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Inclusion of Maintenance in Life Cycle Costs of Flexible and Rigid Pavements

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16. Abstract

Routine maintenance costs are often ignored in life-cycle cost analyses (LCCA) for pavement type selection because the cost data necessary to support the analysis is generally unavailable. The decision to neglect maintenance costs is typically supported by claims that the costs are insignificant and not substantially different between pavement strategies. In this research, maintenance unit costs streams were developed using Monte Carlo simulation techniques based on existing roadway asset data from the Pavement Management System (PMS) and maintenance activity and cost data from the Maintenance Management System (MMS) and were investigated to assess the magnitude and nature of roadway maintenance costs. The feasibility of using the existing data to develop cost streams was evaluated in terms of quality and quantity. Simulated maintenance cost streams were developed from the observed probability of incurring maintenance and maintenance cost distributions. These streams were then analyzed to determine whether the magnitude of maintenance costs dictates their inclusion in LCCA for pavement type selection, and to assess differences in costs with respect to location, pavement type, and traffic volume. The results indicated that maintenance costs can be appropriately neglected from LCCA for pavement type selection, but should be considered when estimating the true cost of a pavement. Maintenance costs were found to be relatively constant throughout the initial 12 years of pavement life and sufficiently small in magnitude to be within the level of accuracy of the cost estimate of pavement construction. Significant differences in maintenance costs were found for roadways of different pavement types, in different geographic locations, and carrying different traffic volumes.

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EXECUTIVE SUMMARY

Life cycle cost analysis (LCCA) is an analytical technique used to evaluate the long-term total economic worth of competing alternative investments. It has been widely applied to the pavement selection process for highway construction. Routine roadway maintenance costs are often ignored in LCCA for pavement type selection because the cost data necessary to support the analysis is generally unavailable. The decision to neglect maintenance costs is typically supported by claims that the costs are insignificant and not substantially different between pavement strategies.

In this research, maintenance unit costs streams were developed using Monte Carlo simulation techniques based on existing roadway asset data from the PMS and maintenance activity and cost data from the MMS and were investigated to assess the magnitude and nature of roadway maintenance costs. Simulated maintenance cost streams were developed from the observed probability of incurring maintenance and maintenance cost distributions. These streams were then analyzed to determine whether the magnitude of maintenance costs dictates their inclusion in LCCA for pavement type selection, and to assess differences in costs with respect to location, pavement type, and traffic volume.

Feasibility, in terms of quality and quantity, of using the existing data to develop cost streams was evaluated. The most prevalent quality issues identified within the data were missing data regarding the maintenance activity cost and/or location. Data was filtered to address the issues and produce reliable select data sets. The quantity of select data was sufficient to quantify the probability of cost and the maintenance unit costs for low traffic asphalt primary roads and high traffic asphalt primary roads in the Coastal and Piedmont regions. Select data was not available in sufficient quantity to analyze interstate or concrete pavements. Data from windows of pavement life were compiled because cost data was not available throughout the entirety of the life of a pavement.

Median life-to-date maintenance costs through the initial 12 years of pavement life varied by roadway group and ranged from $576 to $1,256 per lane-mile. Costs of this magnitude can be considered to be "within the noise" of the estimated construction cost and are sufficiently small to be appropriately neglected from LCCA for pavement type selection. Costs were relatively constant throughout the analysis period and no significant relationship was found between the median life-to-date (LTD) maintenance unit costs and pavement age.

Maintenance costs were not equal for all pavement types. Significant differences between maintenance costs of composite and asphalt pavements were found from the comprehensive cost data. Costs varied by geographic region, but data was not sufficient to generalize cost trends across regions. Low traffic volume roadways were more costly to maintain than high traffic roads as a result of greater unit maintenance costs rather than more frequent maintenance activities. Low traffic volume roads exhibited a tendency towards costs much greater than median cost, and the maintenance activity durations and average unit costs were greater than roads with high traffic volumes.

While the results indicated that it is not necessary to include maintenance costs in LCCA, maintenance costs are real costs that should be considered when estimating the true cost of a pavement. Maintenance activity data should continue to be collected and the volume monitored to allow analysis of interstate, concrete, and composite pavements at a future time. Filtered select data should be used for future analyses and the importance of accurately recording both the cost and location of activities should be communicated to those responsible for entering the data.

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1 INTRODUCTION

Life cycle cost analysis (LCCA) is a technique based on economic principles used to evaluate the long-term total economic worth of competing alternative investments. It has been widely applied to the pavement selection process for highway construction. Within the highway construction realm, the initial construction costs can be combined with discounted future costs to allow for a comparison of the net present value of design alternatives and the selection of the most cost effective pavement. Relevant costs that may be included in LCCA are those for initial construction, future rehabilitation and/or reconstruction, future routine maintenance, user costs, traffic control, and salvage value.

1.1 Research Need

The North Carolina Department of Transportation (NCDOT) considers LCCA to be a critical element of the pavement type selection process. Agency costs associated with the initial construction, standard pavement rehabilitation, and a major rehabilitation near the end of pavement life are considered in the LCCA. However, the costs of routine, reactive maintenance activities, that are periodically required to maintain the pavement in a safe and operable condition, are not considered. To represent the true cost of the pavement, these maintenance costs should be included in LCCA.

Routine maintenance costs are often ignored in LCCA for pavement type selection because the cost data necessary to support the analysis is generally unavailable. The decision to neglect maintenance costs is typically supported by claims that the costs are insignificant and not substantially different between pavement strategies.

NCDOT maintains data regarding the type, cost, location, and timing of maintenance activities in the Maintenance Management System (MMS) and data regarding the type and age of pavements in the Pavement Management System (PMS). The data provided an opportunity to evaluate the assumptions that maintenance costs are similar for flexible and rigid pavements, and are insignificant relative to construction and rehabilitation costs.

1.2 Research Objectives and Tasks

The goals of this research were to study and quantify the maintenance costs of flexible, rigid, and composite pavements through the life of the pavements and answer the following questions:

1. Are pavement maintenance costs so small that they need not be included in LCCA?
2. Are pavement maintenance costs small throughout the pavement life?
3. Are pavement maintenance costs approximately equal for rigid, flexible, and composite pavements?

These questions were addressed through completion of the following tasks:

1. Review and synthesize current LCCA literature to establish the current state of practice.
2. Collect pavement data from PMS and maintenance data from MMS for interstate and primary roadways.
3. Evaluate the data to determine the feasibility of developing typical maintenance cost streams.
4. Develop typical maintenance cost streams for rigid, flexible, and composite pavements in terms of average maintenance cost per lane mile for each year of pavement life.
5. Evaluate the magnitude and timing of costs comprising the maintenance cost streams.

2 LITERATURE REVIEW

2.1 Introduction

The aim of this research was to evaluate the costs incurred by maintenance of interstate and primary roadways within North Carolina. To develop a maintenance definition and identify all related costs, it was imperative to first define LCCA and all components of cost that fall within it. Understanding the difference in cost information allowed a precise definition for what items were to be considered maintenance. Also, research studied the current practices by which other state transportation agencies implement maintenance costs in their LCCA. A comparison was made between states' current practices and the computer programs that are used to manage the cost information.

2.2 Tools for Evaluation of Alternatives

Cost-effectiveness is a measure for evaluating and comparing that which is sacrificed (cost) to that which is gained (effectiveness) for the purpose of evaluating alternatives (Lamptey et al., 2005). Life Cycle Cost Analysis (LCCA) and Benefit Cost Analysis (BCA) are two evaluation tools that are used in the selection process for design alternatives. The Federal Highway Administration (FHWA) Life-Cycle Cost Analysis Primer (2002) describes the LCCA as an "approach used to select the most cost-effective alternative that accomplishes a preselected project at a specific level of benefits that is assumed to be equal among project alternatives being considered." In comparison, the BCA approach is a tool that is used when design alternatives will not yield equal benefits, such as when unlike projects are being compared (FHWA, 2002).

2.2.1 Benefit Cost Analysis

The Benefit Cost Analysis approach is often used in capital investment decisions. Research has been implemented to correlate benefit of capital improvement evaluation with maintenance activities. Lamptey et al. (2005) stated that benefits of a well maintained pavement include reduced travel times, reduced vehicle operating and maintenance costs, increased motorist comfort and safety, and reduced rate of pavement deterioration. All of the mentioned benefits can be represented by the area under the performance-time curve. Because the benefits of a well-maintained pavement are difficult to quantify in monetary terms, the area under the performance curve is a good representative of the user benefits. The curve of a well maintained pavement will yield a large area under the curve, which represents significant user benefits. The lesser area under the curve represents a more poorly maintained pavement.

To illustrate the concept of benefit analysis, suppose that the benefit of motorist comfort is being compared to the age of the pavement. Figure 2.1 presents the level of motorist comfort over the life of a pavement. The figure depicts a scenario where reactive maintenance (MC_{P1}) is compared to a well maintained pavement (MC_{P2}).

The MC_{P1} shows a steeper negative slope compared to MC_{P2}, which represents a faster decline in motorist comfort over the life of the pavement. The benefit analysis of the maintenance scenarios can be analyzed by calculating the area under the slopes. The greater negative slope yields a less significant user benefit. This example shows that the well-maintained pavement (MC_{P2}) has a more significant motorist comfort benefit than the reactive maintenance approach because of the greater area under the slope.

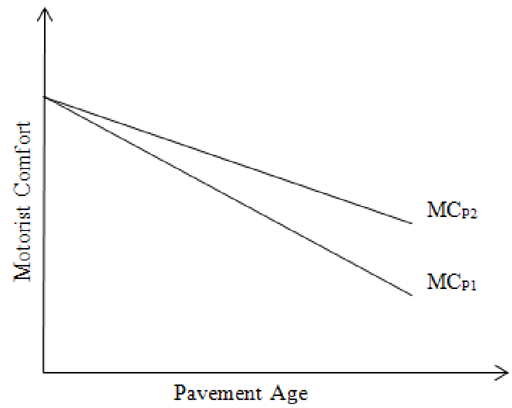

Figure 2.1: Benefit Cost Analysis Concept

2.2.2 *Life Cycle Cost Analysis*

The LCCA is most commonly used in the United States for project-level decisions (Rangaraju et al., 2008). The concept was first developed by the U.S. government in the 1960s for increasing the cost-effectiveness of purchases (Chen et al., 2009). The LCCA approach to evaluating pavement maintenance is often considered most appropriate. The LCCA method assumes that all pavement maintenance investment alternatives have the same benefit. Regardless of the maintenance alternative that is selected, the benefit remains constant, because the road is maintained and restored back to the original condition (Lamptey et al., 2005). To effectively evaluate the pavement alternatives, it was recommended by Geoffroy (1996) to include both the benefits accrued to the users and the cost incurred to provide those benefits. As stated by Lamptey et al. (2005), it may be argued that benefits are cost reductions, and that those benefits are encompassed in the term “life cycle cost analysis.”

2.3 Life Cycle Costs for Pavement Selection

The use of a LCCA for pavement selection requires a comparison of all differing costs incurred between each alternative during an evaluation period (FHWA, 2002). After costs are determined for each alternative, they must be converted into equivalent dollar amounts for comparison. The two most common methods for converting costs are Net Present Value (NPV) and Equivalent Annual Value (EAV). The EAV is the cost per year of a pavement, where the NPV is the present worth of costs incurred over the life of the pavement. The EAV is used when the two pavements being compared do not have the same lifespans. If an NPV of a 12 year old pavement is to be compared with the NPV of a 17 year old pavement, an EAV is necessary.

The analysis of life cycle costs for each pavement alternative is categorized as either agency or user costs. These categories represent the costs incurred by the DOT agency and the costs incurred by the user of the roadway.

2.3.1 *Agency Costs*

Agency costs are further divided into subcategories. Walls and Smith (1998) states that the following agency costs should be evaluated for pavement selection:

1. Initial construction
2. Rehabilitation
3. Maintenance
4. Salvage value or remaining service life

Initial construction costs include the costs incurred by the agency when the project is originally built. This includes engineering, contract administration, supervision, and construction costs (Walls and Smith, 1998). These costs will generally account for a substantial portion of the overall life-cycle cost for a given project. Differences between alternatives can cause this cost to vary significantly. Therefore, its inclusion into the LCCA is critical.

Rehabilitation costs, which can be viewed as reconstruction costs, arise when the condition of a roadway begins to decline toward a set threshold (see Figure 2.2). Rehabilitation occurs at different time intervals for each alternative. For example, a concrete pavement may maintain its integrity longer than an asphalt pavement when subjected to the similar levels of service and climates. The use of LCCA allows comparison of the costs of rehabilitation at these differing time intervals.

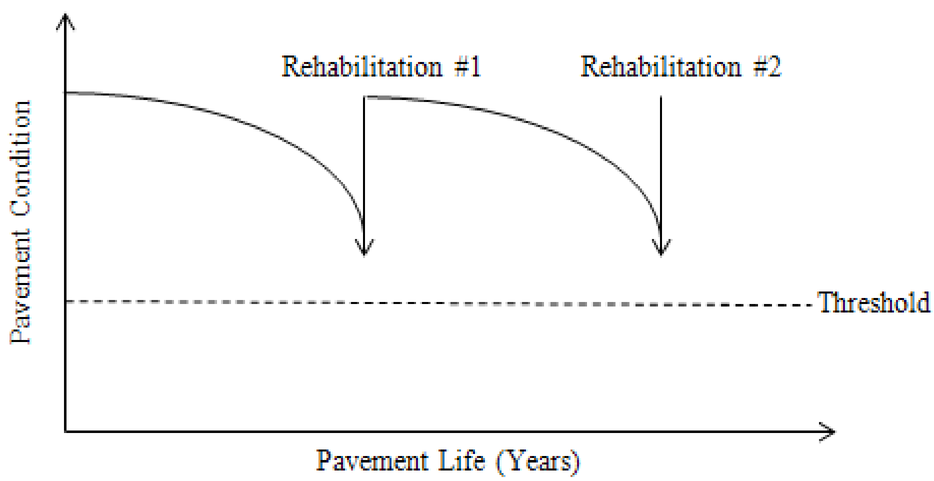

Figure 2.2: Rehabilitation Time Intervals

Maintenance costs differ from rehabilitation in that they are generally not scheduled, but reactive costs (Walls and Smith, 1998). Basically, maintenance costs occur after a problem arises. These costs are often viewed as insignificant when compared to other costs (FHWA, 1998).

The attitudes of transportation department agencies toward maintenance and rehabilitation can be categorized as either Proactive or Reactive (Wilde et al., 1999). A proactive approach to maintenance means that the agency performs repairs on potential problem areas before they become crucial issues. A reactive approach means that an agency waits until the problem becomes severe before taking any action to repair the situation. It is often considered more effective to take the proactive approach to pavement maintenance, but is not commonly performed (Wilde et al., 1999).

To illustrate the benefit of proactive maintenance, the case of the City of Bedford, Texas was presented by Wilde et al. (1999). The city performed an investigation in which it was determined that the street network was in need of repair. The street network was in fairly good condition, which prompted concern from city residents on whether or not the maintenance and rehabilitation work was necessary. To defend the decision to proactively perform repairs to the streets, the city presented the data in Table 2.1 to show the current and projected backlog. The data demonstrates that the funds required to keep the condition of the street network at an acceptable level would more than double over a four year period. It was predicted that proactively maintaining the network and clearing the total backlog would slow deterioration and the estimated $34 million cost would not be required. Alternatively, if only routine maintenance was performed, the current deterioration trends would continue, and major rehabilitation would be required by October 2001.

Table 2.1: Current and Projected Funding Requirements for the Street Network of the City of Bedford, Texas (Wilde et al., 1999)

	As of June 1, 1997	**Projected October 1997**	**Projected October 2001**
Operating Budget	$ 3,812,115	$ 3,909,943	$ 4667,460
Capital Improvement	$ 11,567,366	$ 13,108,452	$ 38,516,708
Subtotal	$ 15,379,480	$ 17,018,395	$ 43,184,169
Current Funding	($ 1,127,750)	($ 688,750)	($ 8,763,020)
Total Backlog	$ 14,251,730	$ 16,329,645	$ 34,485,686

An illustration of this effect can be seen in Figure 2.3. The proactive maintenance option reduces the rate of pavement deterioration and a more acceptable pavement distress level is maintained for a longer period of time. The awareness of maintenance cost trends can be beneficial for budgeting and scheduling the future repair of pavement.

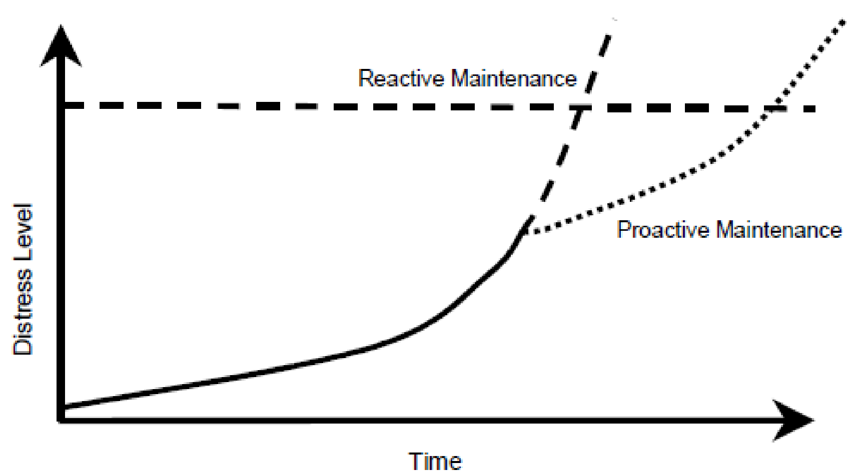

Figure 2.3: Comparison of Proactive and Reactive Maintenance Approaches (Wilde et al., 1999)

The salvage value or remaining service life costs, for an alternative is viewed as a credit to the agency. The salvage value is the value the agency receives for recycling material at the end of the usable life. The remaining service life is the value retained by an alternative after the evaluation period.

2.3.2 User Costs

Transportation departments provide a service to users in the form of roads and highways. The use of a LCCA, pertaining to users, has two functions. The first is to demonstrate to the user that the department is sensibly spending tax dollars in an investment decision, commonly referred to as stewardship. The second is to include user costs into the analysis. User costs can include time delay, crash, and vehicle operating costs. According to FHWA (2002), these costs are difficult to assign value to, especially time delay costs. As it is necessary to only include costs which differ between alternatives into a LCCA, Rangaraju (2008) suggests that user costs be considered independent of agency costs, rather than combining these costs into a lump sum. Most of the state DOTs incorporating user costs into the analysis only consider user delay costs during construction and major rehabilitation activities. The opportunities to incorporate user costs into LCCA are still being explored (Rangaraju et al., 2008). In any case, it is seen as good practice to include user costs in a LCCA.

2.4 Historical Background

The American Association of State Highway and Transportation Officials (AASHTO) first introduced the life cycle cost analysis for highway construction with the publication of the "Red Book" in 1960 (Wilde et al., 1999). This manual helped to establish the concept of economically evaluating the design and selection process of pavement type. To further advance the development of LCCA procedures for pavement selection and design in the 1960s, two projects were undertaken. The National Cooperative Highway Research Program (NCHRP) conducted an investigation to promote the concept of LCCA, and the Texas Transportation Institute (TTI) and the Center for Transportation Research (CTR) developed the Flexible Pavement System (FPS). The FPS is a computer program that is used to analyze alternative pavement designs and compare the life cycle costs (Wilde et al., 1999).

In 1991, The Intermodal Surface Transportation Efficiency Act (ISTEA) required that metropolitan planning organizations consider 'the use of life-cycle costs in the design and engineering of bridges, tunnels, or pavement" (Walls and Smith, 1998). In January 1994, President Bill Clinton signed the Federal Executive Order 12893 which required all federal agencies to use a "systematic analysis of expected benefits and costs…appropriately discounted over the full life cycle of each project" in making major infrastructure investment decisions (Rangaraju et al., 2008). The National Highway System Designation Act of 1995 further required that state departments of transportation perform life cycle cost analysis on all pavement projects with a cost of $25 million or greater (Wilde et al., 1999).

After three years of being a federally legislated requirement, the Transportation Equity Act for the 21st Century (TEA-21) removed the LCCA requirement in the 1998. The objective of TEA-21 was to expand the knowledge of implementing life cycle cost analysis, without mandating states to conduct an analysis for any project. However, the FHWA and AASHTO continue to promote and assist state agencies in the development of LCCA procedures. According to the 2012 North Carolina General Assembly (NCGA), the Life Cycle Cost Analysis Committee has recommended that the NCDOT continue to take measures "to develop and utilize the most efficient methods of designing and constructing transportation projects." The Committee also recommends that the 2013 General Assembly "create a new committee, or task an appropriate existing committee, to continue the Life Cycle Cost study of issue related to more effective and efficient construction of transportation projects" (NCGA, 2012).

2.5 Life Cycle Cost Analysis in Pavement Selection

There are over four million miles of public roads stretching across the United States. In 2013, the federal spending rate was $91 billion per year for highway capital improvements, which was well below the estimated $170 billion needed to effectively improve roadway conditions (ASCE, 2013). With more than one-third of major roads in poor or mediocre condition, ASCE (2013) has stated that a reform in the federal highway program is needed to “emphasize performance management, cost-benefit analysis, and accountability.” With highway funding continuing to fall short of infrastructure needs, an effective management of roadway investments is becoming a necessity (Chan et al., 2008). In result of the decreased funding, the FHWA considers the use of LCCA as an important analytical tool that is applicable to a broad range of routine decisions facing State and local transportation agencies (FHWA, 2002).

The FHWA does not currently mandate the use of LCCA, but instead provides guidance through various publications. FHWA has published “Life-cycle Cost Analysis in Pavement Design” interim technical bulletin (FHWA, 1998), the “Life-cycle Cost Analysis Primer” (FHWA, 2002), and the “Economic Analysis Primer” (FHWA, 2003).

In the “Life-Cycle Cost Analysis in Pavement Design” bulletin, FHWA states that transportation investment decisions should consider all costs that are directly related to the period over which the alternatives are being compared. Agency costs to be considered include all costs incurred directly by the agency over the life of the project, including the costs of future routine and preventative maintenance. It is noted that cost data for routine maintenance is typically not available. It is further stated that such costs can generally be ignored because they are “not very high” and there is reportedly little difference between most alternative pavement strategies (FHWA, 1998). However, the FHWA “Life-Cycle Cost Analysis Primer” (2002) states that specific future rehabilitation and maintenance costs are dictated by the design alternative selected, and therefore shall be considered relevant. The FHWA LCCA strategy requires that maintenance and rehabilitation activities be forecasted as accurately as possible because they identify these costs as a sizeable portion of the total life cycle cost of a project (FHWA, 2002).

In 2006, Chan et al. (2008) conducted interviews with state transportation officials and found that 29 states reported that maintenance costs are considered in LCCA. Figure 2.4 shows the 2006 survey results of DOT LCCA practices in pavement type selection. No information was provided regarding the manner in which maintenance costs are considered because each state DOT uses slightly different analysis periods, maintenance strategies and discount rates (Wilde et al., 1999). Maintenance costs are often determined by applying historical unit costs, as stated by Indiana DOT (INDOT). Chan et al. (2008) expressed that as pavement technologies and designs advance over time, pavements would have different optimal maintenance schedules from pavements constructed decades ago.

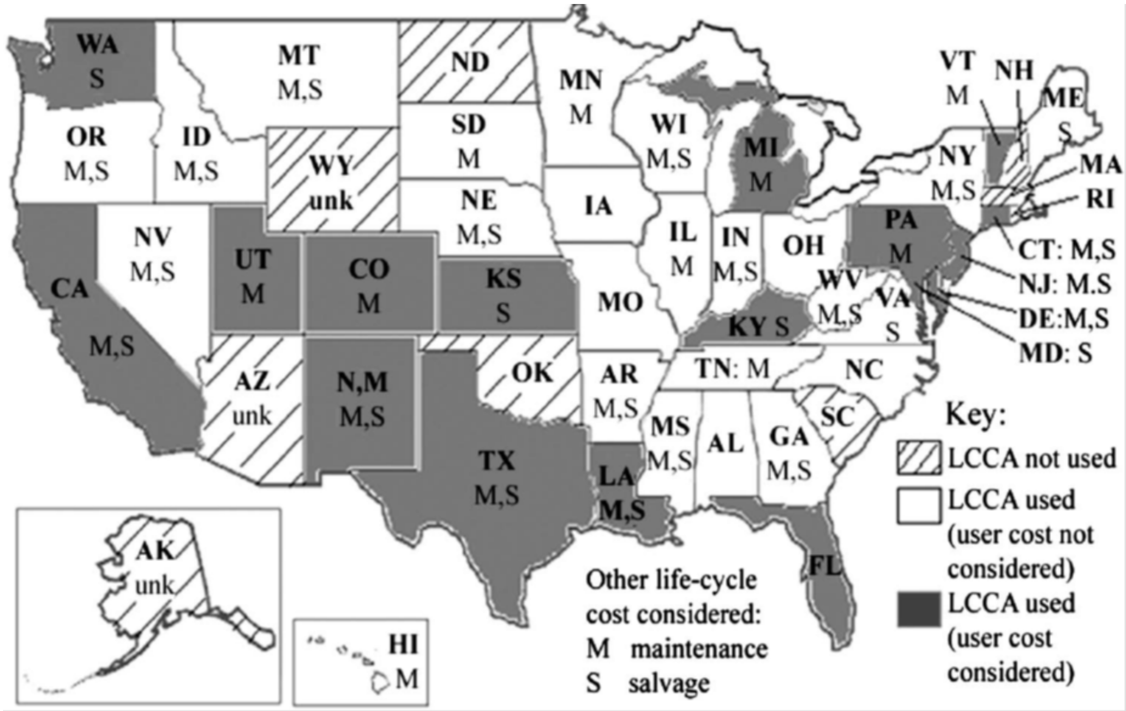

Figure 2.4: 2006 Survey Results of DOT LCCA Practices in Pavement Type Selection (Chan et al., 2008)

The following year, the AASHTO Research Advisory Committee (RAC) sponsored a survey that examined the LCCA practices of state transportation agencies (AASHTO, 2007). The results of the 2007 study provided a more definitive understanding of the practices for LCCA of pavement selection type. As a portion of the survey, the RAC gathered information about how states assume maintenance type and frequencies. Of the 18 states that responded to the survey, three states (Delaware, Rhode Island, and Texas) stated that they currently do not utilize LCCA for the determination of pavement type. Table 2.2 is a summary of the reported maintenance data collection method for each responding state.

Table 2.2: Summary of 2007 AASHTO LCCA Survey

State	Data Used to Determine Maintenance Treatments
Alabama	Historical
Arkansas	Theoretical
Colorado	Historical
Delaware	N/A
Florida	Historical & engineering judgment
Illinois	Historical and theoretical
Indiana	Theoretical and semi empirical
Kansas	Theoretical
Missouri	Historical and theoretical
Montana	Historical
New Jersey	Primarily historical
New York	Historical
Ohio	Historical data adjusted for improvements in specifications and materials
Rhode Island	N/A
South Carolina	Theoretical
Texas	N/A
Washington	No Response
Wyoming	Historical

It is important to note the discrepancy of some states' responses to the surveys between 2006 and 2007. In the 2006 survey, Texas claimed to use LCCA in the selection process, but the following year stated that LCCA is not considered. In 2011, the California Department of Transportation (Caltrans) Division of Research and Innovation (DRI) also performed a preliminary investigation into the current LCCA practices of different states. In this investigation, DRI identified that Texas DOT does, in fact, consider LCCA and has developed a Pavement Design Process, Pavement Design Guide (Caltrans, 2011).

