8.81	0.12	0.23	0.24	0.03
5	28.64	28.66	0.36	6.61	6.62	0.43	8.80	8.81	0.12	0.24	0.26	0.04
6	28.64	28.66	0.36	0.71	0.68	0.09	8.80	8.81	0.12	0.21	0.20	0.02
7	28.64	28.66	0.36	0.79	0.76	0.09	8.80	8.81	0.12	0.23	0.24	0.02
8	28.64	28.66	0.36	0.75	0.76	0.07	8.80	8.81	0.12	0.22	0.22	0.02
9	28.64	28.66	0.36	0.62	0.61	0.06	8.80	8.81	0.12	0.18	0.18	0.02
10	28.64	28.66	0.36	0.63	0.68	0.09	8.80	8.81	0.12	0.19	0.20	0.03
11	28.64	28.66	0.36	0.66	0.72	0.11	8.80	8.81	0.12	0.20	0.22	0.03
12	28.64	28.66	0.36	0.6	0.57	0.08	8.80	8.81	0.12	0.18	0.17	0.02
13	28.64	28.66	0.36	0.63	0.60	0.08	8.80	8.81	0.12	0.18	0.18	0.02
14	28.64	28.66	0.36	0.59	0.59	0.04	8.80	8.81	0.12	0.18	0.18	0.01
15	28.64	28.66	0.36	0.63	0.60	0.10	8.80	8.81	0.12	0.18	0.18	0.03
16	28.64	28.66	0.36	6.46	6.48	0.29	8.80	8.81	0.12	0.19	0.19	0.02
17	28.64	28.66	0.36	6.20	6.24	0.38	8.80	8.81	0.12	0.16	0.15	0.02
18	28.64	28.66	0.36	6.33	6.36	0.39	8.80	8.81	0.12	0.16	0.17	0.04
19	28.64	28.66	0.36	6.21	6.20	0.31	8.80	8.81	0.12	0.15	0.16	0.03
20	28.64	28.66	0.36	6.36	6.35	0.44	8.80	8.81	0.12	0.17	0.17	0.03
21	28.64	28.66	0.36	0.55	0.52	0.11	8.80	8.81	0.12	0.16	0.15	0.03
22	28.64	28.66	0.36	0.49	0.44	0.13	8.80	8.81	0.12	0.14	0.13	0.04
23	28.64	28.66	0.36	0.49	0.46	0.08	8.80	8.81	0.12	0.14	0.14	0.02
24	28.64	28.66	0.36	0.49	0.47	0.07	8.80	8.81	0.12	0.15	0.13	0.03
25	28.64	28.66	0.36	0.46	0.45	0.06	8.80	8.81	0.12	0.13	0.14	0.02
26	28.64	28.66	0.36	0.40	0.40	0.05	8.80	8.81	0.12	0.12	0.12	0.02
27	28.64	28.66	0.36	0.47	0.49	0.07	8.80	8.81	0.12	0.14	0.14	0.02
28	28.64	28.66	0.36	0.48	0.48	0.07	8.80	8.81	0.12	0.14	0.14	0.02
29	28.64	28.66	0.36	0.52	0.50	0.12	8.80	8.81	0.12	0.16	0.16	0.03
30	28.64	28.66	0.36	0.51	0.50	0.08	8.80	8.81	0.12	0.15	0.15	0.03

Table G.6 Quantities of Modules and Signal Heads Required Annually (5-year Period; Independent Replacement)

Year	Modules in Place (Avg.)	Modules in Place (Med.)	Modules in Place (St. Dev.)	Modules Replaced (Avg.)	Modules Replaced (Med.)	Modules Replaced (St. Dev.)	Signal Heads in Place (Avg.)	Signal Heads in Place (Med.)	Signal Heads in Place (St. Dev.)	Signal Heads Replaced (Avg.)	Signal Heads Replaced (Med.)	Signal Heads Replaced (St. Dev.)