Caltrans DRI recommended that the next step of their investigation should be to contact those states that have a long history of using LCCA for pavement design such as Colorado, Michigan, Pennsylvania, and Washington. Pennsylvania has developed a custom spreadsheet for LCCA and Michigan uses custom LCCA software. Colorado mentioned that the maintenance costs are based on historical data and an average annual cost was developed for both flexible and rigid pavements (AASHTO, 2007). The 2007 AASHTO survey also identified that the New York DOT was working on collecting maintenance information from their network and developing a model for maintenance treatments based on AADT.

2.6 Inclusion of Maintenance Costs in Life Cycle Cost Analysis

Cambridge Systematics (CS) collected and analyzed data from FHWA Highway Statistics on maintenance information for Texas and the country as a whole. Texas Department of Transportation (TxDOT) developed a methodology to determine whether or not tax revenue and fees associated with road segments equal the construction and maintenance costs associated with the same road segments. At the request of TxDOT, CS issued The Highway Construction Equity Gap (2008) report that aimed to refine and correct any deficiencies found in the methodology. The analysis of the data showed that TxDOT's average interstate routine maintenance costs for 2004 and 2005 were $5,320 and $6,027 per lane mile, respectively. The TxDOT default value for interstate maintenance costs is $4,400 per lane mile, in 2004 U.S. dollars (Cambridge, 2008).

The Florida Department of Transportation (FDOT) also reported 2002 annual costs for constructing, milling and resurfacing, and routine maintenance of urban and rural highways (FDOT, 2003). These costs are summarized in Table 2.3.

Table 2.3: FDOT 2002 Highway Costs per Centerline Mile (FDOT, 2003)

	2-Lane, Rural	**2-Lane, Urban**	**4-Lane, Rural**	**4-Lane, Urban**
New Construction	$2,172,300	$2,821,800	$4,018,600	$4,765,100
Milling and Resurfacing	$477,800	$422,100	$686,900	$541,200
Routine Annual Maintenance	$21,700	$26,300	$40,700	$58,500

2.7 Existing Pavement Life Cycle Cost Analysis Computer Programs

Life cycle costs for pavement design are analyzed differently from state to state. Chan et al. (2008) performed an evaluation of the Life-Cycle Cost Analysis practices used by the Michigan DOT (MichDOT). For each road section that was chosen, actual initial construction and maintenance costs were collected from the finalized construction contracts, while actual maintenance schedules were gathered from databases managed by MichDOT. The data provided from MichDOT showed that the actual maintenance costs that were carried out on the roadways were different from the estimated schedule in the LCCA. Chen et al. (2008) suggests that this observation could be the explanation for why MichDOT does not specify future maintenance events in the LCCA. To fix the issue of inaccurate maintenance scheduling, Chen et al. (2008) states that a greater emphasis should be paid to developing a more accurate estimate of future maintenance costs, as well as establishing a process to monitor actual maintenance costs experienced.

In 2011, a preliminary investigation was performed by the Caltrans Division of Research and Innovation to develop an understanding about tools and practices related to the LCCA process for highway improvements (Caltrans, 2011). As a portion of this investigation, Caltrans reviewed the current LCCA practices in 17 states. Caltrans reviewed each state practice and summarized their findings in Table 2.4.

Table 2.4: Summary of Caltrans Review of State LCCA Tools

State	LCCA Tool	Analysis Period (yrs)
California	RealCost	20,35,55
Colorado	RealCost	40
Florida	RealCost	40
Georgia	Custom Spreadsheet	30,40
Illinois	Not specified	45
Indiana	RealCost	At least 50 (new)
Michigan	DARWin and custom software	10 to 20
Minnesota	Custom Spreadsheet	35 to 50
New York	Not specified	Range
Ohio	Not specified	35
Oregon	RealCost	40 (new), 50 (Interstate)
Pennsylvania	Custom Spreadsheet	50
Texas	Custom software	30
Utah	Not specified	25 to 40
Virginia	Not specified	50
Washington	RealCost	50
Wisconsin	Custom software	50

Many states have developed computer software programs for further analysis and organization of the LCCA process, beyond the database collection presented by the MichDOT. To understand the rising need for a more accurate tool of measurement, this section will outline various life cycle cost systems that are currently in practice.

2.7.1 Flexible Pavement System and Rigid Pavement System - Texas DOT

The Texas Department of Transportation implemented the Flexible Pavement System (FPS) and Rigid Pavement System (RPS) program in the 1960s (Wilde et al., 1999). The Rigid Pavement Rehabilitation Design System is a modification of the original RPS-3 program. The FPS program is for Microsoft Windows and is currently in its 21st version (Lie and Scullion, 2011). The variance of all influential variables is calculated and the variability of the overall life cycle cost is subsequently determined. These variables include alternate design considerations such as traffic data, confidence levels, analysis periods, and overlay schedules.

2.7.2 LCCP/LCCPR – Maryland

The University of Maryland developed a set of LCCA programs that analyze flexible and rigid pavements (Wilde et al., 1999). These programs incorporate user operating costs associated with pavement roughness among other variables (Lamptey et al., 2005). The programs are intended for project-level pavement management analysis, but are not as applicable to the comparison of alternate designs.

2.7.3 Pavement Management System – Nevada DOT

The Nevada DOT (NDOT) has implemented a pavement management system (PMS) at the network level and a pavement evaluation system at the project level (Sebaaly et al., 1996). NDOT has had an operational PMS since 1980, composed of performance data, performance modeling, LCCA, and network optimization. The LCCA assesses alternate design types for rehabilitation and maintenance strategies. The LCCA actual costs are divided into first costs, annual maintenance costs, and salvage values.

To select appropriate figures for annual maintenance costs, the actual annual expenditures are collected in the NDOT Pavement Maintenance Management System (PMMS). Using the PMMS program, the NDOT suggests that cumulative annual maintenance costs following the application of a rehabilitation or maintenance treatment will become uniform after x number of years (Sebaaly et al., 1996). In other words, NDOT found that there is significant variability in multiple pavement sections maintenance costs for individual years, but the cumulative costs of the sections will show less variability. It is difficult to predict the cost that will be spent each year of the section life, but the cumulative annual cost spent on each section, at a given year, is more consistent.

2.7.4 Highway Performance Monitoring System - FHWA

The Highway Performance Monitoring System (HPMS) records and updates information on the current condition of U.S. highways as a way of assessing the future highway needs. The FHWA developed this program to meet the requirements of U.S. Code, Title 23, Section 307A (Wilde et al., 1999). The program is not developed for a project-level analysis, and instead is used to determine an overall estimate of conditions and future needs of the highway system.

2.7.5 LCCOST – Asphalt Institute

The LCCOST program considers the initial cost of construction, multiple rehabilitation actions throughout the design life, and user costs during initial construction (Wilde et al., 1999). In addition, the program can consider routine maintenance activities that will be applied each year between rehabilitation activities. Salvage value of the pavement selection is also considered by the model.

2.7.6 DARWin - AASHTO

The life cycle cost program of DARWin accounts for project dimensions, initial construction, rehabilitation strategies, and the salvage value of the pavement. This program is intended to provide project-specific agency costs, and perform as a database for managing materials, material properties, costs, and other aspects of pavement design and construction (Wilde et al., 1999).

2.7.7 Highway Design and Maintenance Standards Model – World Bank

The Highway Design and Maintenance Standards Model (HDM-III) computer program was developed for evaluating highway projects, standards, and programs in developing countries (Lamptey et al., 2005). The HDM-III program considers construction costs, maintenance costs, and vehicle operating costs. The Expenditure Budgeting Model (EBM) is used with the HDM to compare options under year-to-year budget constraints. The outputs of this program are used with a spreadsheet.

2.7.8 RealCost – FHWA

RealCost is software that is used as a tool for pavement designers to incorporate life-cycle costs into their pavement design decisions. The software does not calculate agency costs for individual activities, but the program allows for these values to be manually input (FHWA, 2004). RealCost calculates the LCCA based on agency and user costs and outputs a comparison of alternative options.

2.8 Summary

The LCCA for pavement design includes both agency and user costs. Each state DOT has a unique guideline for analysis of the life cycle costs for pavement design alternatives. Some states identify routine maintenance costs as a portion of their LCCA, while other states reportedly neglect these costs. The opinions of whether or not routine maintenance costs are significant enough to be included are debated by various publications. Studies have not been performed to quantify the impact of maintenance costs on the life cycle costs of a pavement.

3 DATA COLLECTION AND ASSESSMENT

The maintenance cost histories for interstate and primary roadways were compiled from data contained in the PMS and MMS, as shown in Figure 3.1. Data regarding the roadway asset, such as identification, location, pavement type, and construction history, was extracted from the PMS and combined with maintenance history data from the MMS. Maintenance history data included the type, location, timing, and cost of maintenance activities.

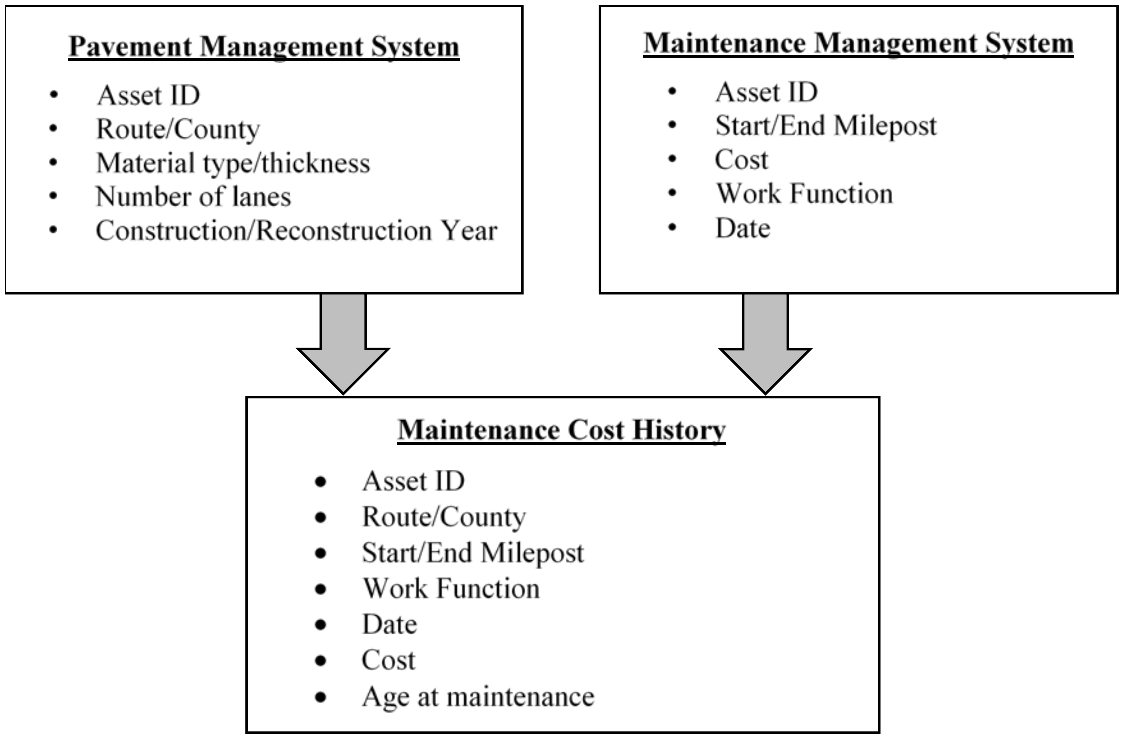

Figure 3.1: Maintenance History Data Collection Process

3.1 Pavement Management System (PMS)

Data from the PMS was used to identify roadway segments, classify them by location and pavement type, and establish the pavement age in each year. The Network Master table in the PMS was used to identify the following for each roadway segment:

1. Asset ID
2. County
3. Construction/Reconstruction Year
4. Number of lanes
5. Beginning and ending mileposts
6. Pavement surface material
7. Traffic volume (annual average daily traffic)

The Asset ID is an eight digit code used to identify the roadway type, direction, and route number, as shown in Figure 3.2. The county in which the roadway is located is identified by a three digit code, ranging from 001 to 100 and corresponding to the list of counties provided in Appendix A.

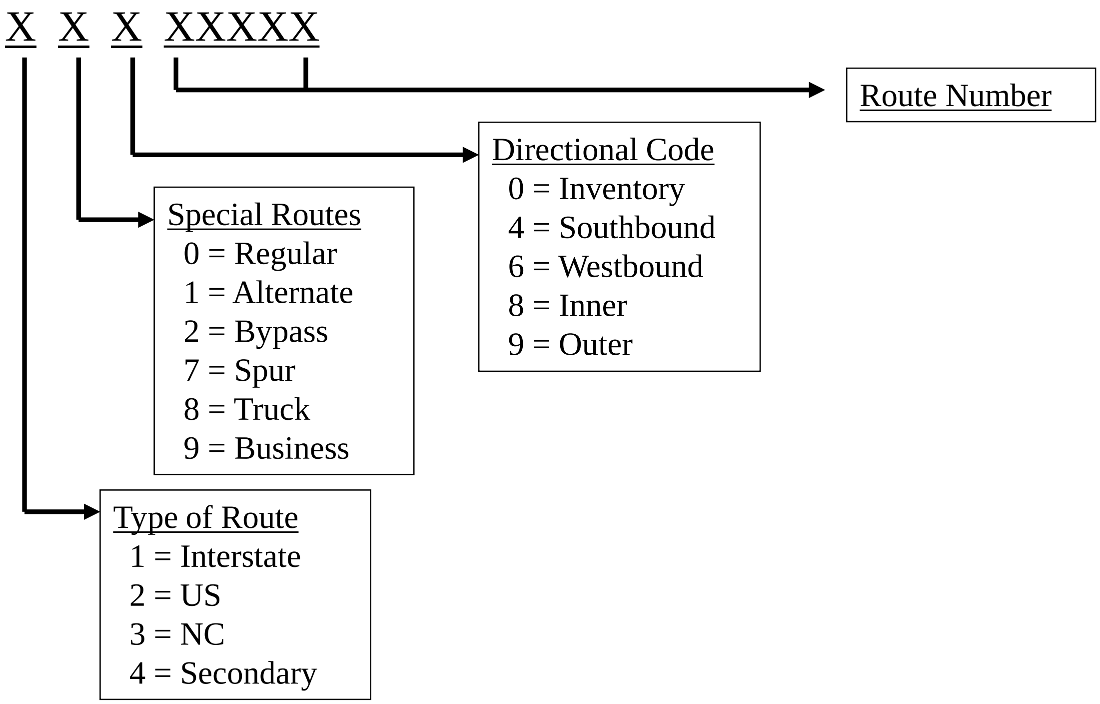

Figure 3.2: NCDOT Route Identification Code (NCDOT 2012)

Only the current pavement surface material is identified in the Network Master table and the Construction History table was used to determine the previous pavement materials and to distinguish between asphalt and composite roadways. The composite roadways were those sections currently surface with asphalt (ASP), but originally constructed of concrete. The Construction History and Network Master tables were cross referenced to identify sections incorrectly identified in either database.

The Construction History data from the PMS was used to overlap all road surface history information over the identified roadway segment from the Network Master. Roadway segments were neglected if the construction history and initial pavement type could not be clearly matched to within a 0.01 mile length. This tolerance of 0.01 miles was selected to minimize the uncertainty in pavement type across the segment, while also recognizing that a perfect match is difficult between the two tables.

Roadway sections were classified by traffic volume as shown in Table 3.1. Separate high/low traffic volume threshold values were used for interstate, US routes, and NC routes.

Table 3.1: Traffic Volume Thresholds by Roadway Classification

	Primary		**Interstate**
	NC Routes	**US Routes**	
High Traffic	5k+ AADT	15k+ AADT	50k+ AADT
Low Traffic	0 – 5k AADT	0 – 15k AADT	0 – 50k AADT

Roadway sections were sorted based on:

1. Location – Coastal, Piedmont, or Mountains
2. Roadway Classification – Interstate or Primary
3. Pavement Type – Asphalt, Concrete, or Composite
4. Traffic Volume – High or Low

The lengths of sections identified from the PMS were analyzed to determine an appropriate minimum section length to control inflation of maintenance costs when expressed as cost per lane mile, while maintaining a sufficient number of sections for analysis. The number of sections with lengths of 0.66 miles and 0.80 miles were evaluated, corresponding to cost multipliers of 1.5 and 1.25, respectively. Table 3.2 presents a summary of the number and percentage of sections by length for each roadway grouping. A minimum section length of 0.80 miles was selected to limit the inflation of costs, while also incorporating the vast majority of the data for analysis.

The greatest number roadway sections have an asphalt surface and approximately 80 percent are asphalt pavements (i.e. constructed entirely of asphalt and not composite pavements). Asphalt pavements are spread across the state, are largely primary roadways, and there is no apparent trend related to traffic volume. The same is generally true for composite pavements, although the number of composite sections in the Mountains region is noticeably smaller than in other geographic regions.

The number of concrete pavements is substantially less than asphalt surfaced pavements and comprised approximately 5 percent of the roadway sections identified. Concrete pavements are nearly exclusively interstate roadways and are most prevalent in the Piedmont region.

Table 3.2: Summary of Roadway Sections from PMS by Length and Type

Type	Road Class.	Region	Traffic Vol.	Total	Length > 0.66 mi n	Length > 0.66 mi Pct	Length > 0.80 mi n	Length > 0.80 mi Pct	Length > 1.00 mi n	Length > 1.00 mi Pct
Asphalt	Interstate	Coastal	High	0	0	0%	0	0%	0	0%
			Low	197	188	95%	187	95%	181	92%
		Mountain	High	0	0	0%	0	0%	0	0%
			Low	93	91	98%	90	97%	86	92%
		Piedmont	High	23	23	100%	23	100%	23	100%
			Low	152	143	94%	136	89%	132	87%
	Primary	Coastal	High	1,527	1,100	72%	997	65%	838	55%
			Low	3,347	2,683	80%	2509	75%	2237	67%
		Mountain	High	648	423	65%	382	59%	315	49%
			Low	1,622	1,287	79%	1,195	74%	1,060	65%
		Piedmont	High	1,107	753	68%	693	63%	546	49%
			Low	1,842	1,439	78%	1342	73%	1153	63%
Composite	Interstate	Coastal	High	0	0	0%	0	0%	0	0%
			Low	89	88	99%	88	99%	83	93%
		Mountain	High	0	0	0%	0	0%	0	0%
			Low	75	75	100%	74	99%	72	96%
		Piedmont	High	68	68	100%	67	99%	66	97%
			Low	153	145	95%	141	92%	131	86%
	Primary	Coastal	High	269	193	72%	173	64%	150	56%
			Low	642	494	77%	451	70%	390	61%
		Mountain	High	73	47	64%	41	56%	34	47%
			Low	159	111	70%	102	64%	84	53%
		Piedmont	High	532	330	62%	291	55%	226	42%
			Low	438	305	70%	282	64%	229	52%
Concrete	Interstate	Coastal	High	0	0	0%	0	0%	0	0%
			Low	70	68	97%	66	94%	37	53%
		Mountain	High	43	34	79%	32	74%	17	40%
			Low	61	54	89%	52	85%	35	57%
		Piedmont	High	206	188	91%	180	87%	120	58%
			Low	165	149	90%	145	88%	79	48%
	Primary	Coastal	High	1	0	0%	0	0%	0	0%
			Low	3	2	67%	2	67%	2	67%
		Mountain	High	0	0	0%	0	0%	0	0%
			Low	6	5	83%	5	83%	2	33%
		Piedmont	High	99	90	91%	83	84%	30	30%
			Low	3	1	33%	1	33%	1	33%

3.1.1 Determination of Pavement Age

The "birth year" of each roadway section pavement was defined as the year in which initial construction or rehabilitation/reconstruction occurred. As many as four birth years for each section were determined from the Construction History table in the PMS and used to determine the pavement age at which maintenance activities were performed. Recently constructed pavements may not have had four birth years, but for older pavements four rehabilitation/reconstruction events were determined to be sufficient to extend beyond the earliest maintenance activities in MMS dating from 2002.

3.1.2 Adjustment of Section Lengths

The start and end mileposts in the Network Master and Construction History tables in the PMS are not consistent and it was necessary to match the pavement type (based on sections from the Network Master) with pavement age (based on sections from the Construction History). This matching process resulted in adjusted sections with starting and ending mileposts defining sections with consistent pavement types and ages.

For each roadway section obtained from the Network Master table, the start milepost was compared to the start milepost from the Construction History table and the greater of the two mileposts was assigned to the adjusted section. Similarly, the end mileposts were compared and the lesser of the two mileposts was assigned to the adjusted section. Adjusted sections with lengths less than the 0.80 mile threshold were removed from the study. Examples of section adjustments are provided in Table 3.3.

Table 3.3: Section Adjustment for Consistent Pavement Type and Age

			Network Master		Construction History		Adjusted Section	
County	**Route**	**Year**	**Start MP**	**End MP**	**Start MP**	**End MP**	**Start MP**	**End MP**
007	20000264	2000	7.458	8.377	7.513	8.927	7.513	8.377
007	30000032	1995	0	1.421	0	1.333	0	1.333
007	30000099	1993	9.51	11.420	0	10.942	9.51	10.942

3.2 Maintenance Management System (MMS)

Data from MMS was used to identify activities, quantify the costs, and determine the timing of routine maintenance work on the roadway segments. The maintenance data collected from the MMS included:

1. Route
2. Start and End Mileposts
3. Date of performance
4. Cost of maintenance
5. Work function

The starting and ending mileposts in the MMS pertain to the work performed and do not correspond to the beginning and ending mileposts of the roadway sections. Therefore, it was necessary to match maintenance activities with roadway sections or portions of sections and apportion costs appropriately. Methods for apportioning costs are discussed section 3.3 of this report.

AASHTO (2005) defined routine pavement maintenance as “work that is planned and performed on a routine basis to maintain and preserve the condition of the highway system or to respond to specific conditions and events that restore the highways system to an adequate level of service.” According to AASHTO, Pavement Rehabilitation consists of “structural enhancements that extend the service life of an existing pavement and/or improve its load carrying capacity” (Geiger, 2005). This project defined maintenance as “work that is planned and performed on a routine basis to maintain and preserve the condition of the road segment and restore the system to an adequate level of service, without extending the service life and/or improving its load carrying capacity.”

Work functions consistent with the definition of maintenance were identified from the list of all available work functions. Within the MMS, work functions are defined by a four digit code and have been recently updated. Appropriate work function codes from both the old and new catalog were identified and used. Table 3.4 provides a complete list of maintenance work functions. Only maintenance activities matching these work functions were extracted from the MMS and included in this study.

Table 3.4: Summary of New and Old MMS Work Functions for Maintenance Activities

	Number	Name	Measure
Old Work Function Catalog	3702	Hot Mix Short Overlay/Leveling	TON
	3711	Manual Patching	TON
	3712	Mechanical Patching	TON
	3713	Spray Injection Patching	SYD
	3714	AST Patching	SYD
	3715	Full Depth Patch Hot MIX	TON
	3716	Full Depth Patch Hot AST	SYD
	3717	Mill/Grind ASP PVMT	SYD
	3718	MNTC of Cracks in ASP Asphalt	LML
	3731	Temp Patch PCC PVMT	TON
	3732	Patch PCC PVMT	SYD
	3733	PVMT Jacking/Underseal	CYD
	3735	MNTC of Cracks Concrete	LML
	5086	Contract - Resurfacing	TON
	5100	Contract - Full Depth Patch Hot Mix	TON
	5105	Contract - Temp Patch Portland PVMT	LML
	5115	Contract - PVMT Jacking/Underseal	SYD
	5120	Contract - MNTC of Cracks Concrete PVMT	LML
New Work Function Catalog	2800	Single Seal	SYD
	2802	Double Seal	SYD
	2804	Triple Seal	SYD
	2806	Slurry Seal	SYD
	2808	Specialty Seals	SYD
	2810	Microsurface	SYD
	2812	Hot Mix Asphalt Overlay	TON
	2816	Asphalt PVMT Repair/Patch	SYD
	2817	Mechanical Asphalt Patching	TON
	2818	Full Depth Asphalt PVMT Repair	TON
	2820	Mill/Grind Asphalt PVMT	SYD
	2822	MNTC of Cracks and Joints	LML
	2824	Concrete Pavement Repair	SYD

3.3 Maintenance Cost History

The maintenance cost history of roadway sections was compiled by determining the maintenance costs incurred and apportioning the costs to the sections. Because the maintenance activities from the MMS do not necessarily correspond to individual roadway sections, it was necessary to apportion the cost of maintenance based on the lengths of the maintenance activities and roadway sections. Three conditions existed and rules for apportioning cost were developed:

1. Maintenance activity extends beyond roadway section in both directions – apportioned cost was based on the ratio of roadway section length to maintenance activity length
2. Maintenance activity wholly contained within the roadway section – entire maintenance cost was apportioned to the roadway section
3. Maintenance activity extends beyond roadway section in either direction – apportioned cost was based on the ratio of maintenance activity length within the section to the entire maintenance activity length

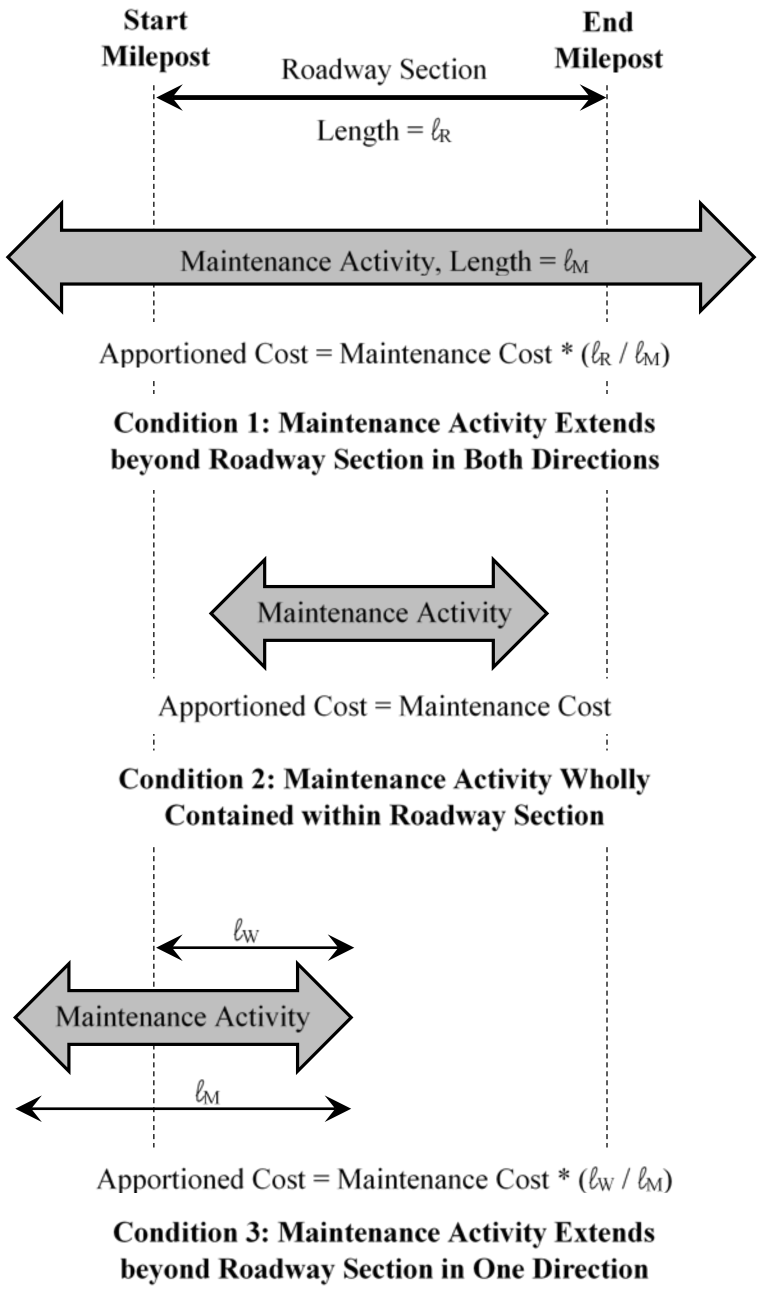

Figure 3.3: Maintenance and Roadway Section Configurations

For conditions 2 and 3 above, the maintenance activity was not performed across the entirety of the roadway section length. In these instances, it was assumed that maintenance was performed only where needed and additional maintenance would have been performed if necessary. The result of this assumption is that the apportioned maintenance cost was considered applicable to the full length of the roadway section.

Maintenance costs for each roadway section were adjusted to a common 2012 economic basis using the Consumer Price Index (CPI) data maintained by US Bureau of Labor Statistics and then divided by the number of lanes and section length to yield the unit maintenance cost expressed as cost per lane mile.

3.4 Maintenance Cost Summary

Maintenance costs were summarized by roadway section and pavement age for each roadway group (e.g. coastal, primary, asphalt, high traffic roadways). For each section, the adjusted unit maintenance costs were aggregated by year performed and the associated pavement age in each year determined. It was also necessary to determine the years (ages) for which a section did not incur maintenance and to assign a unit maintenance cost of $0 to the sections in these years (ages).

A section was considered to not have experienced maintenance when there were no recorded maintenance tasks for the given year and maintenance data was typically available for the year. Based on a review of the maintenance activities extracted, entry of maintenance activities into MMS began as early as 2002. Therefore, 2003 was the first complete year for which maintenance data were typically available.

Cost summaries were used to quantify the maintenance costs by pavement age and to estimate the likelihood of roadway sections incurring maintenance at each age. A brief excerpt of the maintenance cost summary for the Piedmont, interstate, asphalt, low traffic (PIAL) group is provided as Table 3.5. It is important to note that the table is an excerpt from the much large summary and the values presented may not accurately reflect the roadway group as a whole.

Table 3.5: Excerpt of Maintenance Cost Summary

Roadway Section			Annual Maintenance Unit Cost ($/ln-mi) at Age				
Route	**From Milepost**	**To Milepost**	**1**	**2**	**3**	**4**	**5**
10000085	6.22	7.50	$ 0	$ 174.49	$ 27.56	$ 0	$ 49.48
10400085	20.74	21.61	$ 0	$ 75.87	$ 0	$ 0	$ 0
10600040	0.00	2.07	$ 0	$ 0	$ 13.83	$ 0	$ 26.16
10600040	2.07	3.31	$ 0	$ 0	$ 13.83	$ 0	$ 26.16
10600040	4.05	6.04	$ 28.60	$ 37.03	$ 0	$ 0	$ 13.83
10600040	6.67	7.58	$ 0	$ 0	$ 26.16	$ 28.60	$ 37.03
10600040	7.91	8.97	$ 0	$ 0	$ 34.88	$ 38.13	$ 49.37
10600040	9.70	11.63	$ 0	$ 0	$ 18.45		
10600840	0.73	1.56	$ 0	$ 0	$ 0	$ 0	$ 0
19000040	0.00	1.20	$ 0	$ 1,099.34	$ 0	$ 0	$ 0
19000085	10.61	12.37					
19000085	12.37	14.31					
19400085	8.04	9.96					
19400085	9.96	11.55					
Data Available			10	10	10	9	9
Maintenance Cost Incurred			1	4	6	2	6
Probability of Maintenance			10%	40%	60%	22%	67%

3.5 Data Assessment

The quantity and quality of the maintenance cost data was assessed to determine the feasibility of developing maintenance cost streams. Data quantity was assessed to determine if sufficient volumes of data existed to develop maintenance cost streams for the initial 12 years and/or 20 years of pavement life. The 12 year period is the pavement age at first planned rehabilitation (NCDOT 2013) and the 20 year period is the conventional life of asphalt pavements. Approximately 30 cost observations, exclusive of zero cost observations, were required at each pavement age to reasonably represent the maintenance costs.

Data quality was assessed to identify any issues observed within the data that would bring into question the accuracy and/or validity of the data. Reliable data was required to allow development of meaningful maintenance cost streams.

3.5.1 Data Quantity Assessment

Overall, the quantity of maintenance cost data was substantial and sufficient to allow development of cost streams and further analysis for a portion of the roadway groups. However, maintenance data was not available for some roadway groups and not available in sufficient quantity for other groups. The principle issue regarding the quantity of data was that data was only available for the most recent approximately nine year period (2003 to 2012). This precluded the development of cost streams for individual roadway sections and required that roadway sections within a group be aggregated by pavement age.

Table 3.6 provides the number of maintenance cost data points by roadway group and pavement age. The values presented in the table include both the number of sections with observed maintenance activities and cost, as well as those assigned a cost of zero as discussed in section 3.4 of this report. The number of available cost data points generally reflects the number of roadway sections, as presented in Table 3.2. The values presented in Table 3.2 are the volume of cost data points, which were annual unit maintenance costs for individual roadway sections.

The largest volumes of data were available for primary roadways with asphalt or composite pavements. For primary asphalt pavements, data were available for each age to 20 years for both high and low traffic volumes in all geographic regions. Substantial data to 20 years of age was available for primary composite pavements with both high and low traffic volumes in all geographic regions, with the exception of high traffic volumes in the Piedmont region where little data was available at any age. Sufficient data volumes were not available for primary concrete pavements in any region or traffic volume.

Maintenance cost data for interstate roadways of any pavement type were either not available or not available in sufficient volume for the Coastal and Mountains regions. No data was available for high traffic volume interstate roadways in these regions, with the exception of concrete pavements in the Mountains region where the data was extremely limited in volume. Data for low traffic volume composite and concrete pavements in these regions was severely limited in volume and not sufficient to 12 years of age. Low volume asphalt pavements in the Coastal and Mountains regions was available in sufficient volumes to 12 years of age.

Data for interstate pavements in the Piedmont region were generally more available, but were limited in volume. High traffic volumes of all pavement types were severely limited and not sufficient to 12 years of age, while low traffic volumes were of sufficient quantity to 12 years of age.

Table 3.6: Summary of Roadway Group Maintenance Data Count by Pavement Age

				Number of Maintenance Data Points at Age																			
				1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Coastal	Interstate	Asph	High	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
			Low	151	129	157	123	101	101	100	137	147	157	118	102	54	36	36	9	11	10	4	4
		Comp	High	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
			Low	79	79	76	72	66	60	34	28	16	12	13	13	12	8	8	0	1	1	1	1
		Conc	High	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
			Low	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Primary	Asph	High	510	480	467	484	448	417	363	379	389	358	360	335	308	288	275	268	221	226	207	204
			Low	1,411	1,329	1,249	1,189	1,157	1,136	1,034	975	945	944	837	863	851	908	864	810	748	702	630	547
		Comp	High	98	95	92	91	93	77	70	63	62	48	50	62	47	44	53	55	59	41	38	42
			Low	194	166	157	148	167	157	162	191	167	166	142	158	155	168	183	171	158	141	143	154
		Conc	High	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
			Low	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mountain	Interstate	Asph	High	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
			Low	68	65	46	33	28	44	51	60	61	54	54	44	31	32	18	18	8	2	2	2
		Comp	High	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
			Low	59	59	27	11	14	14	16	20	22	19	19	23	29	25	18	14	12	12	8	0
		Conc	High	20	20	20	0	0	0	2	2	2	2	2	2	2	2	2	2	0	0	0	0
			Low	22	22	37	37	37	37	37	37	21	21	18	15	5	0	0	0	0	0	0	0
	Primary	Asph	High	223	218	215	221	214	196	193	196	179	179	164	151	135	110	95	79	71	55	37	29
			Low	560	597	607	656	651	693	713	685	635	543	486	398	318	263	252	235	218	201	176	168
		Comp	High	22	27	26	26	26	22	15	14	14	10	10	5	5	5	7	4	4	7	7	7
			Low	69	70	64	63	69	56	46	45	51	38	38	39	34	30	22	26	22	23	15	15
		Conc	High	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
			Low	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Piedmont	Interstate	Asph	High	17	17	13	15	15	11	11	10	12	13	13	11	11	6	3	2	2	1	1	1
			Low	91	91	100	102	67	67	69	77	78	65	50	54	43	31	27	25	25	4	4	4
		Comp	High	49	49	49	40	39	29	23	22	24	22	21	17	19	22	18	11	8	6	2	2
			Low	106	104	101	101	85	79	86	91	69	50	49	49	40	28	24	18	16	2	2	2
		Conc	High	69	73	73	73	68	50	54	34	21	33	40	53	53	60	74	74	61	53	50	49
			Low	44	44	20	27	63	63	63	60	45	45	45	38	29	33	8	10	10	9	8	17
	Primary	Asph	High	415	406	385	371	374	363	355	366	338	300	231	230	206	201	190	162	136	134	123	107
			Low	828	778	741	712	698	700	684	705	688	664	619	560	523	465	391	358	281	252	219	210
		Comp	High	120	129	119	123	127	124	121	129	85	82	74	67	72	81	78	71	75	76	76	69
			Low	174	168	150	147	160	162	132	135	127	119	108	91	91	86	74	63	59	55	64	52
		Conc	High	16	8	8	8	8	8	4	2	8	10	10	17	17	17	17	17	17	17	9	9
			Low	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

3.5.2 Data Quality Assessment

The quality of the collected maintenance data was assessed to identify and evaluate the extent of any data quality issues. The assembled maintenance activities were reviewed collectively and four issues were noted that impacted the quality of the maintenance data. A summary of the maintenance data and the extent of data quality issues is provided in Table 3.7. The identified issues were:

1. Maintenance activities recorded with $0 total cost – The portion of maintenance activity records with a cost of $0 ranged from small (4.6 percent for coastal interstates) to significant (20.8 percent for mountain interstates). The average portion was 15.9 percent for interstate roadways, 14.9 percent for primary roadways, and 15.0 percent overall. This lack of cost data caused the observed maintenance costs to be lower than the actual costs and decreases the probability of maintenance.

2. Multiple maintenance records with identical costs, work functions, and start/end dates, but with different locations – Similar maintenance activities apparently performed in multiple locations were recorded with the same total cost. Activities for which the recorded cost was $0 were not considered duplicates and are not included in the values in Table 3.7. Three circumstances regarding the recorded locations were noted:

    a. same route with different mileposts – apparently multiple locations on the roadway
    b. same route with similar mileposts – possible attempt to correct location data
    c. different routes with or without milepost data – apparently multiple locations on different roadways

    Duplication was most prevalent in data in the Mountains region, in which an average of 14.8 percent of maintenance records were duplicates. It was also more prevalent in the primary roadway data than in the interstate roadway data. For primary roadways, an average of 11.7 percent of the records were duplicates. The multiple inclusion of the total cost for these activities caused the observed maintenance costs to be greater than the actual costs.

3. Maintenance activities recorded without specific milepost locations – This was by far the most extensive issue observed in the data. On average, 36.9 percent of maintenance activity records were associated with no specific start or end mileposts. Rather, the only location data was start and end mileposts of the roadway section. In these instances, the mileposts from the roadway section were used to calculate the unit maintenance cost. Typically, the roadway mileposts defined the total length of the route in the county. This caused the observed unit maintenance costs to be lower than the likely actual unit costs.

4. Maintenance activities with durations greater than one year – This was the least extensive issue observed in the data. It was more prevalent in the interstate roadway data than in the primary roadway data, but in all cases the extent was very low at 0.5 percent overall. This issue did not impact the maintenance costs, but did bring into question the age of the

pavment at the time of maintenance. The decision was made to apply the cost to the age of the pavement at the completion of the maintenance activity.

Table 3.7: Summary of Maintenance Activities Data

Road Class.	Region	Total	Missing Cost Data	Duplicate Costs	Missing Milepost Data	Durations greater than 1 year
Interstate	Coastal	241	4.6%	6.6%	36.1%	0.4%
	Piedmont	1,110	16.2%	8.9%	45.0%	1.8%
	Mountain	480	20.8%	14.4%	40.0%	0.0%
Primary	Coastal	6,130	13.0%	11.9%	36.3%	0.4%
	Piedmont	9,123	16.5%	10.8%	37.8%	0.5%
	Mountain	2,000	13.7%	14.9%	29.2%	0.2%

The assessment of data quality led to two decisions:

1. Develop cost streams from the comprehensive data set to develop a baseline of maintenance costs
2. Address the identified quality issues by filtering the data to generate a select data set to produce a more accurate understanding of the true cost of maintenance and to allow comparison of comprehensive and select data to determine the impact of the quality issues

3.6 Filtering Select Data

Rules were developed to address the identified data quality issues and to more specifically address the discrepancies in timing of the start of maintenance data collection. These rules were applied to the maintenance cost data collected to produce a set of select data. The rules were:

1. Total cost was included in the recorded maintenance data – a non-zero cost was recorded for the activity
2. Start and end mileposts for the maintenance activity were specified – milepost data was included in the maintenance activity data
3. Maintenance activity mileposts specified were not equal to asset mileposts – the specified maintenance mileposts were not the entirety of the roadway asset in the county
4. Maintenance activity start milepost was less than the end milepost – the recorded mileposts were not reversed
5. Maintenance activity was performed in a location (county) and time (year) in which maintenance data was routinely recorded – starting years were indentified for individual counties

Based on the relatively large volumes of maintenance data in the comprehensive dataset, rules 1 through 5 above were applied to the following 10 roadway groups:

1. Coastal – Primary – Asphalt – High Traffic (CPAH)
2. Coastal – Primary – Asphalt – Low Traffic (CPAL)
3. Coastal – Primary – Composite – High Traffic (CPOH)
4. Coastal – Primary – Composite – Low Traffic (CPOL)
5. Mountains – Primary – Asphalt – High Traffic (MPAH)
6. Mountains – Primary – Asphalt – Low Traffic (MPAL)
7. Mountains – Primary – Composite – Low Traffic (MPOL)
8. Piedmont – Primary – Asphalt – High Traffic (PPAH)
9. Piedmont – Primary – Asphalt – Low Traffic (PPAL)
10. Piedmont – Primary – Composite – Low Traffic (PPOL)

The resulting filtered, select data was then summarized to determine the number of maintenance cost data points in each county by year. The summaries for each roadway group revealed the staggered nature of the year in which maintenance data was first collected. The start year was identified for each county and was the year from which maintenance data was considered available in that county and included in the select data. The summary for PPAL roadways is provided as Table 3.8 as an example. Counties for which no start year was identified were not included in the select data.

The quantity of select data was significantly less than the comprehensive data and was not sufficient to support further analysis of all 10 of the identified roadway groups. Select data of sufficient volume was available for:

1. Coastal – Primary – Asphalt – High Traffic (CPAH)
2. Coastal – Primary – Asphalt – Low Traffic (CPAL)
3. Mountains – Primary – Asphalt – Low Traffic (MPAL)
4. Piedmont – Primary – Asphalt – High Traffic (PPAH)
5. Piedmont – Primary – Asphalt – Low Traffic (PPAL)

Table 3.9 provides the start year identified for each county in these roadway groups.

Table 3.8: Summary of Select Maintenance Cost Data Points for PPAL Roadways

County		Number of Maintenance Cost Data Points in Year									Start Year
		2004	2005	2006	2007	2008	2009	2010	2011	2012	
1	Alamance	-	-	-	-	59	8	1	-	-	
2	Alexander	3	2	14	3	26	-	-	1	-	
4	Anson	-	-	30	51	31	1	7	-	20	
13	Cabarrus	-	-	-	2	-	11	12	1	10	
17	Caswell	-	-	4	39	13	4	3	5	3	2006
18	Catawba	-	-	-	3	10	-	-	-	-	
19	Chatham	-	-	-	38	42	39	5	-	23	2007
23	Cleveland	-	-	2	20	10	13	30	12	48	2007
29	Davidson	12	3	4	-	3	12	48	60	27	2009
30	Davie	-	-	2	-	6	1	-	-	-	
32	Durham	-	-	-	-	-	12	4	2	6	2009
34	Forsyth	-	-	12	64	61	26	37	5	22	2006
35	Franklin	-	-	2	5	14	1	34	15	31	2007
36	Gaston	-	-	4	10	3	7	6	-	-	
39	Granville	-	-	7	28	7	-	-	35	13	
41	Guilford	-	3	-	34	55	157	110	-	5	2007
49	Iredell	-	-	-	-	-	-	-	-	-	
53	Lee	-	-	5	5	8	31	58	18	11	2006
55	Lincoln	-	-	1	6	2	2	19	12	7	2006
60	Mecklenburg	-	-	11	9	27	36	10	10	7	2006
62	Montgomery	-	-	4	16	28	24	41	76	16	2007
63	Moore	-	-	1	2	7	30	9	5	-	
68	Orange	-	-	-	-	14	-	-	-	4	
73	Person	-	-	72	150	294	481	242	18	177	2006
76	Randolph	-	-	-	10	-	7	11	20	4	
77	Richmond	-	-	-	1	36	6	47	68	25	2008
79	Rockingham	-	-	-	12	31	50	43	19	4	2007
84	Stanly	-	2	1	3	11	21	14	31	15	2008
85	Stokes	69	177	56	149	146	242	99	31	65	2004
90	Union	-	-	11	9	6	2	-	-	-	
91	Vance	-	-	-	8	6	3	22	29	8	2007
92	Wake	-	-	-	1		-	-	-	-	
93	Warren	-	-	25	57	38	48	48	48	31	2006

Table 3.9: Select Data Start Years by County and Roadway Group

	PPAH	PPAL	CPAH	CPAL	MPAL		PPAH	PPAL	CPAH	CPAL	MPAL
Alamance						Johnston			2006		
Alexander						Jones			2006		
Alleghany					2006	Lee	2006	2006			
Anson						Lenoir			2007	2005	
Ashe					2007	Lincoln	2005	2006			
Avery					2006	Macon					
Beaufort			2006	2007		Madison					2005
Bertie			2008	2007		Martin				2007	
Bladen				2006		McDowell					2006
Brunswick			2007	2007		Mecklenburg	2006	2006			
Buncombe					2006	Mitchell					
Burke					2009	Montgomery	2007	2007			
Cabarrus	2007					Moore					
Caldwell						Nash				2007	
Camden				2005		New Hanover					
Carteret			2006	2007		Northampton		2006	2006		
Caswell		2006				Onslow			2006	2006	
Catawba						Orange					
Chatham	2006	2007				Pamlico				2008	
Cherokee					2009	Pasquotank					
Chowan				2006		Pender					
Clay						Perquimans					
Cleveland		2007				Person		2006			
Columbus			2007	2006		Pitt			2006		
Craven				2007		Polk					2007
Cumberland			2007	2008		Randolph					
Currituck			2010	2007		Richmond		2008			
Dare				2006		Robeson			2006		
Davidson		2009				Rockingham		2007			
Davie						Rowan					
Duplin			2007	2007		Rutherford					
Durham		2009				Sampson				2006	
Edgecombe				2007		Scotland					
Forsyth	2006	2006				Stanly		2008			
Franklin		2007				Stokes	2004	2004			
Gaston	2006					Surry					2006
Gates				2007		Swain					2007
Graham						Transylvania				2006	
Granville						Tyrrell					
Greene				2006		Union	2006				
Guilford		2007				Vance		2007			
Halifax			2007	2007		Wake					
Harnett						Warren		2006			
Haywood						Washington					
Henderson					2007	Watauga					2008
Hertford				2006		Wayne			2006		
Hoke						Wilkes					
Hyde				2007		Wilson			2006	2007	
Iredell						Yadkin					2009
Jackson					2004	Yancey					

The volume of select data for each of the five roadway groups was approximately one-third of the volume of comprehensive data. Table 3.10 provides the number of maintenance cost data points in both the comprehensive and select data sets for the five roadway groups. Table 3.11 provides the number of select maintenance cost data points in each year of pavement age for the roadway groups.

Table 3.10: Volume of Maintenance Cost Data Points

Roadway Group	**Number of Maintenance Cost Data Points**	
	Comprehensive Data Set	**Select Data Set**
CPAH	6,987	2,386
CPAL	19,129	6,860
MPAL	9,055	2,915
PPAH	5,393	1,795
PPAL	11,077	3,556

Table 3.11: Summary of Roadway Group Maintenance Select Data Count by Pavement Age

Roadway Group	Number of Maintenance Data Points at Age																			
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
PPAH	112	135	143	142	123	123	124	139	103	87	56	68	74	69	63	59	55	47	43	30
PPAL	286	235	199	199	200	205	202	223	214	221	209	181	180	160	135	124	121	89	87	86
CPAH	200	183	157	163	129	126	127	122	105	98	114	124	131	108	116	101	98	73	59	52
CPAL	536	489	433	443	439	384	368	323	349	307	257	281	281	309	318	290	311	264	263	215
MPAL	168	185	172	197	209	239	261	251	235	193	176	138	95	78	66	46	35	39	64	68

3.7 Observed Maintenance Costs

The maintenance costs observed from the MMS data for each roadway group were analyzed to provide two pieces of information:

1. The probability of incurring maintenance cost at each pavement age
2. The distribution of maintenance unit costs greater than $0 at each pavement age.

This information was developed from both the comprehensive and select data sets for roadway groups where a minimum of 30 data points at each age were available to ages 12 and 20 years. Sufficient data for a 20 year period were available within the comprehensive data set for the following roadway groups:

1. Coastal – Primary – Asphalt – High Traffic (CPAH)
2. Coastal – Primary – Asphalt – Low Traffic (CPAL)
3. Coastal – Primary – Composite – High Traffic (CPOH)
4. Coastal – Primary – Composite – Low Traffic (CPOL)
5. Mountains – Primary – Asphalt – High Traffic (MPAH)
6. Mountains – Primary – Asphalt – Low Traffic (MPAL)
7. Piedmont – Primary – Asphalt – High Traffic (PPAH)
8. Piedmont – Primary – Asphalt – Low Traffic (PPAL)
9. Piedmont – Primary – Composite – High Traffic (PPOH)
10. Piedmont – Primary – Composite – Low Traffic (PPOL)

Sufficient data for a 12 year period were available within the comprehensive data set for the following roadway groups:

1. Coastal – Interstate – Asphalt – Low Traffic (CIAL)
2. Mountains – Primary – Composite – Low Traffic (MPOL)
3. Piedmont – Interstate – Asphalt – Low Traffic (PIAL)
4. Piedmont – Interstate – Composite – Low Traffic (PIOL)
5. Piedmont – Interstate – Concrete – Low Traffic (PICL)

This information was also developed for a 20 year period from the select data set for the following roadway groups:

1. Coastal – Primary – Asphalt – High Traffic (CPAH)
2. Coastal – Primary – Asphalt – Low Traffic (CPAL)
3. Mountains – Primary – Asphalt – Low Traffic (MPAL)
4. Piedmont – Primary – Asphalt – High Traffic (PPAH)
5. Piedmont – Primary – Asphalt – Low Traffic (PPAL)

3.7.1 Probability of Incurring Maintenance

The probability of incurring maintenance was calculated for each pavement age in the 12 or 20 year period. It was calculated as the ratio of the number of observed data points where the maintenance unit cost was greater than $0 to the total number of observed data points. The values generally ranged from 20 to 40 percent for roadway groups with 20 years of data. For roadway groups with 12 years of data, the values were more variable and ranged from 0 to nearly 60 percent. The probabilities for roadways to age 20 years from the comprehensive data in the Coastal, Mountains, and Piedmont regions are provided as Figures 34, 3.5, and 3.6, respectively. Probabilities for roadways to age 12 years are provided as Figure 3.7.

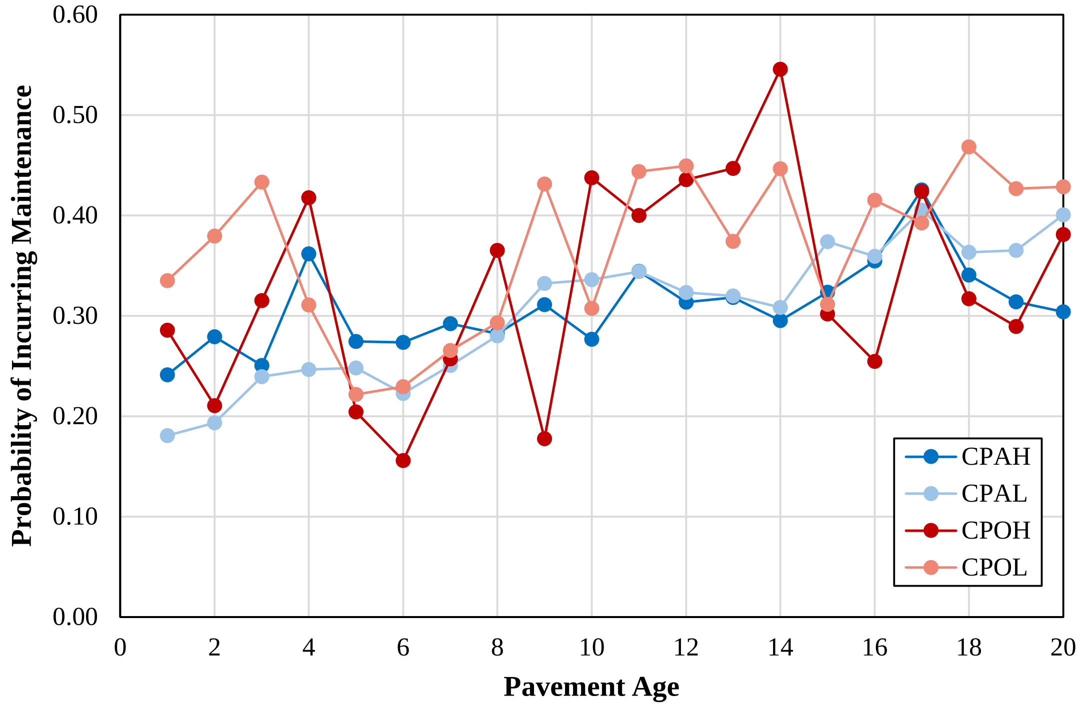

Figure 3.4: Probabilities of Maintenance for Primary Coastal Roadways to 20 Years from Comprehensive Maintenance Data Set

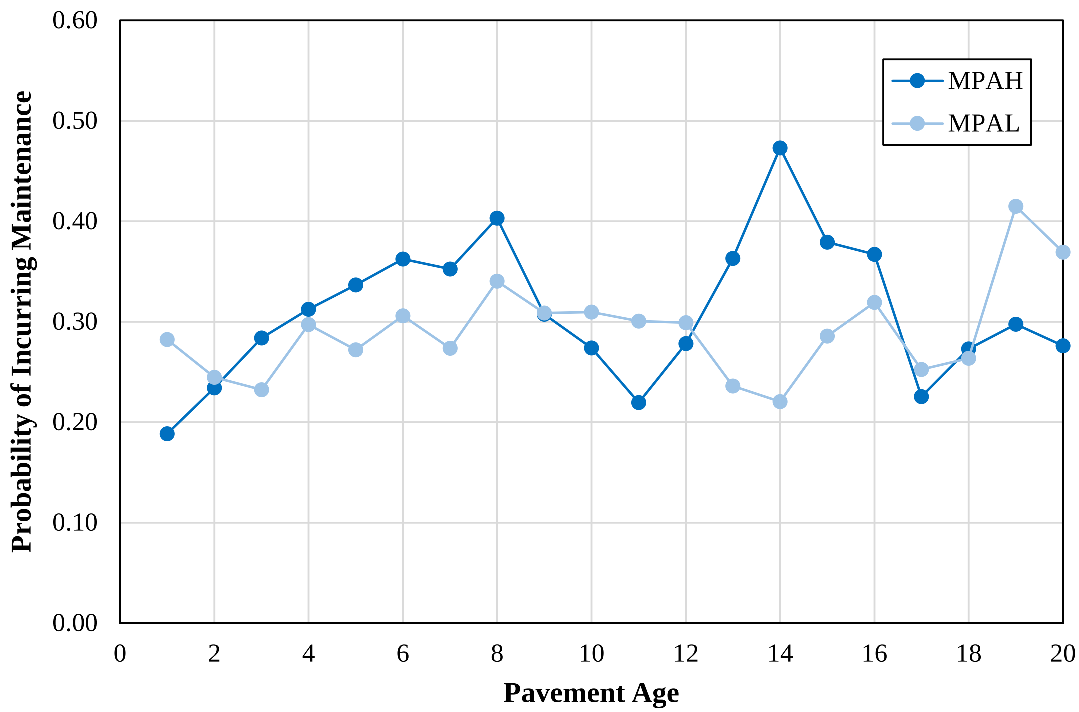

Figure 3.5: Probabilities of Maintenance for Primary Mountains Roadways to 20 Years from Comprehensive Maintenance Data Set