1	28.50	0.71	9.21	9.11	0.20	8.82	8.77	0.20	1.97	1.97	0.06	28.50
2	28.50	0.71	8.04	7.94	0.35	8.82	8.77	0.20	1.88	1.88	0.08	28.50
3	28.50	0.71	7.13	7.12	0.20	8.82	8.77	0.20	1.86	1.85	0.07	28.50
4	28.50	0.71	6.56	6.52	0.33	8.82	8.77	0.20	1.86	1.85	0.09	28.50
5	28.50	0.71	5.79	5.76	0.38	8.82	8.77	0.20	1.76	1.76	0.11	28.50
6	28.50	0.71	0.05	0.05	0.02	8.82	8.77	0.20	-	-	0.01	28.50
7	28.50	0.71	0.05	0.05	0.02	8.82	8.77	0.20	-	-	0.01	28.50
8	28.50	0.71	0.05	0.05	0.02	8.82	8.77	0.20	-	-	0.01	28.50
9	28.50	0.71	0.07	0.06	0.03	8.82	8.77	0.20	0.01	-	0.01	28.50
10	28.50	0.71	0.06	0.04	0.03	8.82	8.77	0.20	0.01	-	0.01	28.50
11	28.50	0.71	0.06	0.06	0.03	8.82	8.77	0.20	0.01	-	0.01	28.50
12	28.50	0.71	0.05	0.04	0.02	8.82	8.77	0.20	-	-	0.01	28.50
13	28.50	0.71	0.07	0.06	0.03	8.82	8.77	0.20	0.01	0.01	0.01	28.50
14	28.50	0.71	0.04	0.04	0.02	8.82	8.77	0.20	0.01	0.01	0.01	28.50
15	28.50	0.71	0.06	0.06	0.02	8.82	8.77	0.20	-	-	0.01	28.50
16	28.50	0.71	5.89	5.82	0.24	8.82	8.77	0.20	1.78	1.77	0.06	28.50
17	28.50	0.71	5.74	5.66	0.25	8.82	8.77	0.20	1.75	1.74	0.08	28.50
18	28.50	0.71	5.74	5.73	0.19	8.82	8.77	0.20	1.75	1.76	0.06	28.50
19	28.50	0.71	5.93	5.88	0.31	8.82	8.77	0.20	1.80	1.79	0.09	28.50
20	28.50	0.71	5.79	5.78	0.36	8.82	8.77	0.20	1.76	1.76	0.11	28.50
21	28.50	0.71	0.06	0.06	0.02	8.82	8.77	0.20	0.01	0.01	-	28.50
22	28.50	0.71	0.06	0.06	0.02	8.82	8.77	0.20	0.01	0.01	0.01	28.50
23	28.50	0.71	0.05	0.05	0.02	8.82	8.77	0.20	-	-	0.01	28.50
24	28.50	0.71	0.07	0.06	0.03	8.82	8.77	0.20	0.01	0.01	0.01	28.50
25	28.50	0.71	0.05	0.04	0.02	8.82	8.77	0.20	-	-	0.01	28.50
26	28.50	0.71	0.06	0.06	0.02	8.82	8.77	0.20	0.01	-	0.01	28.50
27	28.50	0.71	0.06	0.06	0.03	8.82	8.77	0.20	-	-	0.01	28.50
28	28.50	0.71	0.08	0.06	0.04	8.82	8.77	0.20	0.01	0.01	0.01	28.50
29	28.50	0.71	0.05	0.05	0.03	8.82	8.77	0.20	-	-	0.01	28.50
30	28.50	0.71	0.07	0.06	0.02	8.82	8.77	0.20	0.01	0.01	0.01	28.50

Table G.7 Quantities of Modules and Signal Heads Required Annually (1-year Period; Independent Replacement; 0% Inflation)

Year	Modules in Place (Avg.)	Modules in Place (Med.)	Modules in Place (St. Dev.)	Modules Replaced (Avg.)	Modules Replaced (Med.)	Modules Replaced (St. Dev.)	Signal Heads in Place (Avg.)	Signal Heads in Place (Med.)	Signal Heads in Place (St. Dev.)	Signal Heads Replaced (Avg.)	Signal Heads Replaced (Med.)	Signal Heads Replaced (St. Dev.)