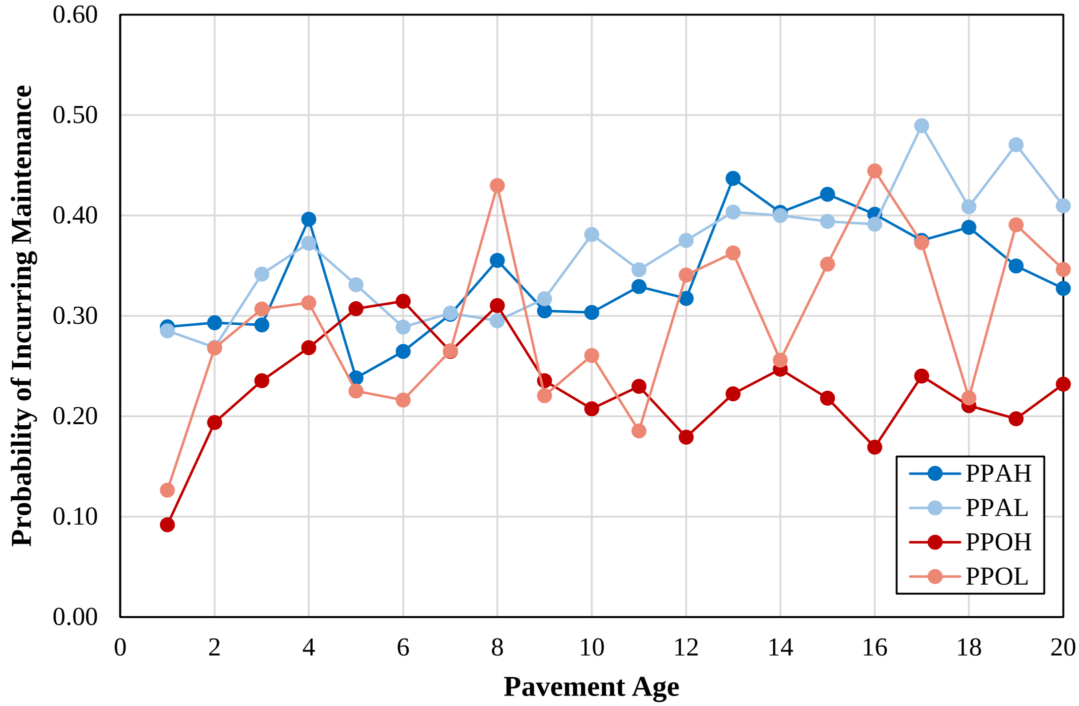

Figure 3.6: Probabilities of Maintenance for Primary Piedmont Roadways to 20 Years from Comprehensive Maintenance Data Set

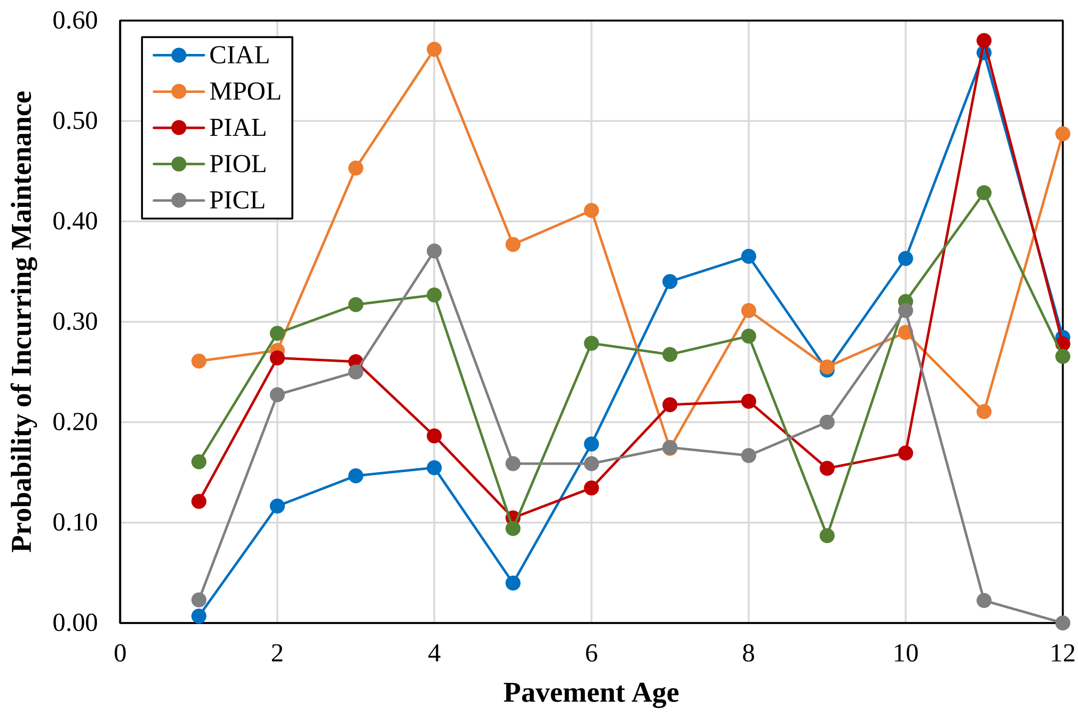

Figure 3.7: Probabilities of Maintenance for Roadways to 12 Years from Comprehensive Maintenance Data Set

In nearly all instances, the probabilities of maintenance from the select data were greater than those from the comprehensive data. Probabilities from the select data were on average approximately 10 percent greater than those from the comprehensive data. This was expected because the $0 total cost maintenance activities were filtered out in the development of the select data.

The values generally ranged from 30 to 50 percent, with individual values as low as approximately 20 percent and as high as approximately 70 percent. Data from the Coastal and Piedmont regions showed a trend of increasing with age, while roadways in the Mountains region were fairly consistent with age.

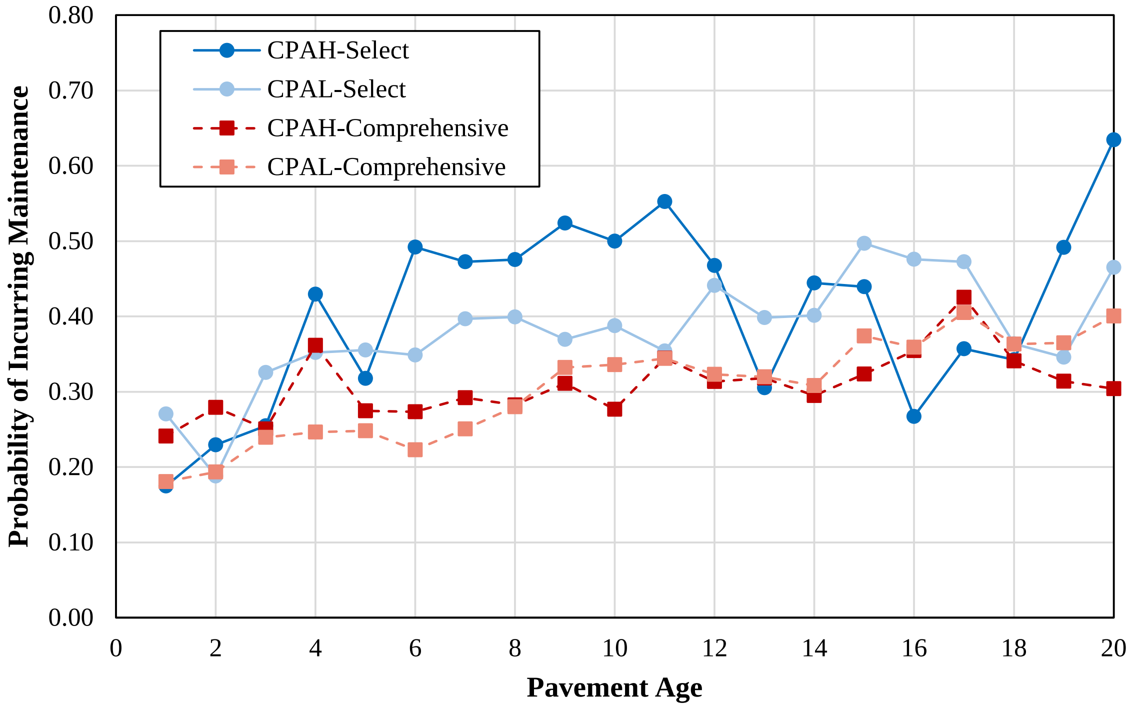

Figure 3.8: Probabilities of Maintenance for Primary Coastal Roadways from Select Maintenance Data Set

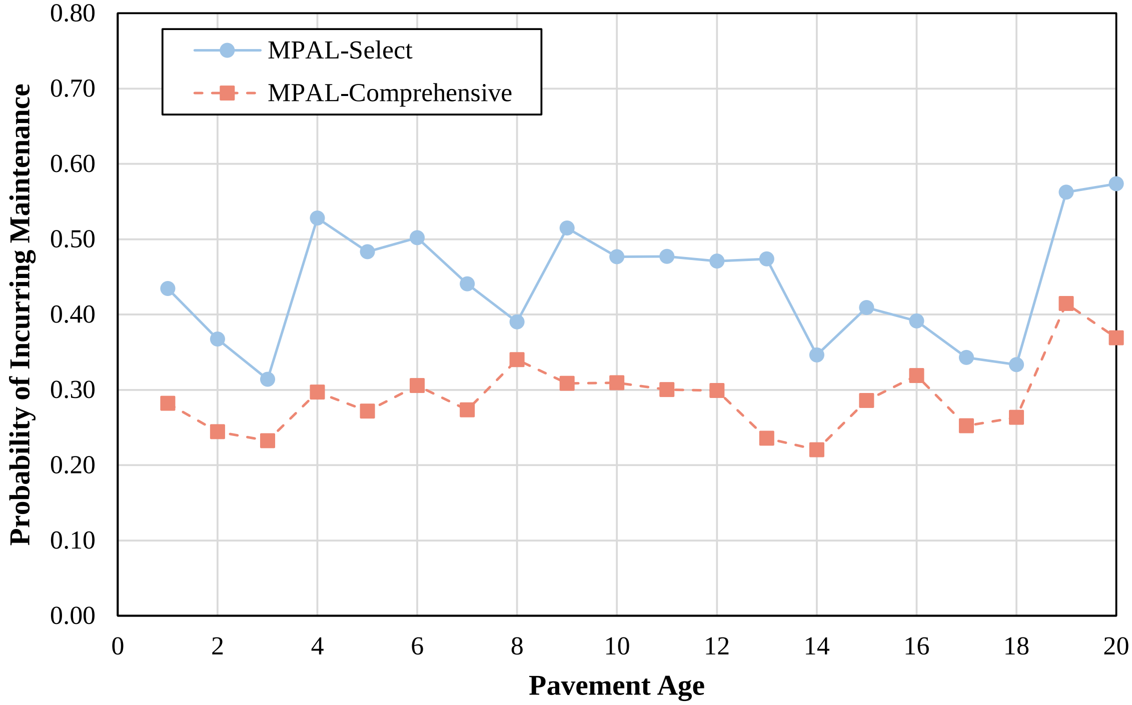

Figure 3.9: Probabilities of Maintenance for Primary Mountains Roadways from Select Maintenance Data Set

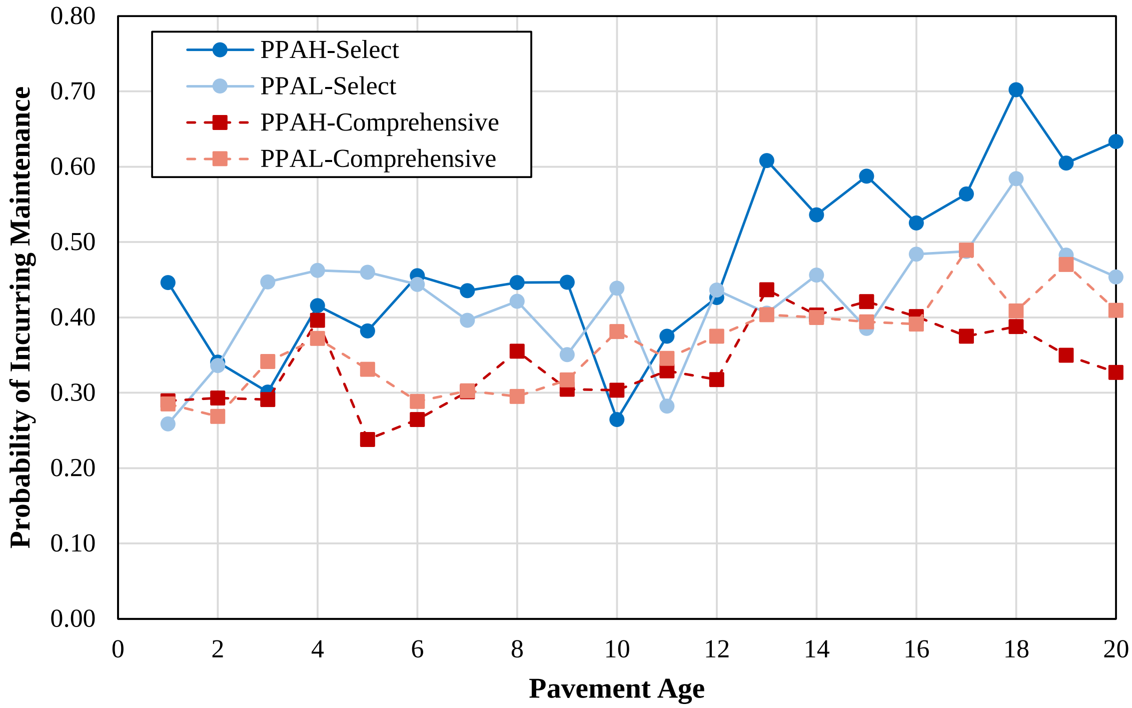

Figure 3.10: Probabilities of Maintenance for Primary Piedmont Roadways from Select Maintenance Data Set

3.7.2 *Maintenance Unit Cost Distributions*

The comprehensive and select data sets were used to develop distributions of maintenance unit costs, for costs greater than $0, at each pavement age for each roadway group. Distributions were used to depict changes in cost with pavement age. Those from the comprehensive data were used to determine for which groups there was sufficient data to develop maintenance cost streams. The distribution charts show the ranges for the second and third quartiles, whiskers extending to the 10th and 90th percentiles, and the number of data points at each pavement age. Charts of the cost distributions from the comprehensive data for all roadway groups are provided in Appendix B. The distribution chart for Piedmont-Primary-Asphalt-Low roadways is provided as Figure 3.11 as an example.

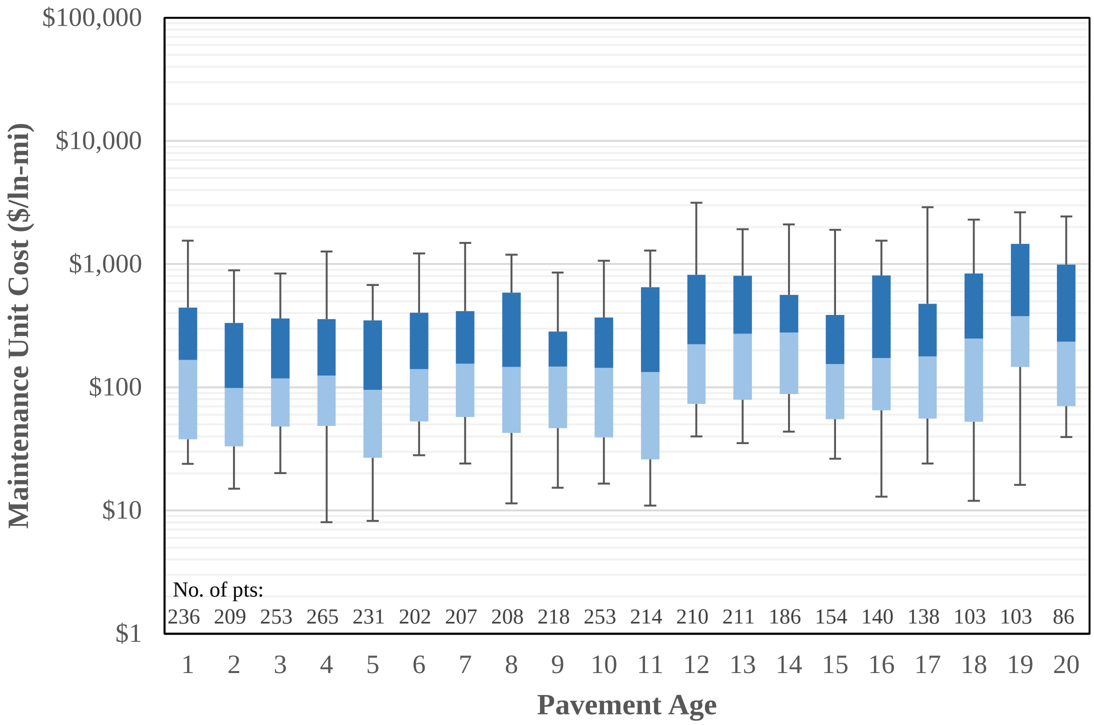

Figure 3.11: Maintenance Unit Cost Distributions for Piedmont-Primary-Asphalt-Low Roadways from Comprehensive Maintenance Data Set

The observed maintenance unit costs from the comprehensive data ranged from less than one dollar to tens of thousands of dollars. Extreme values were noted to generally occur at pavement and age combinations with very few data points. In general, median maintenance unit costs were in the hundreds of dollars, with 10th percentile values in the single dollars and 90th percentiles in the thousands of dollars.

Cost distribution charts for the five roadway groups for which a sufficient volume of select data were available are provided as Figures 3.12 through Figure 3.16.

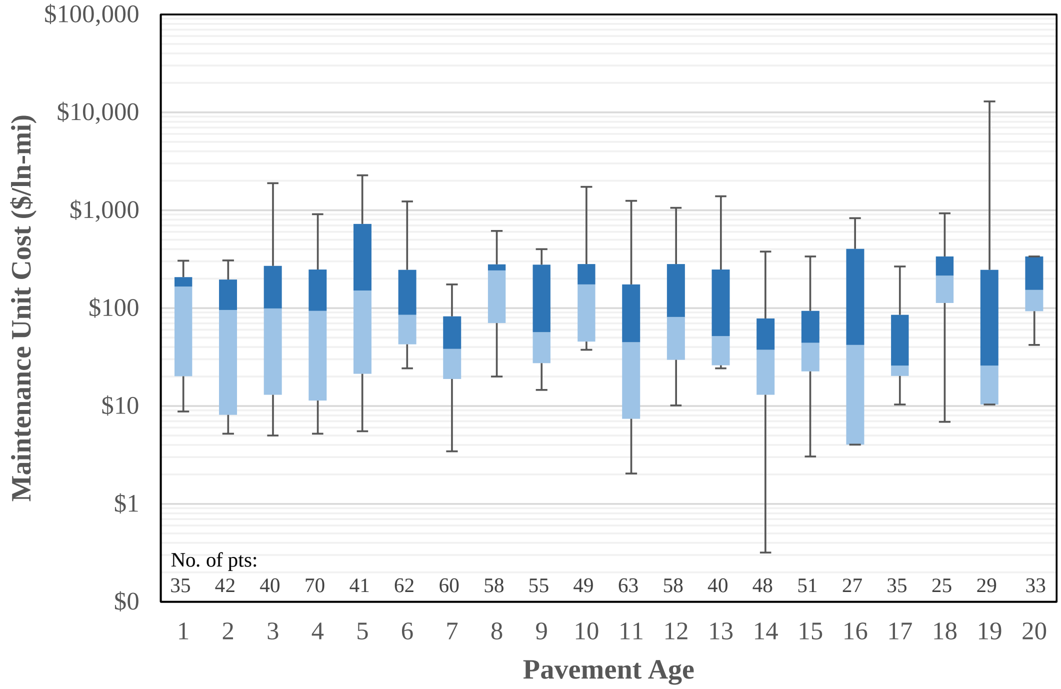

Figure 3:12: Maintenance Unit Cost Distributions for Coastal-Primary-Asphalt-High Roadways from Select Maintenance Data Set

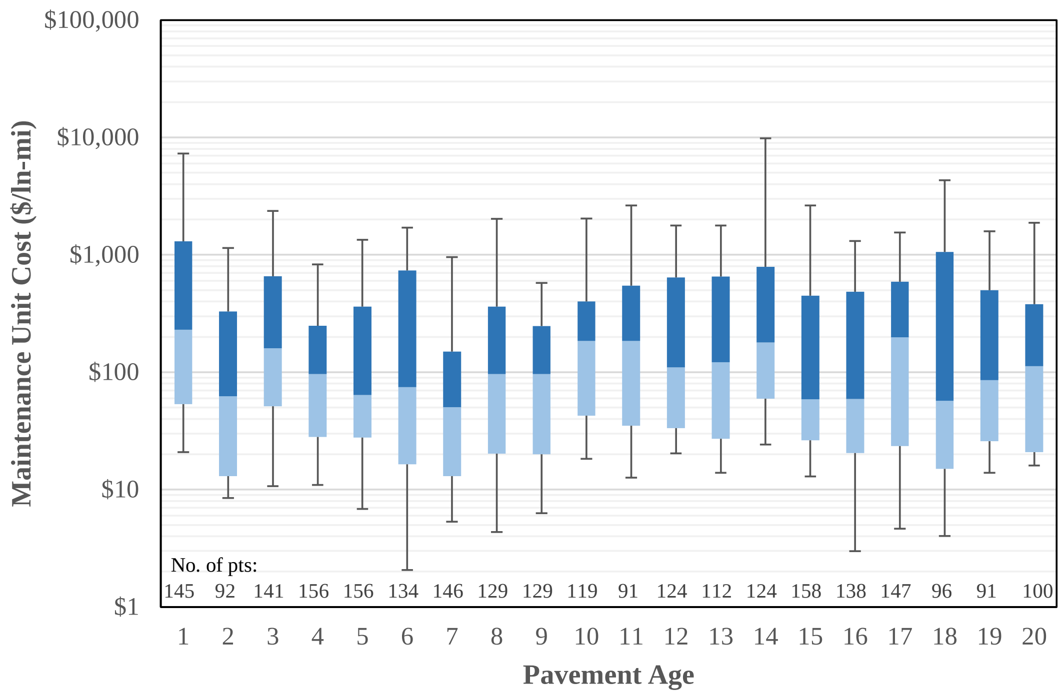

Figure 3:13: Maintenance Unit Cost Distributions for Coastal-Primary-Asphalt-Low Roadways from Select Maintenance Data Set

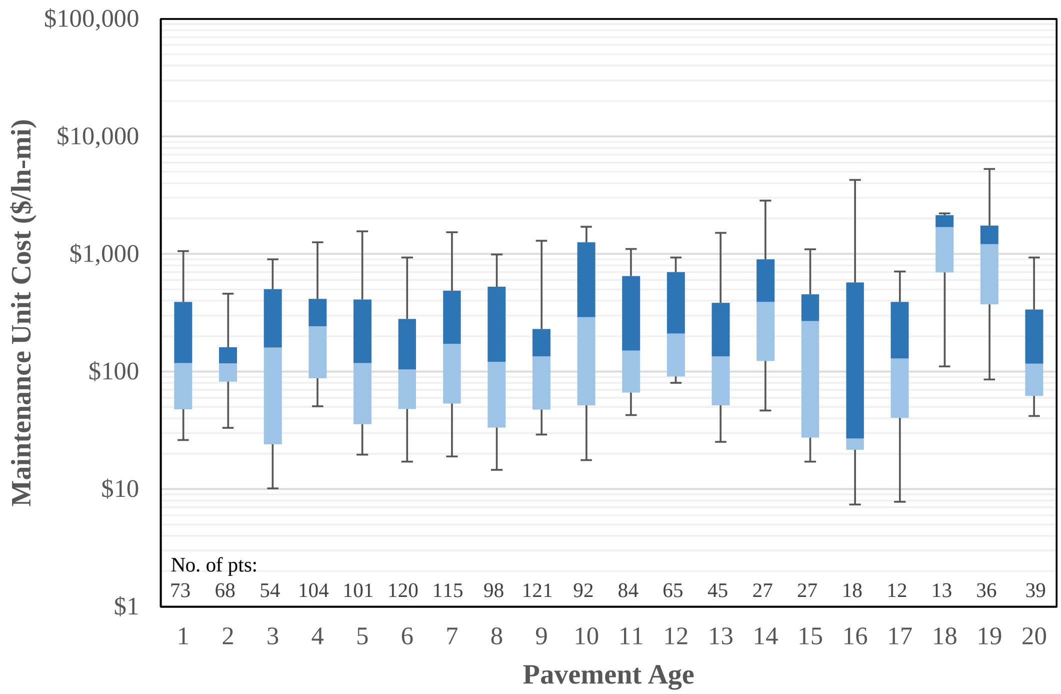

Figure 3:14: Maintenance Unit Cost Distributions for Mountains-Primary-Asphalt-Low Roadways from Select Maintenance Data Set

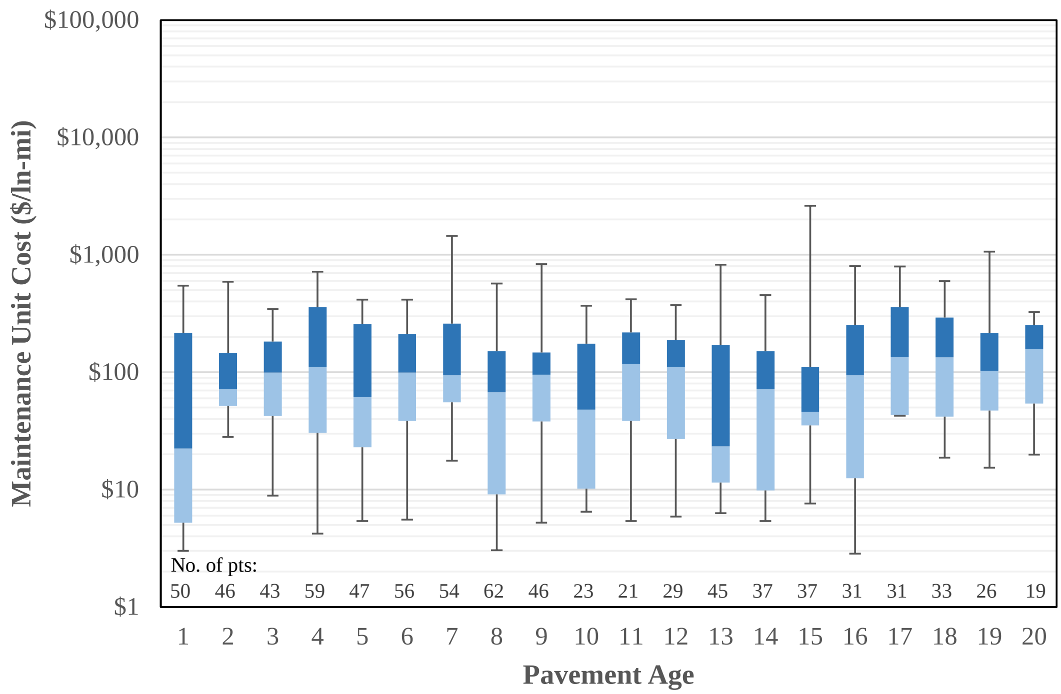

Figure 3:15: Maintenance Unit Cost Distributions for Piedmont-Primary-Asphalt-High Roadways from Select Maintenance Data Set

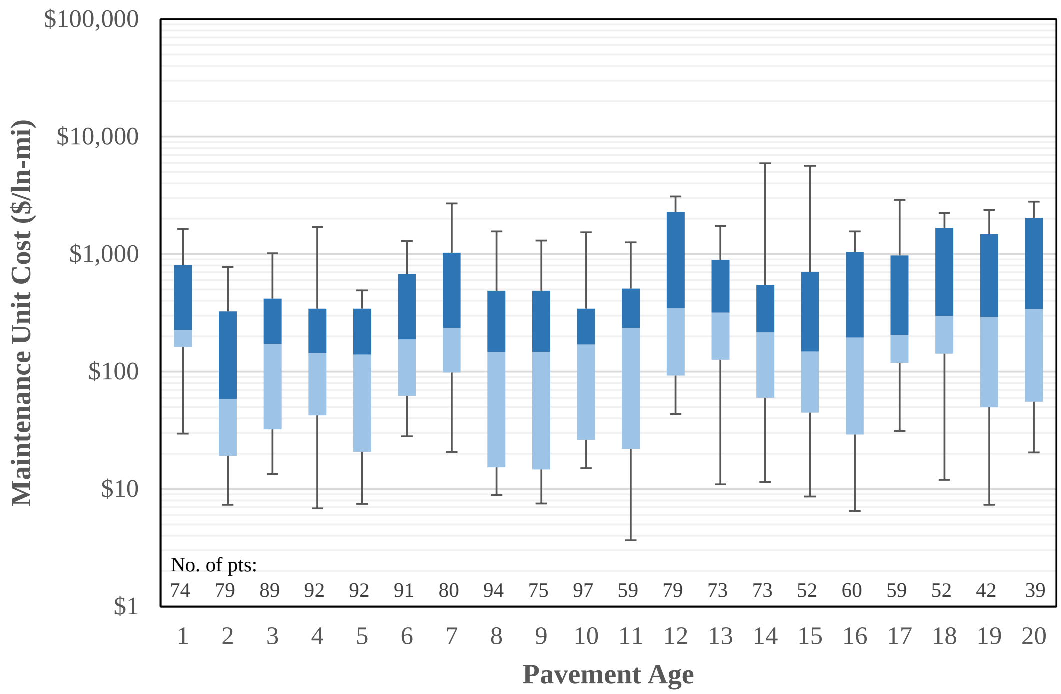

Figure 3:16: Maintenance Unit Cost Distributions for Piedmont-Primary-Asphalt-Low Roadways from Select Maintenance Data Set

The unit costs observed in the select data ranged similarly to the comprehensive data, from less than one dollar to tens of thousands of dollars with limited extreme values. Differences were noted in the select data distributions between low traffic and high traffic volume roadways, with low traffic roadway maintenance costs being generally greater than those for high traffic volume roadways. These differences are summarized in Table 3.12.

Table 3.12: Summary of Unit Cost Distributions from Select Data

	Low Traffic Roadways	**High Traffic Roadways**
Minimum	Less than one dollar to single dollars	Less than one dollar to single dollars
10^{th} Percentile	Tens of dollars	Single dollars
Median	Hundreds of dollars	Tens to low hundreds of dollars
90^{th} Percentile	Near $1,000 to thousands of dollars	Hundreds of dollars
Maximum	Thousands to tens of thousands of dollars	Thousands to tens of low thousands of dollars

4 DEVELOPMENT OF MAINTENANCE COST STREAMS

Streams of maintenance costs were developed from the collected data to evaluate the costs over the life cycle of the pavements. Because data was only available from the past eight years and not over the entirety of pavement life, Monte Carlo simulation was used to produce the maintenance cost streams. The simulation model was developed to consider the probability of incurring maintenance (as described in section 3.7.1) and the distribution of maintenance unit cost at each pavement age to 12 years. The 12 year analysis period was selected based on the expected time to rehabilitation for asphalt pavements (NCDOT, 2013). The availability of data limited the roadway groups for which cost streams could be developed to:

1. Coastal – Primary – Asphalt – High Traffic (CPAH)
2. Coastal – Primary – Asphalt – Low Traffic (CPAL)
3. Coastal – Primary – Composite – High Traffic (CPOH)
4. Coastal – Primary – Composite – Low Traffic (CPOL)
5. Mountains – Primary – Asphalt – High Traffic (MPAH)
6. Mountains – Primary – Asphalt – Low Traffic (MPAL)
7. Mountains – Primary – Composite – Low Traffic (MPOL)
8. Piedmont – Primary – Asphalt – High Traffic (PPAH)
9. Piedmont – Primary – Asphalt – Low Traffic (PPAL)
10. Piedmont – Primary – Composite – Low Traffic (PPOL)

The simulated cost streams resulted in the annual and life-to-date (LTD) maintenance unit costs at each pavement age through the analysis period. Cost stream values were developed and shown as present value 2012 dollars. The present value of these costs was calculated based on a 4 percent discount rate, which is the rate used in the NCDOT LCCA process (NCDOT, 2000).

4.1 Statistical Distributions of Annual Maintenance Unit Cost

Monte Carlo simulation required statistical distributions be fit to the observed maintenance unit costs, where cost was greater than $0, at each pavement age for the roadway groups. Appropriate distributions were fit to the data after outlying data points were identified and removed.

The costs at each age were observed to have the general shape of a lognormal distribution. The Kolmogorov-Smirnov (KS) goodness-of-fit test was applied to assess the fit of the lognormal distributions. The lognormal distribution was found to be appropriate at the 5 percent significance level for 85 percent (102 of 120) of the annual cost distributions, and for 95 percent (114 of 120) at the 1 percent significance level. Therefore, the lognormal distribution was deemed appropriate for all annual cost distributions and a log transformation applied to produce normal distributions. Outlying data points were defined as those greater than two standard deviations from the mean and were removed from the data.

Normal distributions were fit to the annual data for each roadway group after the outliers were removed. These distributions were used in the simulation model to produce the maintenance cost streams.

4.2 Maintenance Unit Cost Stream Simulation Model

The simulation model to develop the maintenance cost streams was a two-step model to consider:

1. Whether maintenance was incurred at each age, and
2. The maintenance unit cost at each age if maintenance was to occur.

The model was used to produce 1,000 iterations of cost at each pavement age for each roadway group. An example of the maintenance cost model is provided as Table 4.1, where rows are years of pavement age and columns are:

[1] **Age** – pavement age

[2] **Probability of Maintenance** – the observed probability of incurring maintenance at each age

[3] **Random Value** – a random sample from the Uniform(0,1) distribution

[4] **Log of Maintenance Unit Cost** – the normally distributed values of log transformed maintenance unit costs, displayed in the table are the mean values

[5] **Maintenance Unit Cost** – the unit cost of maintenance experienced; $0 if the random value in column [3] is greater than the probability of maintenance in column [2], else a random sample from the cost distribution in column [4] inversely transformed to dollars

[6] **Maintenance Unit Cost Present Value** – the present value of the maintenance unit cost in column [5] based on a 4 percent discount rate

[7] **Life-to-Date Maintenance Unit Cost Present Value** – The sum of maintenance unit cost present value in column [6] from year 1 through each calculated year

Table 4.1: Maintenance Cost Stream Simulation Model Example

Age [1]	**Probability of Maintenance [2]**	**Random Value [3]**	**Log of Maintenance Unit Cost [4]**	**Maintenance Unit Cost ($/ln-mi) [5]**	**Maintenance Unit Cost Present Value ($/ln-mi) [6]**	**Life-to-Date Maintenance Unit Cost Present Value ($/ln-mi) [7]**
1	0.282	0.256	2.04	$ 109.18	$ 104.98	$ 104.98
2	0.245	0.489	1.98	$ 0.00	$ 0.00	$ 104.98
3	0.232	0.898	1.99	$ 0.00	$ 0.00	$ 104.98
4	0.297	0.317	2.16	$ 0.00	$ 0.00	$ 104.98
5	0.272	0.316	2.27	$ 0.00	$ 0.00	$ 104.98
6	0.306	0.209	2.09	$ 123.15	$ 97.33	$ 202.31
7	0.273	0.312	2.18	$ 0.00	$ 0.00	$ 202.31
8	0.340	0.096	2.09	$ 123.00	$ 89.87	$ 292.18
9	0.309	0.741	2.20	$ 0.00	$ 0.00	$ 292.18
10	0.309	0.499	2.32	$ 0.00	$ 0.00	$ 292.18
11	0.300	0.744	2.31	$ 0.00	$ 0.00	$ 292.18
12	0.299	0.887	2.26	$ 0.00	$ 0.00	$ 292.18

The 1,000 iterations produced a sample of annual maintenance unit costs (column [6]) and LTD maintenance unit costs (column [7]) at each pavement age through the analysis period.

4.3 Maintenance Unit Cost Streams

The cost stream simulations for each roadway group from the comprehensive and select data resulted in samples of annual maintenance unit costs and LTD maintenance unit costs. The simulated costs were graphed to show the interquartile range, median value, and number of costs greater than $0. Cost streams for the Coastal-Primary-Asphalt-Low roadways are presented in Figures 4.1 and 4.2 as an example. The simulated cost streams from comprehensive data for all roadway groups are provided in Appendix C.

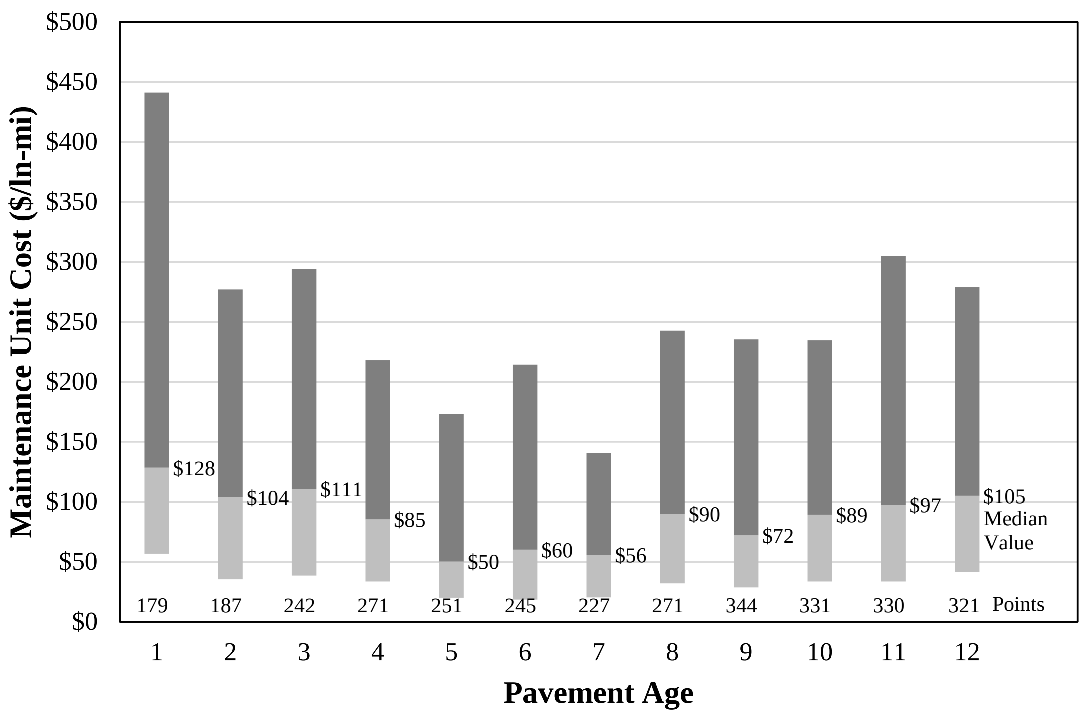

Figure 4.1: Present Value of Annual Maintenance Unit Cost Stream for Coastal-Primary-Asphalt-Low Roadways

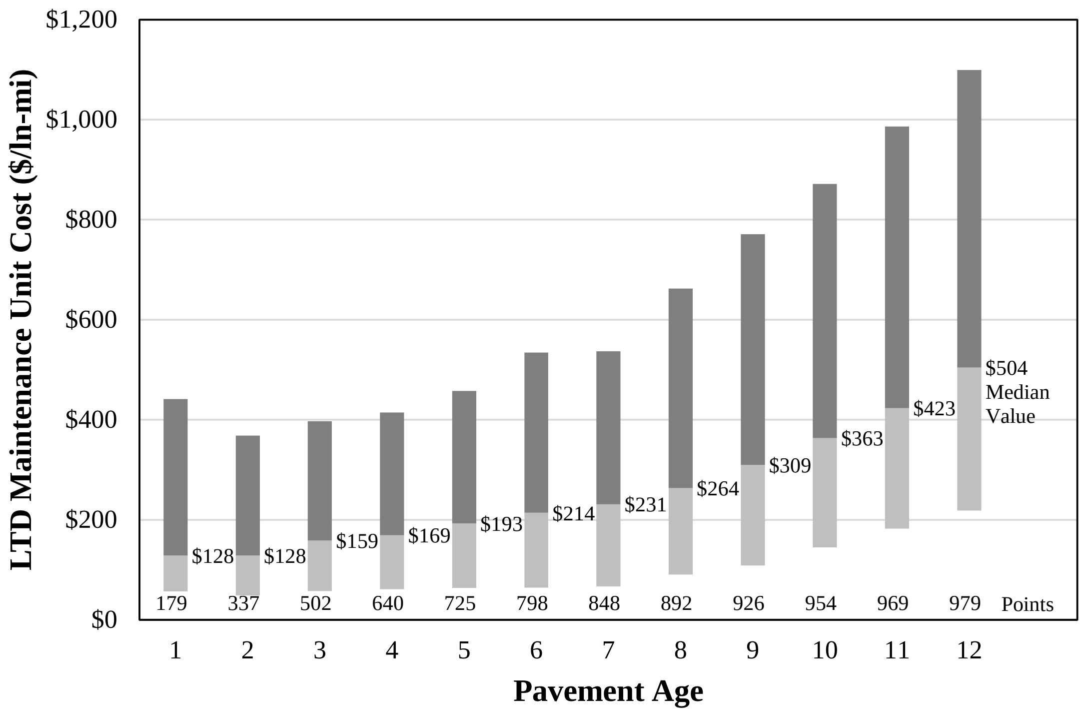

Figure 4.2: Present Value of Life-to-Date Maintenance Unit Cost Stream for Coastal-Primary-Asphalt-Low Roadways

The simulated maintenance unit costs from the comprehensive data generally ranged from a few dollars to the low thousands of dollars. Extreme values of less than one dollar and greater than $100,000 resulted in a limited number of instances. The median values of annual maintenance unit cost were in the tens and low hundreds of dollars, ranging from $16 to $402 per lane-mile. For LTD maintenance unit costs, the median values throughout the analysis period were generally in the hundreds of dollars, ranging from $32 to $936 per lane-mile. At the end of analysis period age 12, the LTD maintenance unit costs ranged from $321 to $936 per lane-mile.

The simulated cost streams from the select data sets are presented in Figures 4.3 to 4.12.

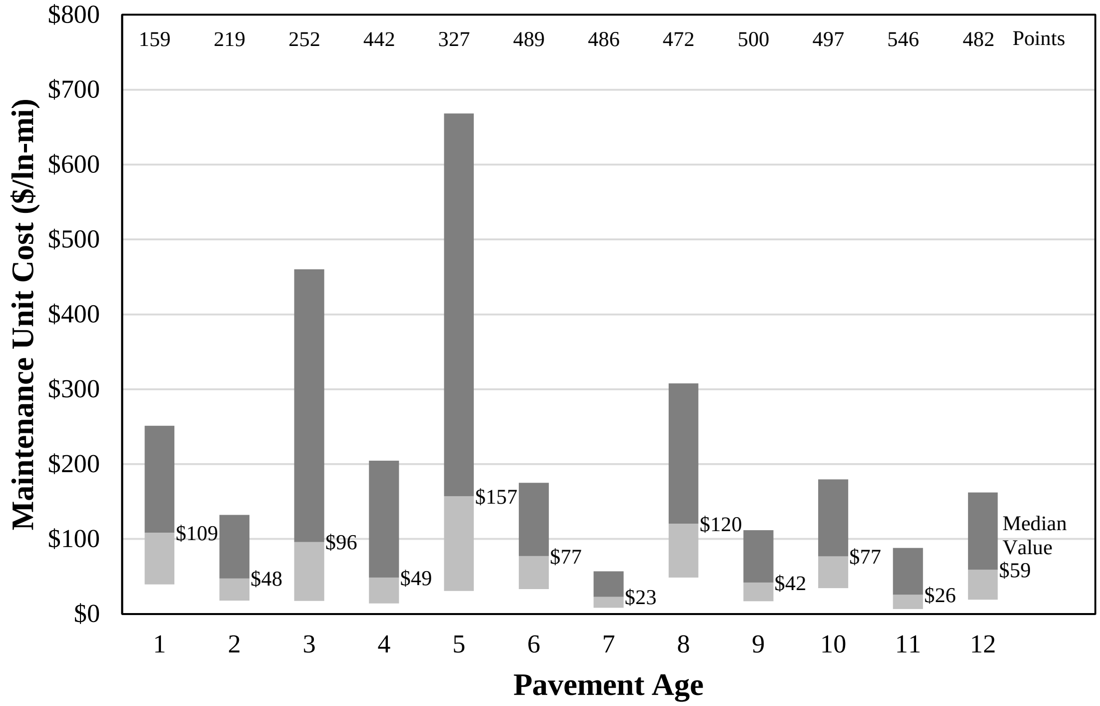

Figure 4.3: Present Value of Annual Maintenance Unit Cost Stream for Coastal-Primary-Asphalt-High Roadways from Select Data

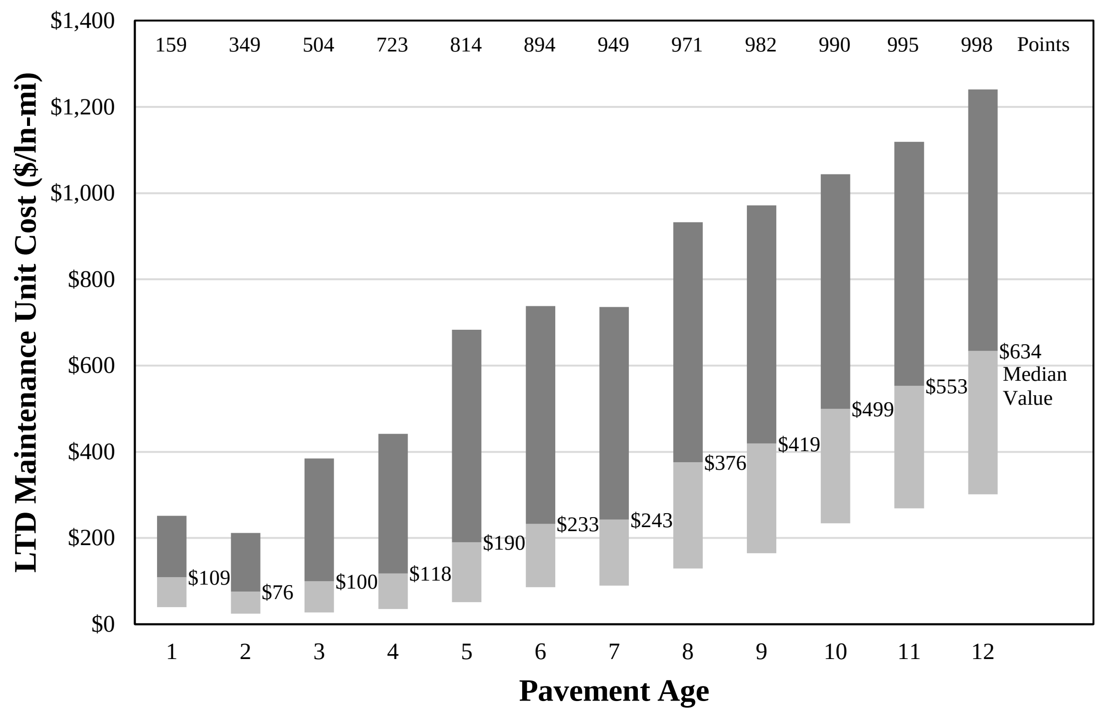

Figure 4.4: Present Value of Life-to-Date Maintenance Unit Cost Stream for Coastal-Primary-Asphalt-High Roadways from Select Data

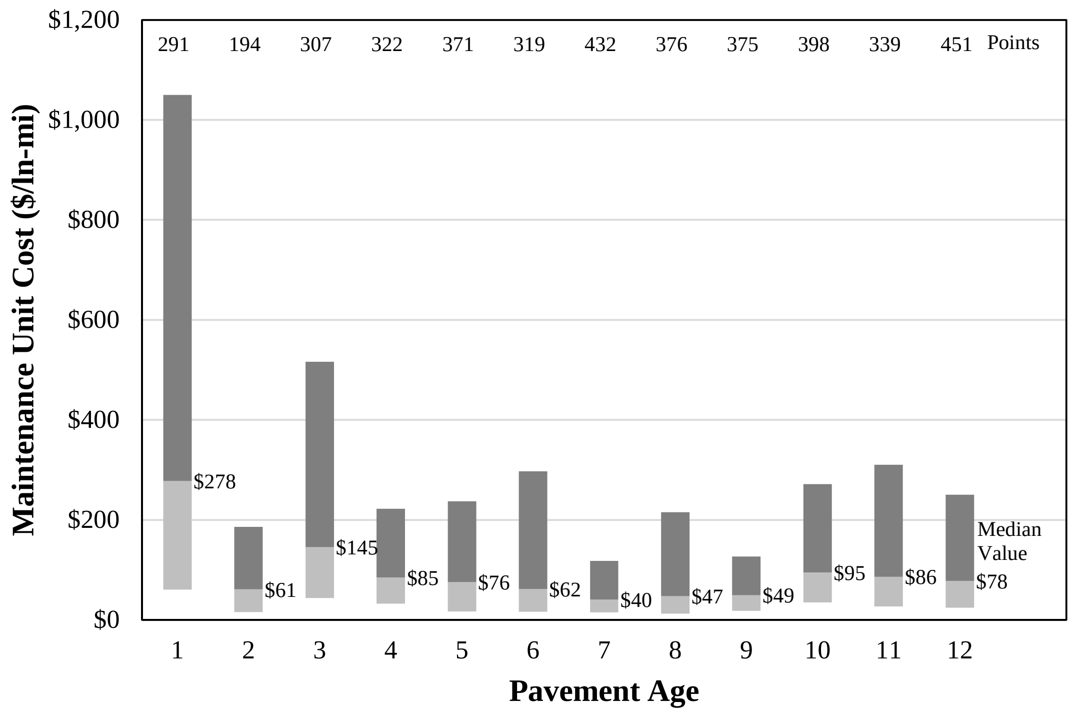

Figure 4.5: Present Value of Annual Maintenance Unit Cost Stream for Coastal-Primary-Asphalt-Low Roadways from Select Data

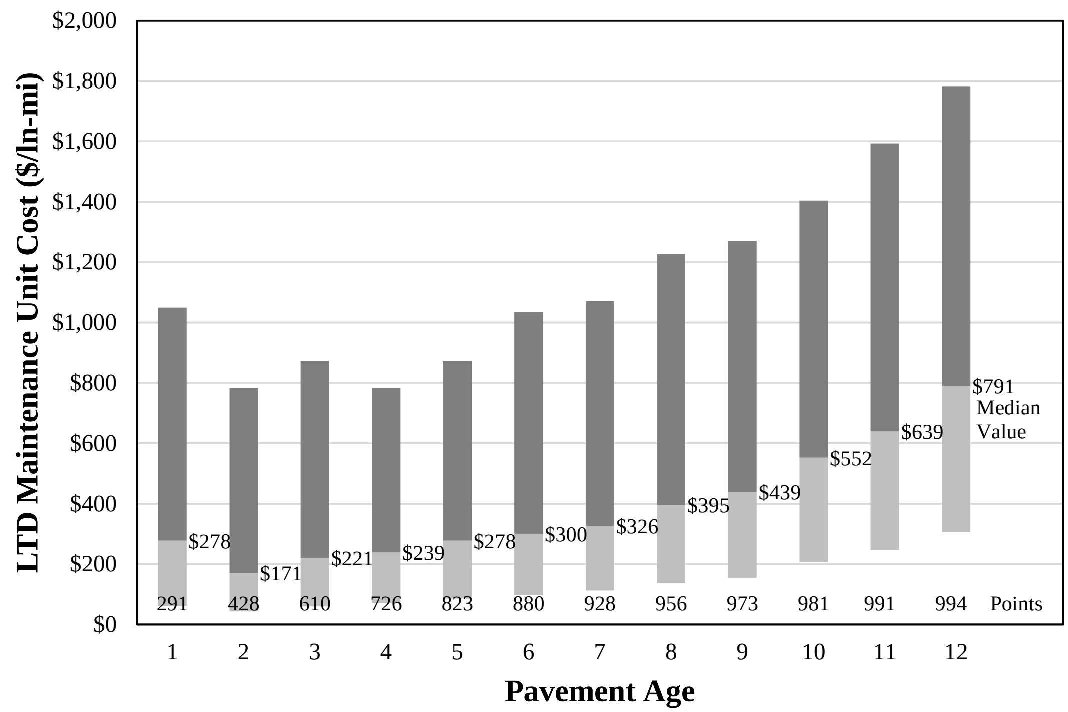

Figure 4.6: Present Value of Life-to-Date Maintenance Unit Cost Stream for Coastal-Primary-Asphalt-Low Roadways from Select Data

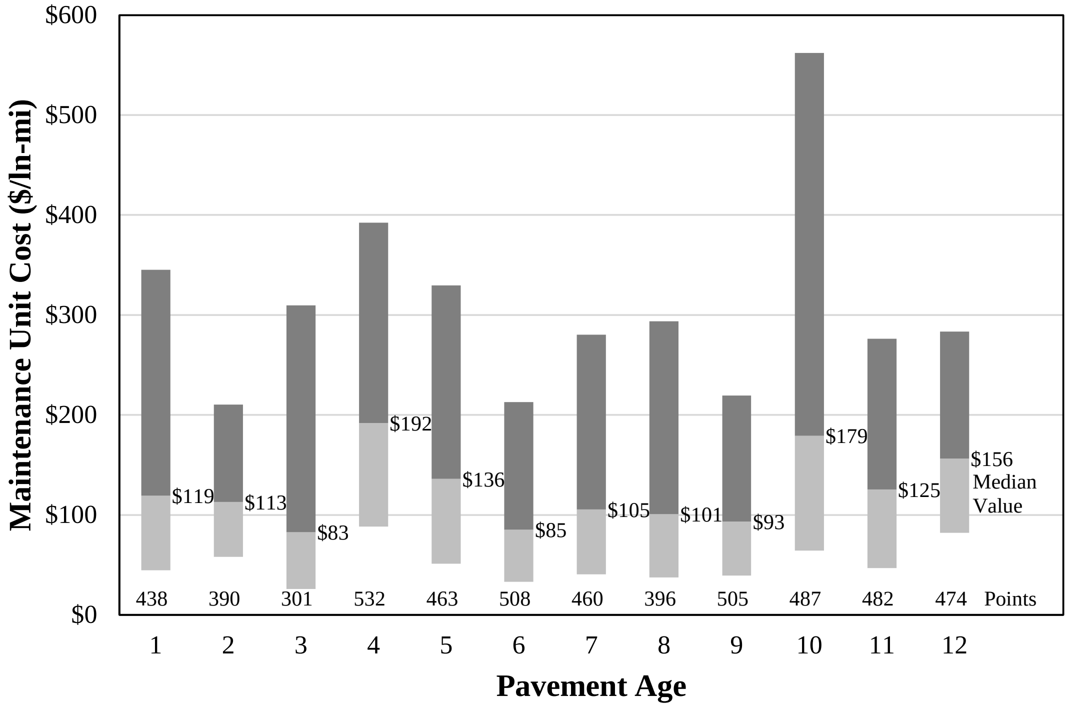

Figure 4.7: Present Value of Annual Maintenance Unit Cost Stream for Mountain-Primary-Asphalt-Low Roadways from Select Data