1	28.52	28.48	0.63	29.46	29.46	0.68	8.76	8.73	0.21	0.26	0.25	0.02
2	28.52	28.48	0.63	0.82	0.83	0.06	8.76	8.73	0.21	0.25	0.25	0.02
3	28.52	28.48	0.63	0.77	0.82	0.15	8.76	8.73	0.21	0.23	0.24	0.04
4	28.52	28.48	0.63	0.80	0.74	0.15	8.76	8.73	0.21	0.23	0.22	0.05
5	28.52	28.48	0.63	0.82	0.82	0.13	8.76	8.73	0.21	0.24	0.24	0.04
6	28.52	28.48	0.63	0.72	0.72	0.09	8.76	8.73	0.21	0.21	0.21	0.02
7	28.52	28.48	0.63	0.72	0.72	0.15	8.76	8.73	0.21	0.21	0.21	0.04
8	28.52	28.48	0.63	0.72	0.74	0.08	8.76	8.73	0.21	0.21	0.20	0.02
9	28.52	28.48	0.63	0.66	0.66	0.11	8.76	8.73	0.21	0.20	0.20	0.04
10	28.52	28.48	0.63	0.72	0.69	0.09	8.76	8.73	0.21	0.22	0.21	0.02
11	28.52	28.48	0.63	0.66	0.62	0.10	8.76	8.73	0.21	0.20	0.19	0.03
12	28.52	28.48	0.63	0.60	0.59	0.12	8.76	8.73	0.21	0.18	0.18	0.04
13	28.52	28.48	0.63	0.56	0.57	0.05	8.76	8.73	0.21	0.16	0.16	0.02
14	28.52	28.48	0.63	0.61	0.59	0.16	8.76	8.73	0.21	0.18	0.18	0.05
15	28.52	28.48	0.63	0.71	0.70	0.11	8.76	8.73	0.21	0.19	0.20	0.03
16	28.52	28.48	0.63	29.14	29.16	0.64	8.76	8.73	0.21	0.17	0.18	0.03
17	28.52	28.48	0.63	0.58	0.62	0.11	8.76	8.73	0.21	0.17	0.18	0.04
18	28.52	28.48	0.63	0.57	0.58	0.09	8.76	8.73	0.21	0.17	0.17	0.03
19	28.52	28.48	0.63	0.52	0.55	0.09	8.76	8.73	0.21	0.16	0.16	0.03
20	28.52	28.48	0.63	0.52	0.52	0.07	8.76	8.73	0.21	0.15	0.15	0.02
21	28.52	28.48	0.63	0.51	0.52	0.12	8.76	8.73	0.21	0.15	0.16	0.03
22	28.52	28.48	0.63	0.46	0.48	0.11	8.76	8.73	0.21	0.13	0.14	0.03
23	28.52	28.48	0.63	0.49	0.52	0.07	8.76	8.73	0.21	0.14	0.15	0.02
24	28.52	28.48	0.63	0.41	0.40	0.10	8.76	8.73	0.21	0.12	0.12	0.03
25	28.52	28.48	0.63	0.47	0.48	0.11	8.76	8.73	0.21	0.14	0.14	0.03
26	28.52	28.48	0.63	0.44	0.46	0.08	8.76	8.73	0.21	0.13	0.14	0.03
27	28.52	28.48	0.63	0.44	0.43	0.08	8.76	8.73	0.21	0.12	0.12	0.03
28	28.52	28.48	0.63	0.49	0.49	0.07	8.76	8.73	0.21	0.15	0.15	0.02
29	28.52	28.48	0.63	0.55	0.54	0.06	8.76	8.73	0.21	0.16	0.16	0.02
30	28.52	28.48	0.63	0.59	0.58	0.06	8.76	8.73	0.21	0.16	0.16	0.02

Table G.8 Quantities of Modules and Signal Heads Required Annually (1-year Period; Joint Replacement; 0% Inflation)

Year	Modules in Place (Avg.)	Modules in Place (Med.)	Modules in Place (St. Dev.)	Modules Replaced (Avg.)	Modules Replaced (Med.)	Modules Replaced (St. Dev.)	Signal Heads in Place (Avg.)	Signal Heads in Place (Med.)	Signal Heads in Place (St. Dev.)	Signal Heads Replaced (Avg.)	Signal Heads Replaced (Med.)	Signal Heads Replaced (St. Dev.)