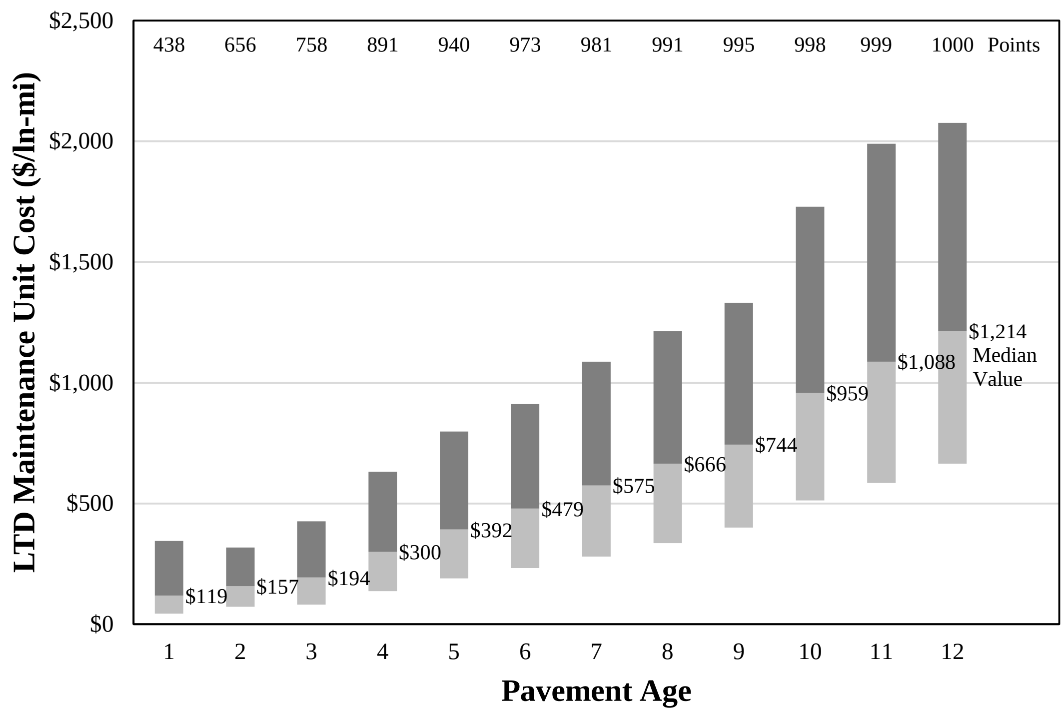

Figure 4.8: Present Value of Life-to-Date Maintenance Unit Cost Stream for Mountain-Primary-Asphalt-Low Roadways from Select Data

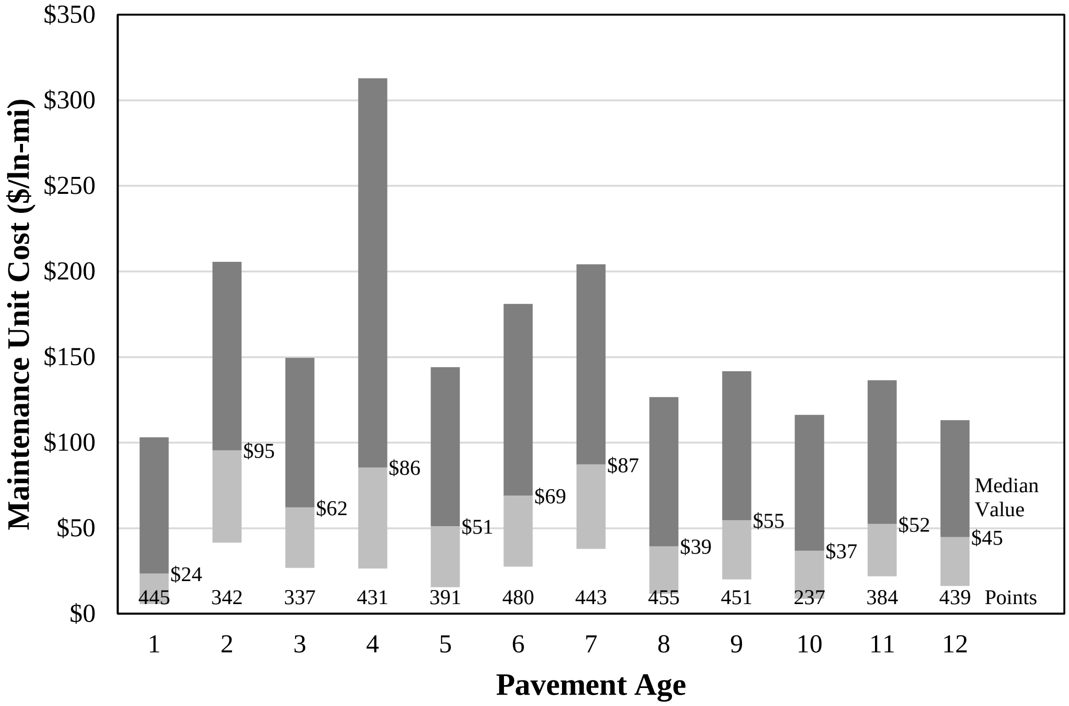

Figure 4.9: Present Value of Annual Maintenance Unit Cost Stream for Piedmont-Primary-Asphalt-High Roadways from Select Data

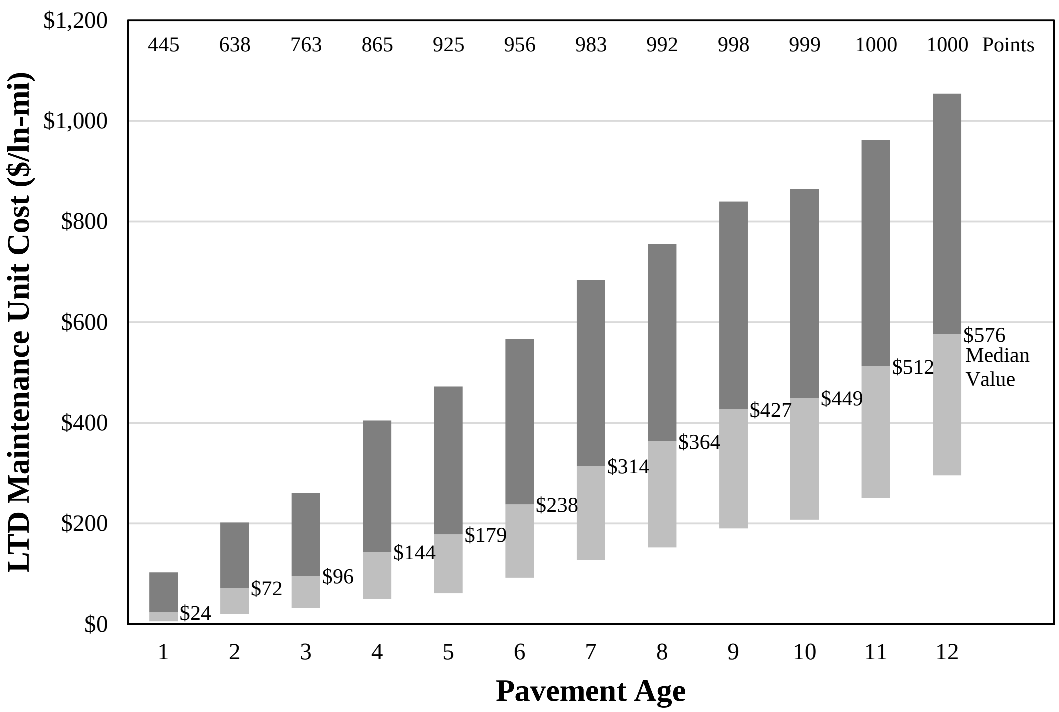

Figure 4.10: Present Value of Life-to-Date Maintenance Unit Cost Stream for Piedmont-Primary-Asphalt-High Roadways from Select Data

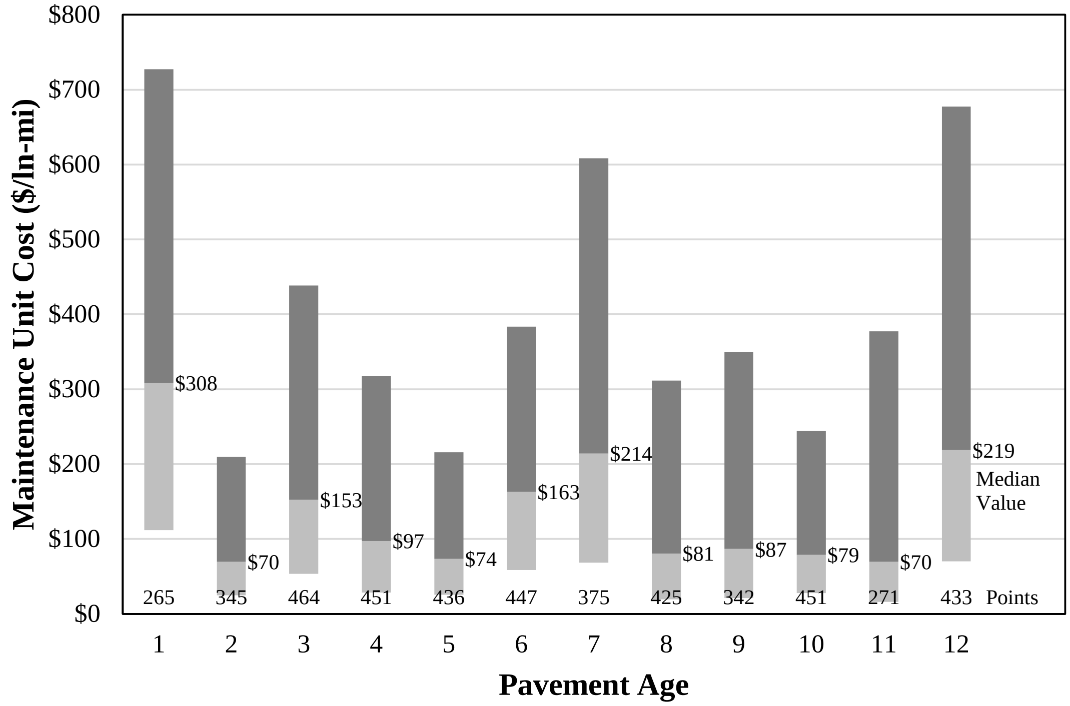

Figure 4.11: Present Value of Annual Maintenance Unit Cost Stream for Piedmont-Primary-Asphalt-Low Roadways from Select Data

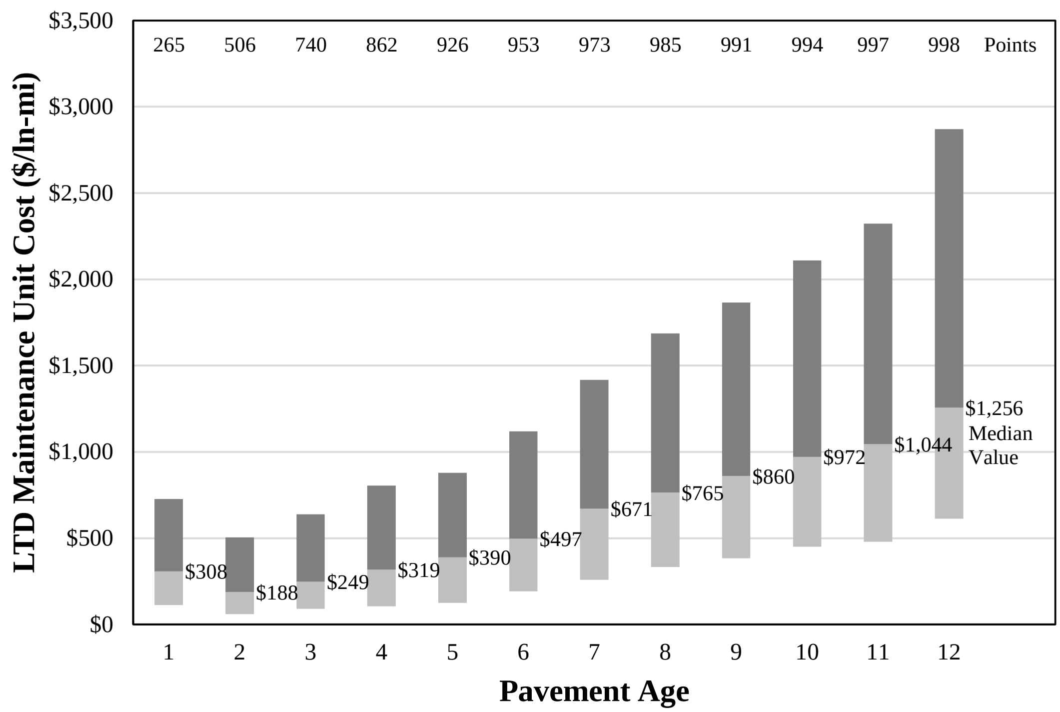

Figure 4.12: Present Value of Life-to-Date Maintenance Unit Cost Stream for Piedmont-Primary-Asphalt-Low Roadways from Select Data

The simulated unit costs from the select data ranged similarly to those from the comprehensive data, generally ranging from a few dollars to the low thousands of dollars with a limited number of extreme values. Median values of annual maintenance unit cost were in the tens and low hundreds of dollars, ranging from $23 to $308 per lane-mile. For LTD maintenance unit costs, median values throughout the analysis period were generally in the hundreds of dollars, ranging from $24 to $1,256 per lane-mile. At the end of analysis period age 12, the LTD maintenance unit costs ranged from $576 to $1,256 per lane-mile.

5 ASSESSMENT OF MAINTENANCE UNIT COST STREAMS

The maintenance unit cost streams were assessed to address the research questions:

1. Are pavement maintenance costs so small that they need not be included in LCCA?
2. Are pavement maintenance costs small throughout the pavement life?
3. Are pavement maintenance costs approximately equal for rigid, flexible, and composite pavements?

Additionally, cost streams were assessed to identify and potentially explain differences in maintenance costs between:

1. Comprehensive and select data sets
2. Geographic locations
3. Low and high traffic volume roadways

With the exception of the research question regarding costs throughout the pavement life, the costs were assessed on the basis of the present value of life-to-date maintenance unit cost at the end of the 12 year analysis period. The median present value of life-to-date maintenance unit cost for roadway groups is provided in Table 5.1.

Table 5.1: Median Present Value of LTD Maintenance Unit Cost through Age 12 Years

Region / Class	Surface	Traffic Volume	Comprehensive Data	Select Data
Coastal / Primary	Asphalt	High	$ 467	$ 634
		Low	$ 504	$ 791
	Composite	High	$ 593	
		Low	$ 865	
Mountains / Primary	Asphalt	High	$ 603	
		Low	$ 670	$ 1,214
	Composite	Low	$ 321	
Piedmont / Primary	Asphalt	High	$ 464	$ 576
		Low	$ 765	$ 1,256
	Composite	Low	$ 936	

5.1 Magnitude of Maintenance Costs

Maintenance costs may appropriately be neglected from LCCA when their magnitude is small compared to the costs of initial construction, rehabilitation/reconstruction, and salvage values. A threshold minimum for maintenance costs is difficult to establish, but the level of accuracy of the estimated initial construction cost is a conservative minimum. Preliminary and engineer's estimates are accurate to approximately ± 10 percent (Peurifoy and Oberlender, 2002). The estimated costs for rehabilitation/reconstruction and salvage values are likely to have a larger accuracy range.

A new 1.5 inch thick course of S9.5B or S9.5C asphalt pavement surface applied at a rate of 168 lbs/sy to a one mile roadway section with a lane width of 12 feet requires 592 tons of asphalt concrete. The average unit cost for these surface course materials was $38 per ton in place, and neglecting all other associated work items, the estimated construction cost would be approximately $22,500.

The estimated maintenance unit costs through the initial 12 year pavement life were generally less than $1,000 with a maximum value of approximately $1,250 per lane-mile. These maintenance costs are approximately 2.5 to 6 percent of the estimated construction cost and well within the range of accuracy for the estimated construction cost.

5.2 Maintenance Costs throughout Pavement Life

There was no discernable pattern of costs with respect to pavement age in either the simulated cost streams or the observed costs. Median annual maintenance unit costs from the select data were regressed against pavement age to assess the relationship. The results are summarized in Table 5.2 and generally indicated an increasing cost with age, but the relationships were not significant at the 0.05 level. This result is counter to the conclusion by Teng et al. (2013) that traffic volume, age, and location are significant variables that affect the costs for maintenance of a roadway.

Table 5.2: Summary of Relationship between Maintenance Costs and Pavement Age

Region / Class / Surface	Traffic Volume	Coefficient ($/ln-mi/yr)	p-value
Coastal/Primary/Asphalt	High	-2.844	0.601
	Low	0.069	0.989
Mountains/Primary/Asphalt	Low	6.147	0.221
Piedmont/Primary/Asphalt	High	3.380	0.175
	Low	10.434	0.078

5.3 Maintenance Costs by Pavement Type

Comprehensive data was sufficient to allow comparison of asphalt and composite pavement types. The cost data available for concrete pavements was extremely limited and not sufficient for comparison. In the Coastal and Piedmont regions, the maintenance cost of composite pavements was 20 to 70 percent greater than for asphalt pavements. This was not the case for the roadways in the Mountains region, but it should be noted that the quantity of data available for composite pavements in the Mountains region was substantially less than for asphalt pavements.

Composite pavements showed a greater probability of maintenance than asphalt pavements in the Coastal region (reference Figure 3.4). In the Coastal region for both high and low traffic volume roadways, the observed maintenance unit costs were generally greater for composite pavements (reference Figures B3 through B6). The observed median unit costs for composite pavements during the initial 12 years ranged from $25 to $628 per lane-mile for high traffic and $67 to $479 for low traffic roadways, while asphalt pavements ranged from $45 to $117 per lane-mile for high traffic and $64 to $164 for high traffic roadways.

In the Piedmont region, probabilities of maintenance were approximately equal or slightly less for composite pavements in the Piedmont Region (reference Figure 3.6). Again, the observed maintenance unit costs were generally greater for composite pavements (reference Figures B20 and B22). The observed median unit costs for low traffic roadways with composite pavements during the initial 12 years ranged from $109 to $567 per lane-mile, while low traffic roadways with asphalt pavements ranged from $95 to $224 per lane-mile.

The simulated costs from the comprehensive data set were used to assess the statistical significance of differences in costs for pavement types. The t-test was applied at a 0.05 significance level between simulated streams of the log transformed present value of LTD maintenance costs at age 12. The t-test was used because the cost distributions appeared symmetric and the t-test is robust with respect to the assumption of normality when using large datasets (Ott and Longnecker, 2001). The costs were found to be significantly different in all cases and the p-values were much less than 0.05, as shown in Table 5.3.

Table 5.3: Comparison of Maintenance Costs for Asphalt and Composite Pavements

Region	**Traffic Volume**	**Asphalt ($/ln-mi)**	**Composite ($/ln-mi)**	**p-value**
Coastal	High	$ 467	$ 593	1.94E-09*
	Low	$ 504	$ 865	5.77E-22*
Mountains	Low	$ 670	$ 321	2.22E-23*
Piedmont	Low	$ 765	$ 936	1.07E-03*

** Statistically significant at the 0.05 level*

5.4 Comparison of Costs from Comprehensive and Select Data

The results produced from the comprehensive and select data sets were assessed to determine the impact of applying the filters to create the select data. The LTD maintenance costs at age 12 ranged from 24 to 81 percent greater for the select data.

The statistical significance of differences in cost between the data sets was assessed. The t-test was applied to the simulated streams of the log transformed present value of LTD maintenance costs at age 12 for each roadway group. The costs were found to be significantly different for all groups, with p-values much less than 0.05 as shown in Table 5.4

Table 5.4: Comparison of Maintenance Costs for Comprehensive and Select Data Sets

Region / Class / Surface	Traffic Volume	Comprehensive Data (Median $/ln-mi)	Select Data (Median $/ln-mi)	p-value
Coastal/Primary/Asphalt	High	$ 467	$ 634	1.18E-10*
	Low	$ 504	$ 791	1.81E-14*
Mountains/Primary/Asphalt	Low	$ 670	$ 1,214	4.21E-45*
Piedmont/Primary/Asphalt	High	$ 464	$ 576	1.16E-06*
	Low	$ 765	$ 1,256	1.92E-22*

** Statistically significant at the 0.05 level*

The increase in maintenance costs was expected because the select data was filtered to not include:

1. artificially low costs resulting from inaccurate or missing to and from mileposts for maintenance activities
2. $0 cost data resulting from missing cost data and missing maintenance activities.

The impact of the filters on the data was an increase in both the probability of incurring maintenance and the maintenance unit costs. The probabilities and costs are shown for comparison in Figures 5.1 to 5.10. The removal of the $0 cost data caused a significant and general increase in the probabilities of maintenance in each year. Overall, probabilities increased by approximately 10 percent, but increases of over 20 percent resulted for some roadway group/age combinations. Maintenance unit costs showed a similar increase as a result of eliminating costs artificially deflated by inaccurate or missing maintenance activity location data. Select data costs averaged approximately $20 per lane-mile more, which is slightly less than a 20 percent increase.

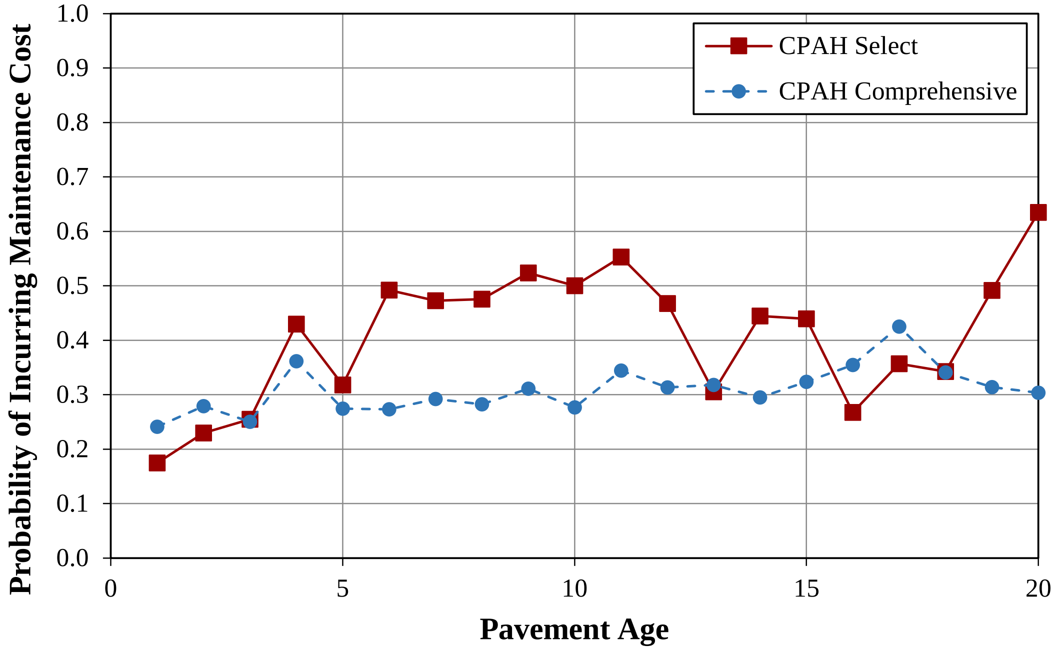

Figure 5.1: Probabilities of Maintenance for Coastal-Primary-Asphalt-High Roadways from Comprehensive and Select Data

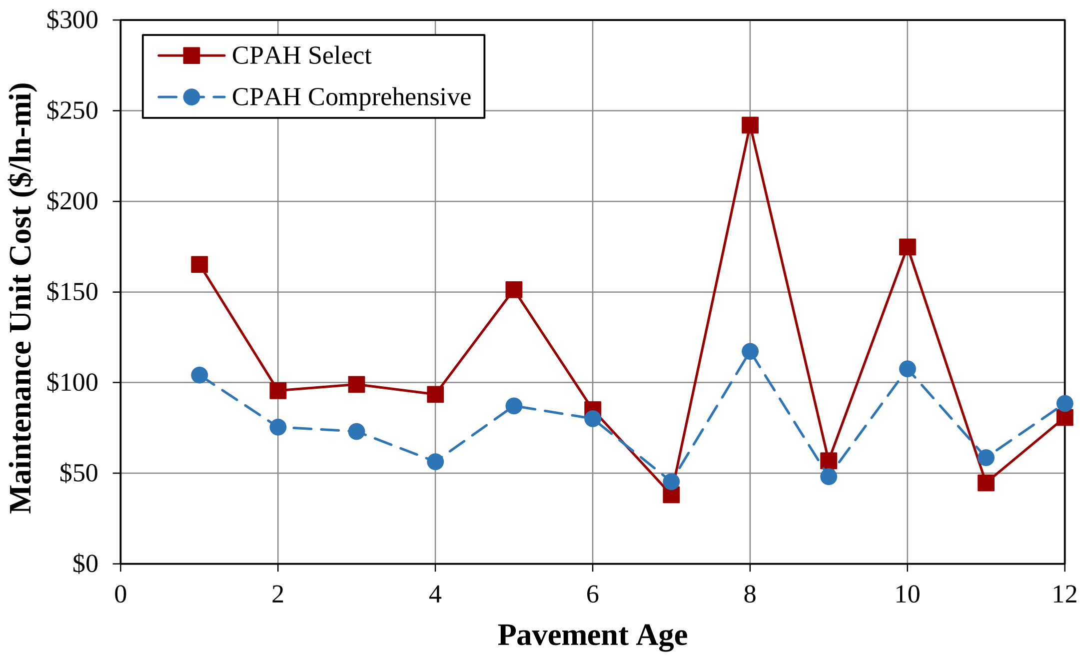

Figure 5.2: Median Maintenance Unit Cost for Coastal-Primary-Asphalt-High Roadways from Comprehensive and Select Data

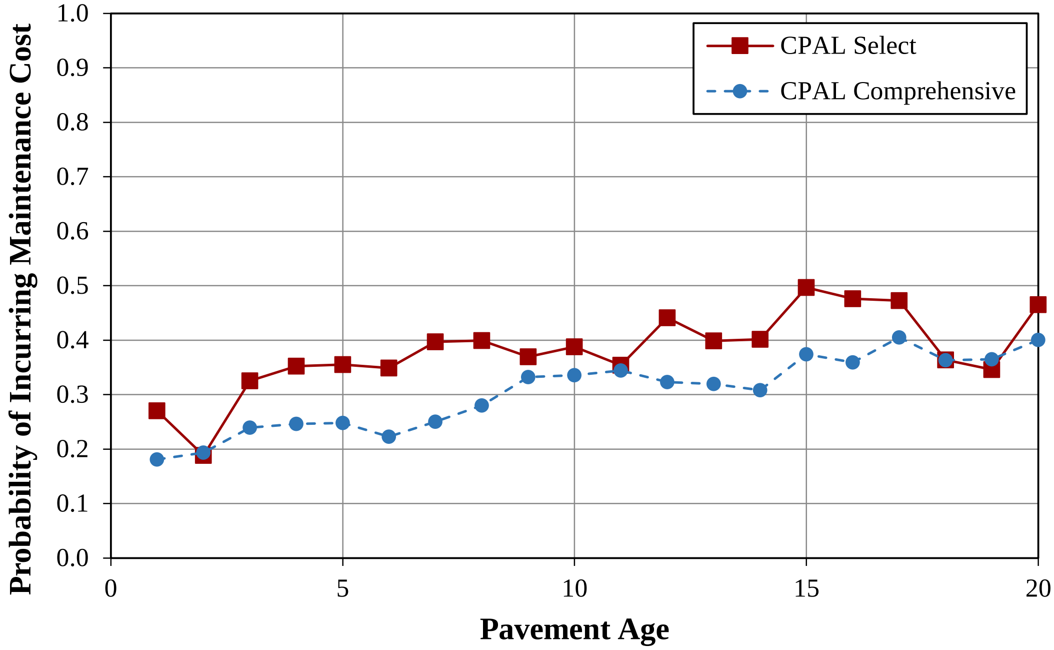

Figure 5.3: Probabilities of Maintenance for Coastal-Primary-Asphalt-Low Roadways from Comprehensive and Select Data

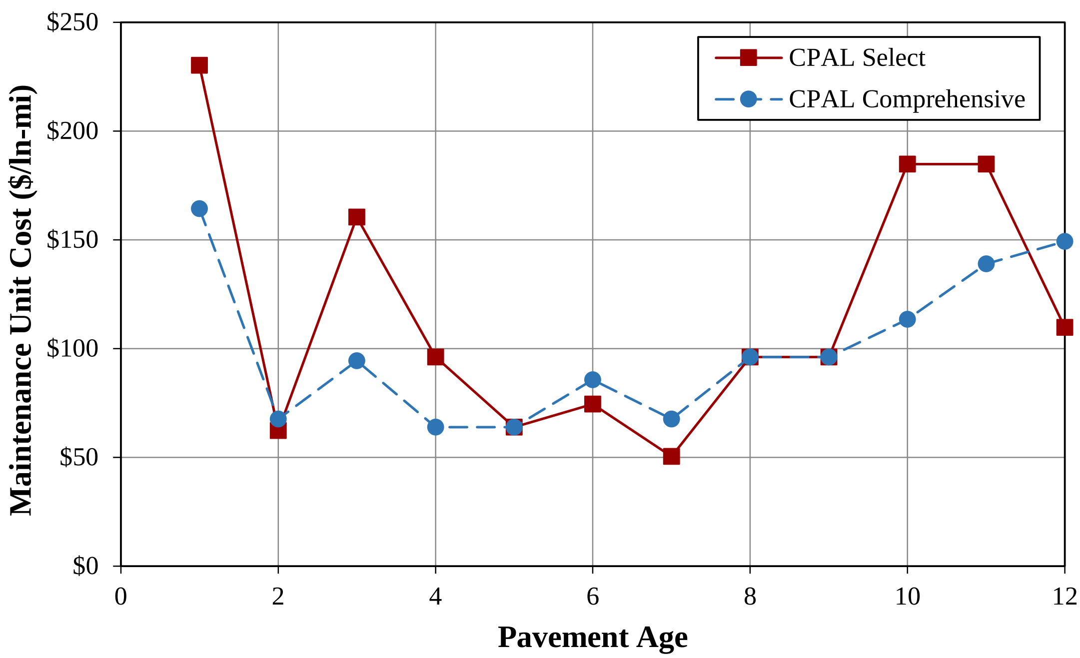

Figure 5.4: Median Maintenance Unit Cost for Coastal-Primary-Asphalt-Low Roadways from Comprehensive and Select Data

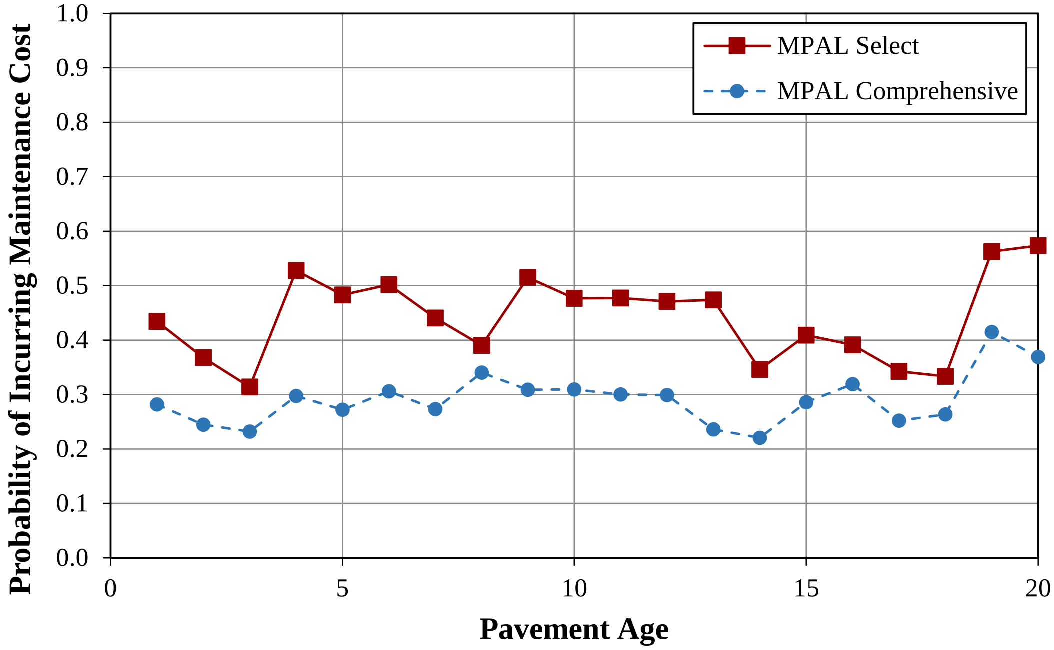

Figure 5.5: Probabilities of Maintenance for Mountains-Primary-Asphalt-Low Roadways from Comprehensive and Select Data

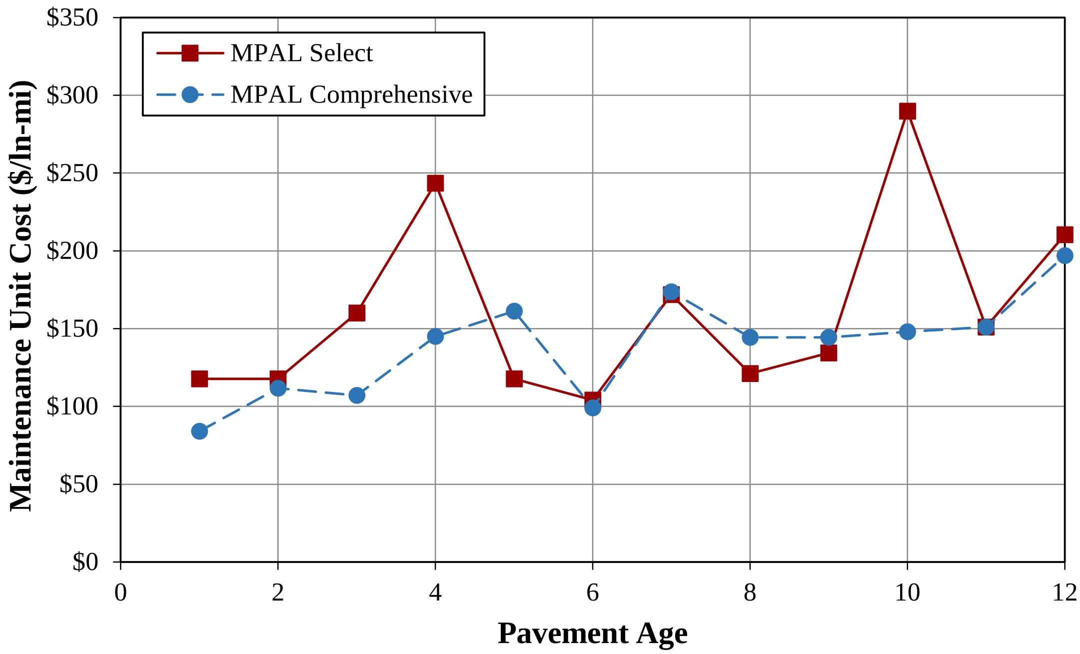

Figure 5.6: Median Maintenance Unit Cost for Mountains-Primary-Asphalt-Low Roadways from Comprehensive and Select Data

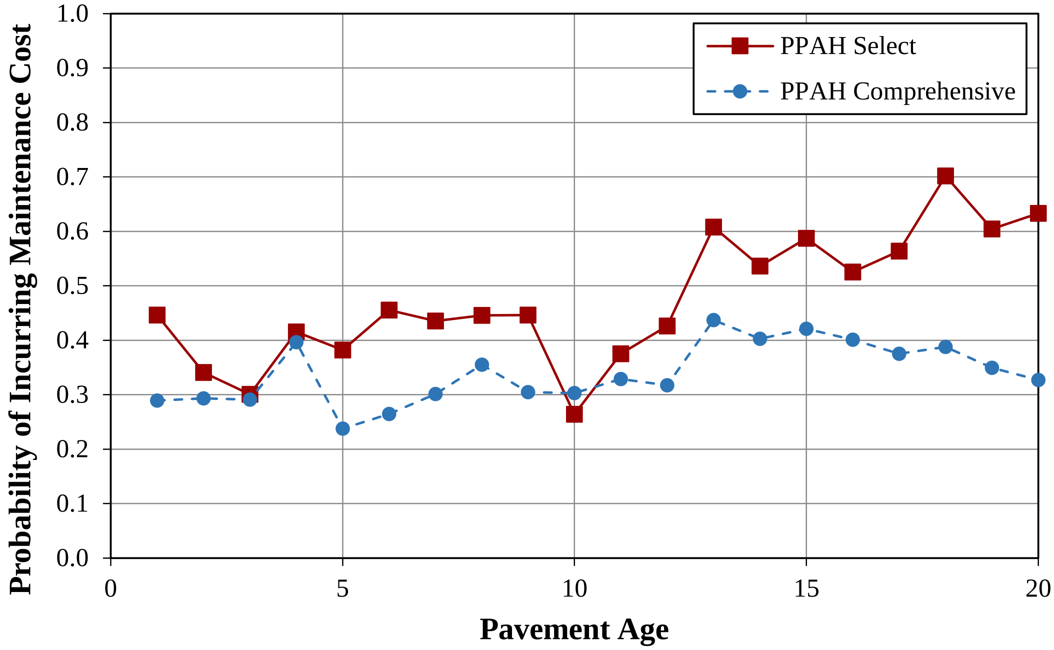

Figure 5.7: Probabilities of Maintenance for Piedmont-Primary-Asphalt-High Roadways from Comprehensive and Select Data

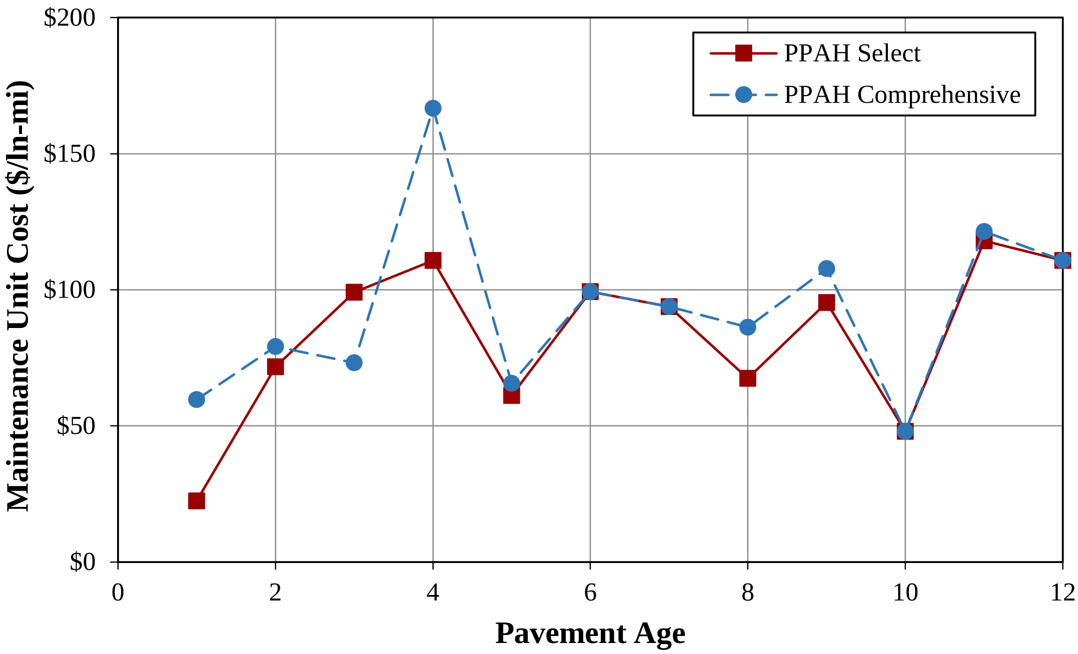

Figure 5.8: Median Maintenance Unit Cost for Piedmont-Primary-Asphalt-High Roadways from Comprehensive and Select Data

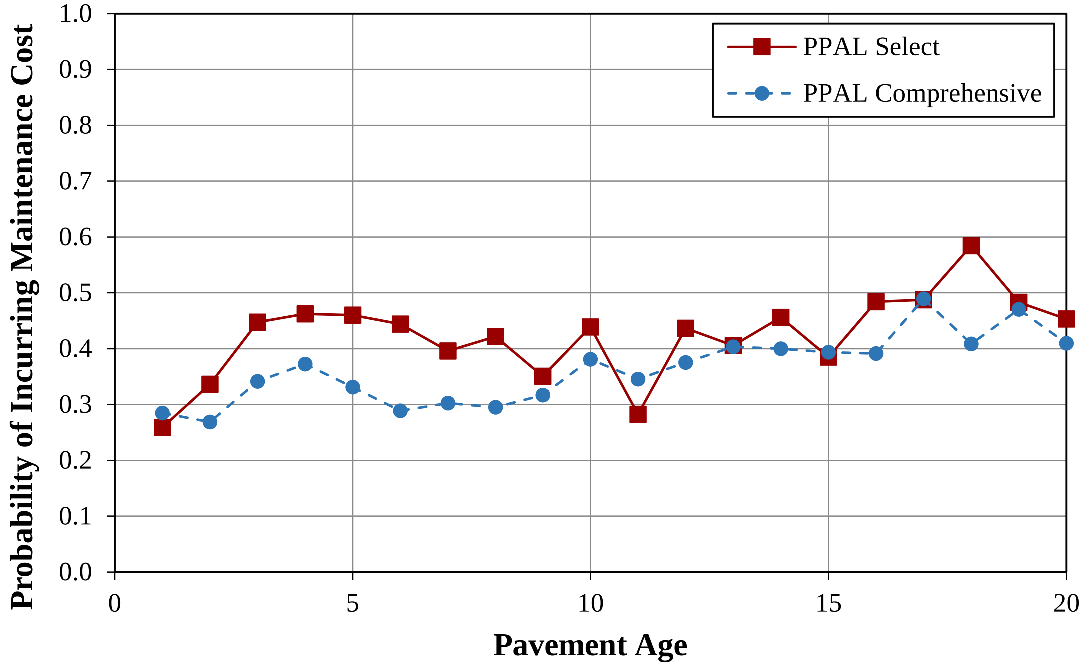

Figure 5.9: Probabilities of Maintenance for Piedmont-Primary-Asphalt-Low Roadways from Comprehensive and Select Data

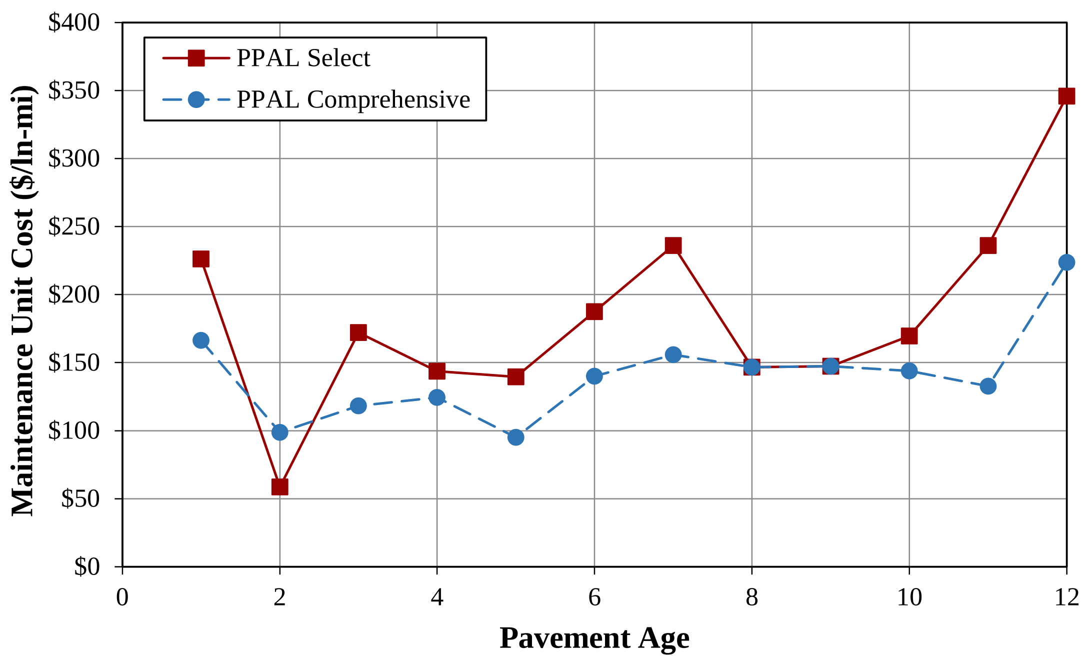

Figure 5.10: Median Maintenance Unit Cost for Piedmont-Primary-Asphalt-Low Roadways from Comprehensive and Select Data

5.5 Comparison of Costs across Geographic Regions

There was no apparent relationship observed between maintenance costs and geographic region. However, it is of value to know whether regional costs are statistically different or can be combined for future analyses. The t-test was first applied to similar roadway groups in different regions and the results are summarized in Table 5.5. Maintenance costs for low traffic volume primary asphalt roadways in the Coastal region were significantly different from those in the Piedmont and Mountains, with p-values substantially less than 0.05. Costs for those roadways in the Piedmont and Mountains were not found to be significantly different, as indicated by a p-value of 0.395. Maintenance costs for high traffic volume primary asphalt roadways were significantly different in the Coastal and Piedmont regions and the p-value was 0.0015.

The LTD maintenance costs at age 12 years were also tested from the comprehensive data to provide further insight, and the results summarized in Table 5.5. Data for primary roadways was available to compare costs of high traffic asphalt, low traffic asphalt, and low traffic composite roadways in the three regions. In all but two of the nine comparisons, the maintenance costs were found to differ significantly between regions. Costs were not significantly different for high traffic primary asphalt roadways and for low traffic primary composite roadways in the Coastal and Piedmont regions.

Table 5.5: Comparison of Maintenance Costs Across Geographic Regions

Data Set	**Comparison**	**Median ($/ln-mi)**	**p-value**
Select	CPAL v PPAL	$ 791 v $ 1,256	8.59E-20*
	CPAL v MPAL	$ 791 v $ 1,214	1.65E-20*
	PPAL v MPAL	$ 1,256 v $ 1,214	3.95E-01
	CPAH v PPAH	$ 634 v $ 576	1.56E-03*
Comprehensive	CPAH v PPAH	$ 467 v $ 464	8.68E-01
	CPAH v MPAH	$ 467 v $ 603	7.29E-07*
	PPAH v MPAH	$ 464 v $ 603	6.24E-09*
	CPAL v PPAL	$ 504 v $ 765	5.72E-16*
	CPAL v MPAL	$ 504 v $ 670	5.66E-08*
	PPAL v MPAL	$ 765 v $ 670	1.92E-03*
	CPOL v PPOL	$ 865 v $ 936	8.56E-02
	CPOL v MPOL	$ 865 v $ 321	5.67E-43*
	PPOL v MPOL	$ 936 v $ 321	8.27E-48*

** Statistically significant at the 0.05 level*

5.6 Comparison of Maintenance Costs for High and Low Traffic Volume Roadways

The t-test was applied to assess differences in LTD maintenance costs at age 12 years for low and high traffic volume roadways. The results indicated that the differences were greater for low traffic volume roadways than high traffic volume roadways. The differences in costs were statistically significant, as shown in Table 5.6.

Table 5.6: Comparison of Maintenance Costs by Traffic Volume

Region/Class/Surface	High Traffic ($/ln-mi)	Low Traffic ($/ln-mi)	p-value
Coastal/Primary/Asphalt	$ 634	$ 791	3.65E-03
Piedmont/Primary/Asphalt	$ 576	$ 1,256	6.03E-65

This was not expected and the probability of incurring maintenance and maintenance cost distributions were investigated. The observed probabilities of incurring maintenance cost for the Piedmont-Primary-Asphalt and Coastal-Primary-Asphalt roadways are provided as Figure 5.11 and 5.12, respectively. The probabilities for high and low traffic volume Piedmont roadways are approximately equal through the first 12 years of pavement life, which was the analysis period. In the Coastal region, the probabilities are approximately equal for the first 6 years, then the probabilities of maintenance are approximately 10 percent greater for high volume roadways through age 12.

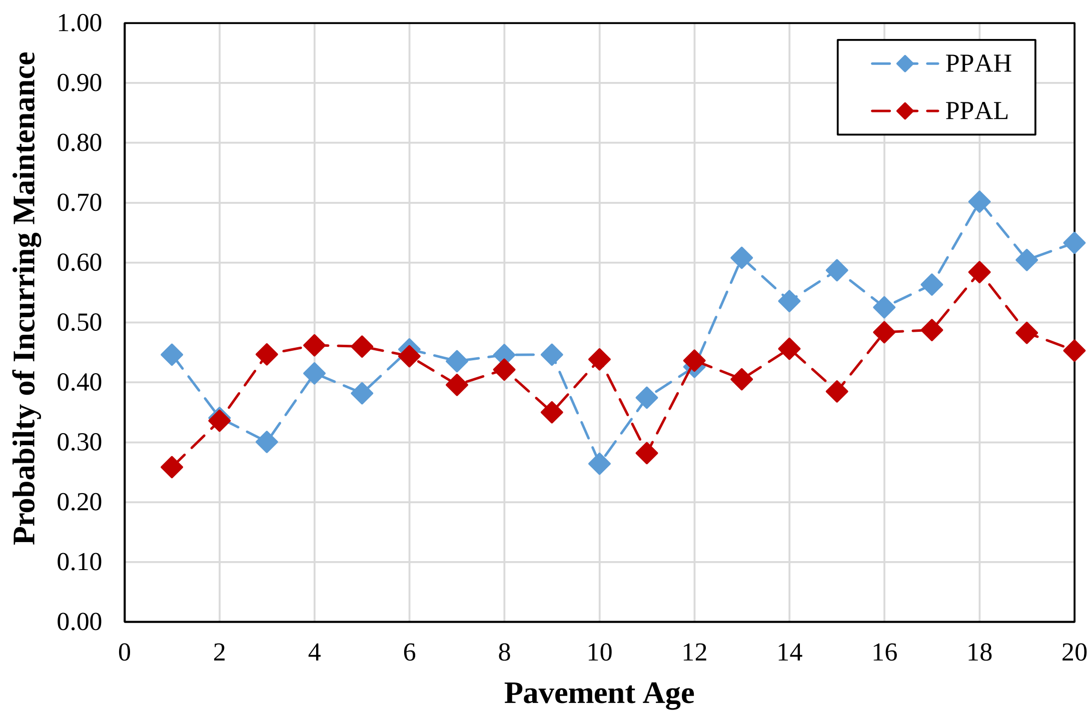

Figure 5.11: Probability of Maintenance for Piedmont-Primary-Asphalt Roadways

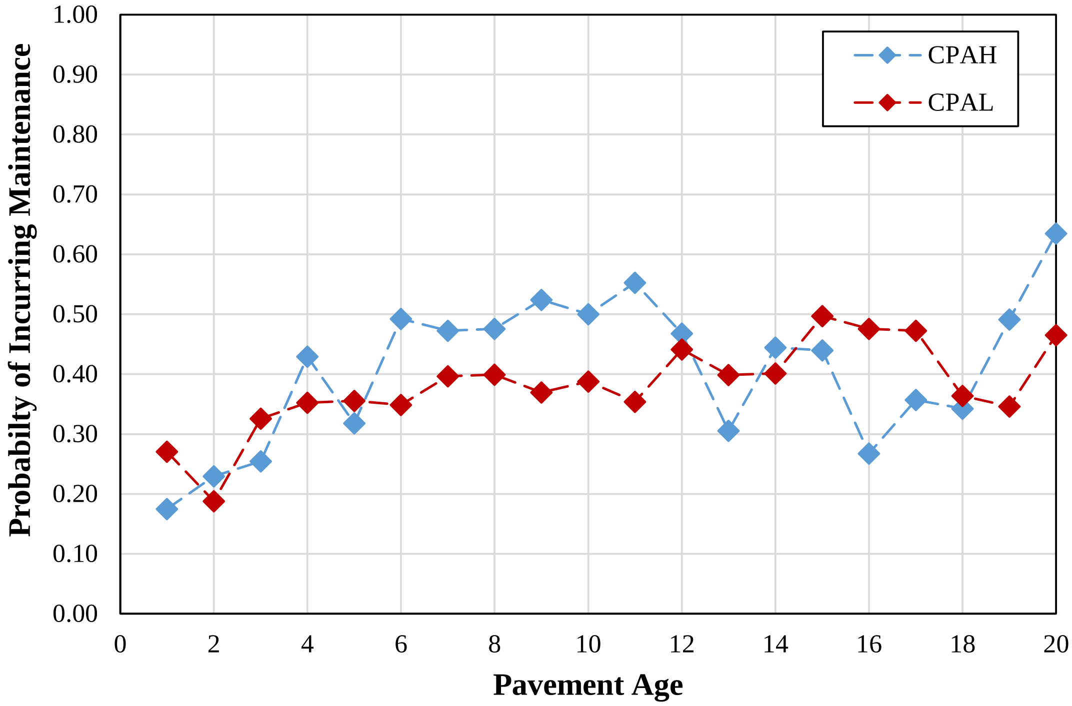

Figure 5.12: Probability of Maintenance for Coastal-Primary-Asphalt Roadways

Review of the maintenance cost distributions revealed a tendency towards larger annual maintenance unit costs for low volume roadways. This tendency in costs is most easily seen in the data for the Piedmont primary asphalt roadways. The median maintenance unit cost at all pavement ages, except age 2 years, is greater for the low volume roadways, as shown in Figure 5.13. Figure 5.14 provides the interquartile range of the unit maintenance cost distributions, where the tendency towards costs much greater than the median values is evidenced by the extended third quartile ranges.

For the Coastal primary asphalt roadways, the difference in median unit costs was not as significant, as shown in Figure 5.15. However, the tendency towards costs much greater than the median values is evident, though not as clearly pronounced, in the cost distributions, as shown in Figure 5.16.