1	28.84	28.59	0.76	28.94	28.69	0.75	8.85	8.82	0.21	8.86	8.84	0.21
2	28.84	28.59	0.76	0.06	0.05	0.01	8.85	8.82	0.21	-	-	0.01
3	28.84	28.59	0.76	0.05	0.06	0.02	8.85	8.82	0.21	-	-	0.01
4	28.84	28.59	0.76	0.06	0.05	0.04	8.85	8.82	0.21	-	-	0.01
5	28.84	28.59	0.76	0.05	0.06	0.03	8.85	8.82	0.21	-	-	0.01
6	28.84	28.59	0.76	0.07	0.06	0.02	8.85	8.82	0.21	0.01	-	0.01
7	28.84	28.59	0.76	0.05	0.04	0.03	8.85	8.82	0.21	0.01	-	0.01
8	28.84	28.59	0.76	0.06	0.06	0.03	8.85	8.82	0.21	0.01	0.01	0.01
9	28.84	28.59	0.76	0.06	0.06	0.02	8.85	8.82	0.21	0.01	0.01	-
10	28.84	28.59	0.76	0.07	0.06	0.04	8.85	8.82	0.21	0.01	0.01	0.01
11	28.84	28.59	0.76	0.05	0.05	0.02	8.85	8.82	0.21	-	-	-
12	28.84	28.59	0.76	0.06	0.06	0.02	8.85	8.82	0.21	0.01	0.01	0.01
13	28.84	28.59	0.76	0.06	0.06	0.03	8.85	8.82	0.21	0.01	0.01	0.01
14	28.84	28.59	0.76	0.05	0.05	0.02	8.85	8.82	0.21	0.01	0.01	0.01
15	28.84	28.59	0.76	0.11	0.11	0.03	8.85	8.82	0.21	0.01	-	0.01
16	28.84	28.59	0.76	28.95	28.73	0.76	8.85	8.82	0.21	8.86	8.84	0.21
17	28.84	28.59	0.76	0.05	0.05	0.02	8.85	8.82	0.21	-	-	-
18	28.84	28.59	0.76	0.06	0.06	0.03	8.85	8.82	0.21	0.01	-	0.01
19	28.84	28.59	0.76	0.06	0.06	0.03	8.85	8.82	0.21	0.01	0.01	0.01
20	28.84	28.59	0.76	0.05	0.06	0.03	8.85	8.82	0.21	0.01	-	0.01
21	28.84	28.59	0.76	0.05	0.04	0.03	8.85	8.82	0.21	0.01	-	0.01
22	28.84	28.59	0.76	0.07	0.07	0.02	8.85	8.82	0.21	0.01	0.01	0.01
23	28.84	28.59	0.76	0.06	0.06	0.02	8.85	8.82	0.21	-	-	0.01
24	28.84	28.59	0.76	0.05	0.06	0.02	8.85	8.82	0.21	-	-	0.01
25	28.84	28.59	0.76	0.05	0.06	0.03	8.85	8.82	0.21	0.01	-	0.01
26	28.84	28.59	0.76	0.05	0.06	0.02	8.85	8.82	0.21	-	-	0.01
27	28.84	28.59	0.76	0.04	0.04	0.02	8.85	8.82	0.21	-	-	-
28	28.84	28.59	0.76	0.06	0.04	0.03	8.85	8.82	0.21	0.01	-	0.01
29	28.84	28.59	0.76	0.08	0.07	0.03	8.85	8.82	0.21	0.01	0.01	0.01
30	28.84	28.59	0.76	0.11	0.12	0.05	8.85	8.82	0.21	0.01	-	0.01

Table G.9 Quantities of Modules and Signal Heads Required Annually (1-year Period; Independent Replacement; 3% Inflation)

Year	Modules in Place (Avg.)	Modules in Place (Med.)	Modules in Place (St. Dev.)	Modules Replaced (Avg.)	Modules Replaced (Med.)	Modules Replaced (St. Dev.)	Signal Heads in Place (Avg.)	Signal Heads in Place (Med.)	Signal Heads in Place (St. Dev.)	Signal Heads Replaced (Avg.)	Signal Heads Replaced (Med.)	Signal Heads Replaced (St. Dev.)
1	28.37	28.50	0.61	29.36	29.54	0.71	8.72	8.76	0.15	0.28	0.29	0.03
2	28.37	28.50	0.61	0.86	0.85	0.14	8.72	8.76	0.15	0.26	0.25	0.04
3	28.37	28.50	0.61	0.80	0.78	0.10	8.72	8.76	0.15	0.24	0.24	0.03
4	28.37	28.50	0.61	0.81	0.82	0.14	8.72	8.76	0.15	0.24	0.24	0.04
5	28.37	28.50	0.61	0.75	0.74	0.06	8.72	8.76	0.15	0.22	0.22	0.02
6	28.37	28.50	0.61	0.78	0.78	0.10	8.72	8.76	0.15	0.23	0.24	0.03
7	28.37	28.50	0.61	0.73	0.70	0.12	8.72	8.76	0.15	0.21	0.21	0.04
8	28.37	28.50	0.61	0.80	0.79	0.10	8.72	8.76	0.15	0.24	0.24	0.03
9	28.37	28.50	0.61	0.63	0.60	0.15	8.72	8.76	0.15	0.19	0.18	0.04
10	28.37	28.50	0.61	0.71	0.67	0.15	8.72	8.76	0.15	0.21	0.20	0.05
11	28.37	28.50	0.61	0.60	0.60	0.08	8.72	8.76	0.15	0.18	0.18	0.02
12	28.37	28.50	0.61	0.66	0.64	0.10	8.72	8.76	0.15	0.20	0.19	0.03
13	28.37	28.50	0.61	0.63	0.62	0.09	8.72	8.76	0.15	0.19	0.19	0.02
14	28.37	28.50	0.61	0.63	0.62	0.09	8.72	8.76	0.15	0.18	0.18	0.02
15	28.37	28.50	0.61	0.69	0.70	0.07	8.72	8.76	0.15	0.19	0.18	0.02
16	28.37	28.50	0.61	29.02	29.20	0.62	8.72	8.76	0.15	0.17	0.18	0.03
17	28.37	28.50	0.61	0.54	0.56	0.09	8.72	8.76	0.15	0.16	0.16	0.03
18	28.37	28.50	0.61	0.48	0.48	0.09	8.72	8.76	0.15	0.14	0.14	0.03
19	28.37	28.50	0.61	0.54	0.52	0.12	8.72	8.76	0.15	0.16	0.16	0.03
20	28.37	28.50	0.61	0.46	0.44	0.08	8.72	8.76	0.15	0.14	0.14	0.02
21	28.37	28.50	0.61	0.55	0.56	0.04	8.72	8.76	0.15	0.17	0.17	0.01
22	28.37	28.50	0.61	0.50	0.52	0.08	8.72	8.76	0.15	0.14	0.15	0.02
23	28.37	28.50	0.61	0.50	0.50	0.07	8.72	8.76	0.15	0.15	0.16	0.02
24	28.37	28.50	0.61	0.45	0.44	0.11	8.72	8.76	0.15	0.13	0.13	0.03
25	28.37	28.50	0.61	0.44	0.45	0.08	8.72	8.76	0.15	0.13	0.12	0.02
26	28.37	28.50	0.61	0.52	0.52	0.08	8.72	8.76	0.15	0.15	0.15	0.03
27	28.37	28.50	0.61	0.45	0.44	0.09	8.72	8.76	0.15	0.13	0.14	0.03
28	28.37	28.50	0.61	0.54	0.55	0.09	8.72	8.76	0.15	0.16	0.17	0.03
29	28.37	28.50	0.61	0.49	0.48	0.09	8.72	8.76	0.15	0.14	0.14	0.02
30	28.37	28.50	0.61	0.66	0.70	0.15	8.72	8.76	0.15	0.18	0.18	0.04