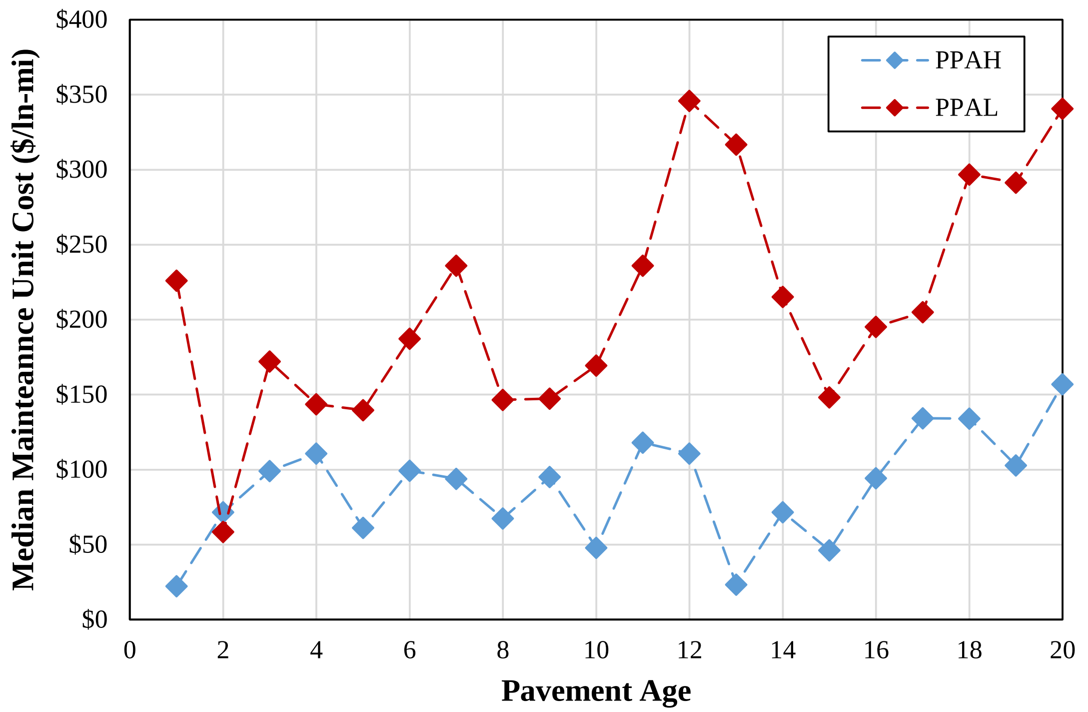

Figure 5.13: Median Maintenance Unit Cost for Piedmont-Primary-Asphalt Roadways

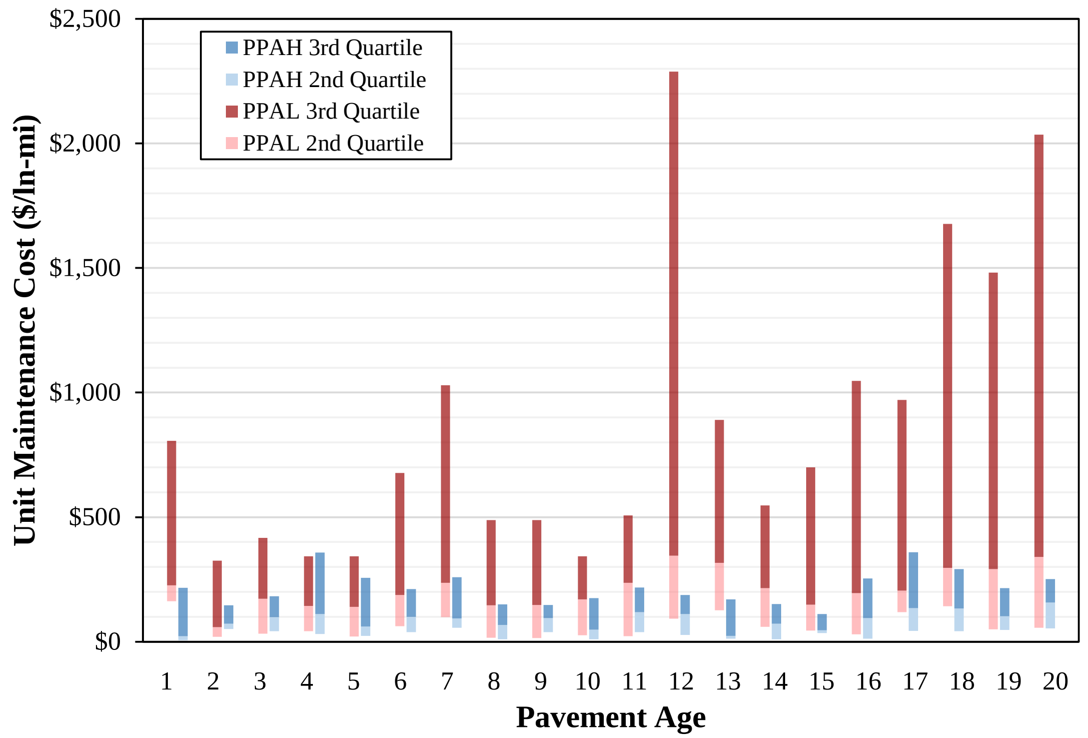

Figure 5.14: Interquartile Range of Unit Maintenance Cost for Piedmont-Primary-Asphalt Roadways

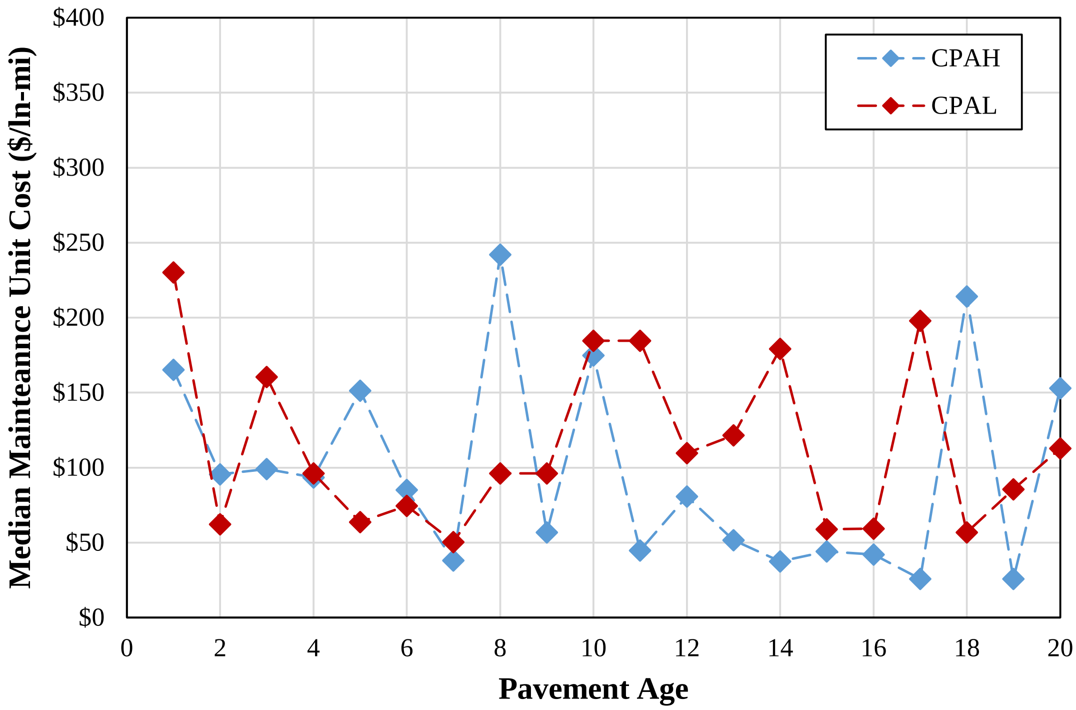

Figure 5.15: Median Maintenance Unit Cost for Coastal-Primary-Asphalt Roadways

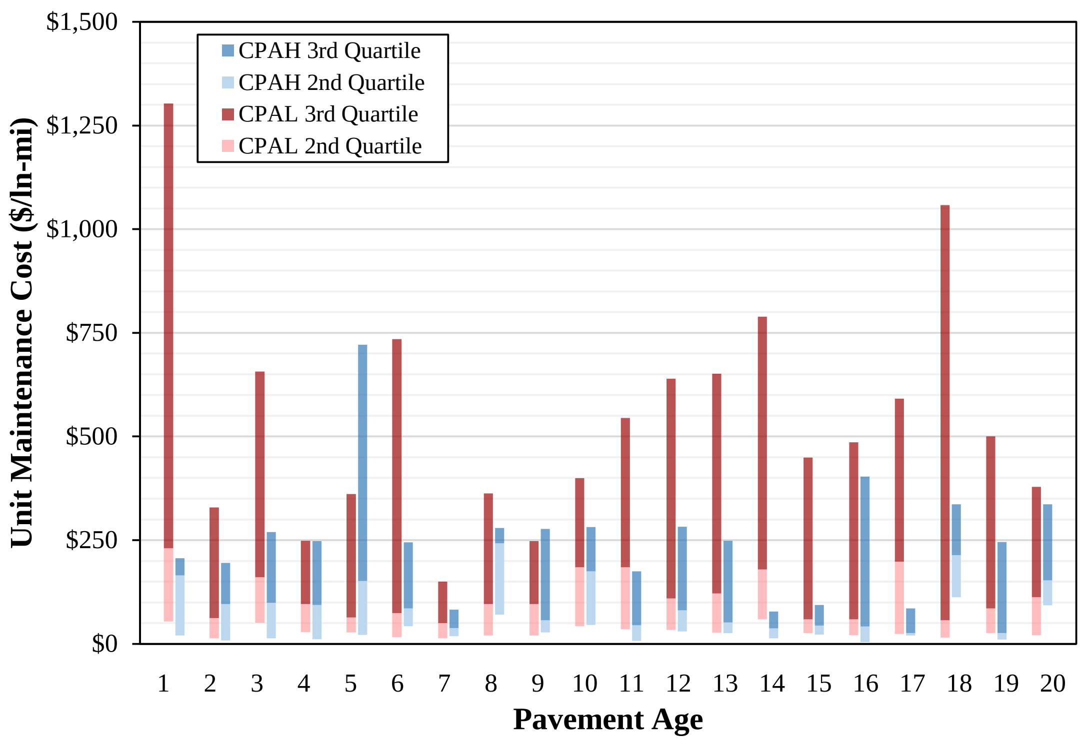

Figure 5.16: Interquartile Range of Unit Maintenance Cost for Coastal-Primary-Asphalt Roadways

Data regarding maintenance activities were examined and differences noted in the activities performed, their average cost, and duration. Pavement maintenance activities are summarized for the Piedmont and Coastal regions in Tables 5.6 and 5.7, respectively.

Activity work functions for Piedmont-Primary-Asphalt roadways were similar in content and proportion. Sealing and overlay activities performed on low traffic roadways that were not performed on high traffic roadways. However, the number and proportion of those activities was very small. Similarly for Coastal-Primary-Asphalt roadways, there were differences in activities performed, but these accounted for a very small portion of the total maintenance activities.

The duration of maintenance activities are expected to be positively correlated with cost and it was noted that the average duration of activities on low traffic roads was generally greater than those on high volume roadways. This general trend can be observed for individual work functions in Tables 5.7 and 5.8. The distribution of activity durations for the Piedmont and Coastal regions is presented as Figures 5.17 and 5.18, respectively. From these figures, the tendency towards longer duration for low traffic roadways is slight in the Coastal region and much more pronounced in the Piedmont region.

As was previously discussed, the maintenance costs tended to be greater for low traffic roadways. This tendency is not absolute across all work functions, but does frequently bear out in the average unit cost for the work functions, as shown in Tables 5.7 and 5.8.

Table 5.7: Maintenance Activity Summary for Piedmont-Primary-Asphalt Roadways

	PPAH				PPAL			
Maintenance Activity	**Count**	**Percent**	**Avg. Duration (days)**	**Avg. Unit Cost ($/ln-mi)**	**Count**	**Percent**	**Avg. Duration (days)**	**Avg. Unit Cost ($/ln-mi)**
2800-Single Seal (SYD)					6	0.1%	41	$ 672
2802-Double Seal (SYD)					18	0.4%	6	$ 729
2804-Triple Seal (SYD)					21	0.4%	15	$ 7,263
2808-Specialty Seals (SYD)					3	0.1%	9	$ 1,978
2812-Hot Mix Asphalt Overlay (TON)	26	0.8%	47	$ 232	94	1.9%	15	$ 2,312
2816-Asphalt Pavement Repair / Patching (SYD)	2,062	63.8%	9	$ 50	2,992	60.1%	25	$ 155
2817-Mechanical Asphalt Patching (TON)	27	0.8%	29	$ 258	121	2.4%	20	$ 693
2818-Full Depth Asphalt Pavement Repair (TON)	158	4.9%	52	$ 516	406	8.2%	23	$ 282
2820-Milling/Grinding Asphalt Pavement (SYD)	47	1.5%	5	$ 205	94	1.9%	21	$ 477
2822-Maintenance of Cracks and Joints in Pavement (LML)	11	0.3%	7	$ 109	244	4.9%	33	$ 638
2824-Concrete Pavement Repair (SYD)	24	0.7%	15	$ 182	19	0.4%	22	$ 271
3702-HOT MIX SHORT OVL/LEVLNG (TON)					2	0.0%	1	$ 550
3711-MANUAL PATCHING (TON)	258	8.0%	6	$ 28	294	5.9%	9	$ 58
3712-MECHANICAL PATCHING (TON)	103	3.2%	5	$ 51	125	2.5%	13	$ 395
3713-SPRAY INJECTION PATCHING (SYD)	103	3.2%	1	$ 25	2	0.0%	1	$ 13
3714-AST PATCHING (SYD)	217	6.7%	1	$ 14	303	6.1%	2	$ 75
3715-FULL DEPTH PATCH HOT MIX (TON)	109	3.4%	6	$ 173	109	2.2%	15	$ 464
3717-MILLING/GRINDING ASP PVMT (SYD)	53	1.6%	3	$ 205	54	1.1%	30	$ 182
3718-MNTC OF CRCKS IN ASP PAVT (LML)	19	0.6%	1	$ 26	65	1.3%	8	$ 422
3732-PATCH PCC Pavement (SYD)	3	0.1%	1	$ 6	2	0.0%	1	$ 6
3735-MNTC OF CRACKS CONC PAVT (LML)	11	0.3%	1	$ 28	4	0.1%	1	$ 35

Table 5.8: Maintenance Activity Summary for Coastal-Primary-Asphalt Roadways

	CPAH				CPAL			
Maintenance Activity	**Count**	**Percent**	**Avg. Duration (days)**	**Avg. Unit Cost ($/ln-mi)**	**Count**	**Percent**	**Avg. Duration (days)**	**Avg. Unit Cost ($/ln-mi)**
2800-Single Seal (SYD)	7	0.3%	10	$ 5,602	12	0.2%	55	$ 5,873
2802-Double Seal (SYD)	14	0.6%	33	$ 9,835	84	1.2%	57	$ 8,599
2804-Triple Seal (SYD)					10	0.1%	81	$ 10,249
2810-Microsurface (SYD)	1	0.0%	155	$ 5,596				
2812-Hot Mix Asphalt Overlay (TON)	77	3.4%	72	$ 2,030	345	4.9%	38	$ 7,437
2816-Asphalt Pavement Repair / Patching (SYD)	1126	49.6%	17	$ 70	3879	55.3%	22	$ 154
2817-Mechanical Asphalt Patching (TON)	33	1.5%	11	$ 398	181	2.6%	20	$ 1,710
2818-Full Depth Asphalt Pavement Repair (TON)	315	13.9%	11	$ 193	487	6.9%	16	$ 403
2820-Milling/Grinding Asphalt Pavement (SYD)	210	9.2%	23	$ 180	263	3.8%	49	$ 236
2822-Maintenance of Cracks and Joints in Pavement (LML)	103	4.5%	57	$ 1,104	437	6.2%	59	$ 1,092
2824-Concrete Pavement Repair (SYD)	10	0.4%	2	$ 11	16	0.2%	2	$ 40
3702-HOT MIX SHORT OVL/LEVLNG (TON)	50	2.2%	30	$ 199	30	0.4%	37	$ 413
3711-MANUAL PATCHING (TON)	200	8.8%	5	$ 55	785	11.2%	7	$ 49
3712-MECHANICAL PATCHING (TON)	8	0.4%	18	$ 669	147	2.1%	24	$ 1,323
3713-SPRAY INJECTION PATCHING (SYD)					14	0.2%	1	$ 7
3714-AST PATCHING (SYD)					37	0.5%	6	$ 56
3715-FULL DEPTH PATCH HOT MIX (TON)	59	2.6%	29	$ 94	95	1.4%	16	$ 173
3716-FULL DEPTH PATCH AST (SYD)					7	0.1%	22	$ 136
3717-MILLING/GRINDING ASP PVMT (SYD)	34	1.5%	17	$ 164	41	0.6%	14	$ 75
3718-MNTC OF CRCKS IN ASP PAVT (LML)	24	1.1%	59	$ 628	118	1.7%	29	$ 240
5086-C CONTRACT RESURFACING (TON)					23	0.3%	45	$ 90,601
5100-C MNTC OF CRCKS ASP PAVT (LML)					2	0.0%	14	$ 2,435

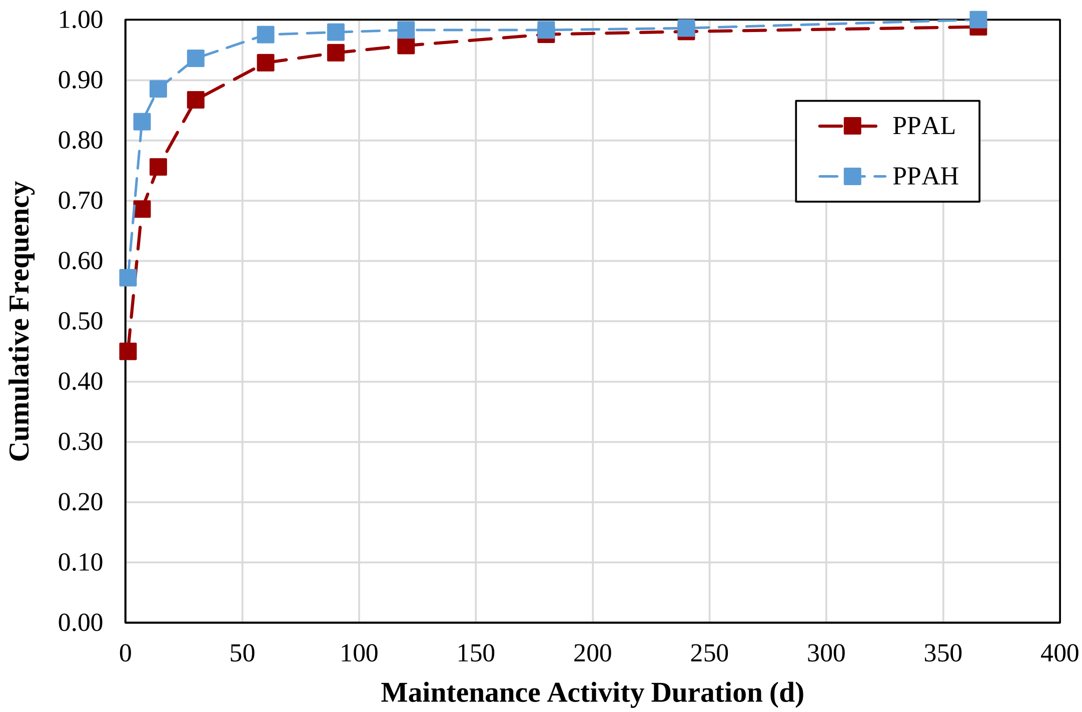

Figure 5.17: Average Duration of Maintenance Activities for Piedmont-Primary-Asphalt Roadways

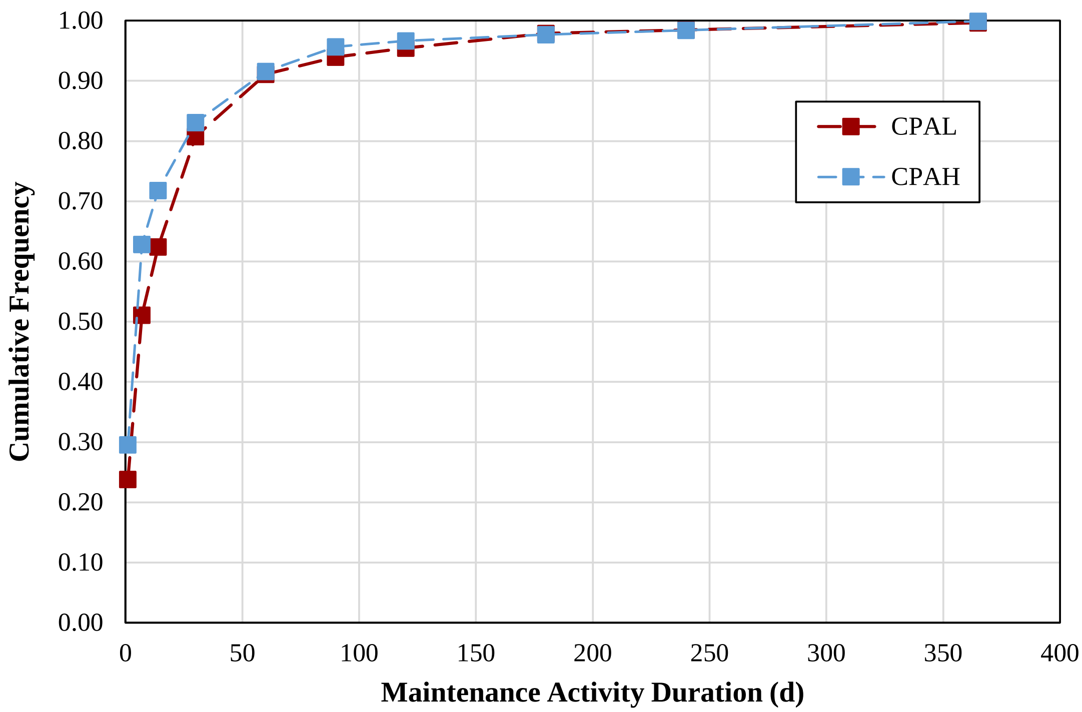

Figure 5.18: Average Duration of Maintenance Activities for Coastal-Primary-Asphalt Roadways

6 SUMMARY AND CONCLUSIONS

In this research, maintenance unit costs streams were developed using Monte Carlo simulation techniques based on existing roadway asset data from the PMS and maintenance activity and cost data from the MMS and were investigated to assess the magnitude and nature of roadway maintenance costs. The feasibility of using the existing data to develop cost streams was evaluated in terms of data quality and quantity. Simulated maintenance cost streams were developed from the observed probability of incurring maintenance and maintenance unit cost distributions. These streams were then analyzed to determine whether the magnitude of maintenance costs dictates their inclusion in LCCA for pavement type selection, and to assess differences in costs with respect to location, pavement type, and traffic volume. The following conclusions were drawn from this research:

1. Maintenance costs are considered to be "within the noise" of the estimated construction cost and the magnitude is sufficiently small to be appropriately neglected from LCCA for pavement type selection. The results indicate that maintenance costs over the initial 12 years of pavement life are approximately 2.5 to 6 percent of a conservative estimate of construction cost, which is well within the estimate accuracy of ± 10 percent.

2. Maintenance costs are small and relatively constant throughout the initial 12 years of pavement life. No significant relationship was found between the median LTD maintenance unit costs and pavement age.

3. Maintenance costs are not equal for all pavement types. While select cost data was not available for composite pavements and no cost data was available for concrete pavements, significant differences between maintenance costs of composite and asphalt pavements were found from the comprehensive cost data. Composite pavements were more costly to maintain than asphalt pavements in the Coastal and Piedmont regions, while the opposite was found in the Mountains region where the volume of data was limited.

4. The existing data can be filtered to appropriately address the quality issues identified and produce reliable select data sets. Four issues were noted in the data collected through 2012:

   a. Activity location data (mileposts) were not recorded in 37 percent of the maintenance activity records
   b. Activities were recorded with $0 total cost in 15 percent of the records
   c. Identical activities were recorded at multiple locations in 11.5 percent of the records
   d. Activities were recorded with durations of over 1 year in 0.5 percent of the records.

5. Sufficient filtered select data is available to accurately and reliably quantify the probability of cost and the maintenance unit costs for high traffic asphalt primary roads in the Coastal and Piedmont regions, and low traffic asphalt primary roads in the Coastal, Piedmont, and Mountains regions. While cost data is not available throughout the entirety of the life of a pavement, substantial volumes of data from windows (or portions) of pavement life can be compiled. Select data was available for asphalt pavements in 73 counties and collection generally started between 2006 and 2008. This data was generally sufficient to provide hundreds of maintenance data points and between 50 and 100 cost data points at each pavement age to 12 years. The minimum amount of data for any single year used was 56 data points and 21 cost points.

6. Maintenance costs vary by geographic region, but data was not sufficient to generalize cost trends across regions. The cost of maintaining low traffic asphalt primary roads in the Coastal region were significantly different from those in Piedmont and Mountains, which were not significantly different. There was a significant difference in maintenance costs for high traffic asphalt primary roads in Coastal and Piedmont regions.

7. Low traffic volume roadways are more costly to maintain than high traffic roads as a result of greater unit maintenance costs rather than more frequent maintenance activities, possibly reflecting differences in design standards and maintenance procedures. In the Coastal and Piedmont regions, the probability of incurring maintenance cost was similar and approximately equal over the 12 year analysis period for roadways with high and low traffic volumes. The median unit costs were greater for low traffic volume roads in the Piedmont region, and costs were similar for high and low volume roads in the Coastal region. Low traffic volume roads exhibited a tendency towards costs much greater than median cost, and the maintenance activity durations and average unit costs were greater than roads with high traffic volumes.

7 RECOMMENDATIONS

The following recommendations are made based on the results and conclusions of this research:

1. Maintenance costs are real costs that should be considered when estimating the true cost of a pavement.
2. Maintenance costs should not be included in LCCA for pavement type selection at this time, as costs cannot be estimated for concrete or composite pavements and the costs for asphalt pavements are sufficiently small to not significantly impact the LCCA results.
3. Maintenance activity data should continue to be collected and the volume monitored to allow analysis of interstate, concrete, and composite pavements at a future time.
4. Variations in maintenance costs with age should not be considered.
5. Maintenance costs should not be considered equal for all pavement types. Further analysis in this regard should be performed when data becomes available, particularly for concrete pavements and pavements in the Mountains region.
6. Filtered select data should be used for any analyses. The importance of accurately recording both the cost and location of activities should be communicated to those responsible for entering the data. Consideration should be given to developing weekly or monthly reports of activities with missing data and open work tasks for review by division maintenance managers or other appropriate personnel.
7. Maintenance costs from different regions should be considered separately and not be aggregated across regions. Additional data should be analyzed when available to determine if generalizations regarding regional costs can be made.
8. Maintenance costs should not be considered equal for low volume and high volume roadways. Additional data should be analyzed when available to determine if this holds true for composite pavements and in other geographic regions.

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APPENDIX A – COUNTY LIST

Table A1: NCDOT County Number and Name List

County Number	County Name	County Number	County Name
001	Alamance	051	Johnston
002	Alexander	052	Jones
003	Alleghany	053	Lee
004	Anson	054	Lenoir
005	Ashe	055	Lincoln
006	Avery	056	Macon
007	Beaufort	057	Madison
008	Bertie	058	Martin
009	Bladen	059	McDowell
010	Brunswick	060	Mecklenburg
011	Buncombe	061	Mitchell
012	Burke	062	Montgomery
013	Cabarrus	063	Moore
014	Caldwell	064	Nash
015	Camden	065	New Hanover
016	Carteret	066	Northampton
017	Caswell	067	Onslow
018	Catawba	068	Orange
019	Chatham	069	Pamlico
020	Cherokee	070	Pasquotank
021	Chowan	071	Pender
022	Clay	072	Perquimans
023	Cleveland	073	Person
024	Columbus	074	Pitt
025	Craven	075	Polk
026	Cumberland	076	Randolph
027	Currituck	077	Richmond
028	Dare	078	Robeson
029	Davidson	079	Rockingham
030	Davie	080	Rowan
031	Duplin	081	Rutherford
032	Durham	082	Sampson
033	Edgecombe	083	Scotland
034	Forsyth	084	Stanly
035	Franklin	085	Stokes
036	Gaston	086	Surry
037	Gates	087	Swain
038	Graham	088	Transylvania
039	Granville	089	Tyrrell
040	Greene	090	Union
041	Guilford	091	Vance
042	Halifax	092	Wake
043	Harnett	093	Warren
044	Haywood	094	Washington
045	Henderson	095	Watauga
046	Hertford	096	Wayne
047	Hoke	097	Wilkes
048	Hyde	098	Wilson
049	Iredell	099	Yadkin
050	Jackson	100	Yancey

APPENDIX B – DISTRIBUTIONS OF MAINTENANCE UNIT COST FROM COMPREHENSIVE MAINTENANCE DATA SETS

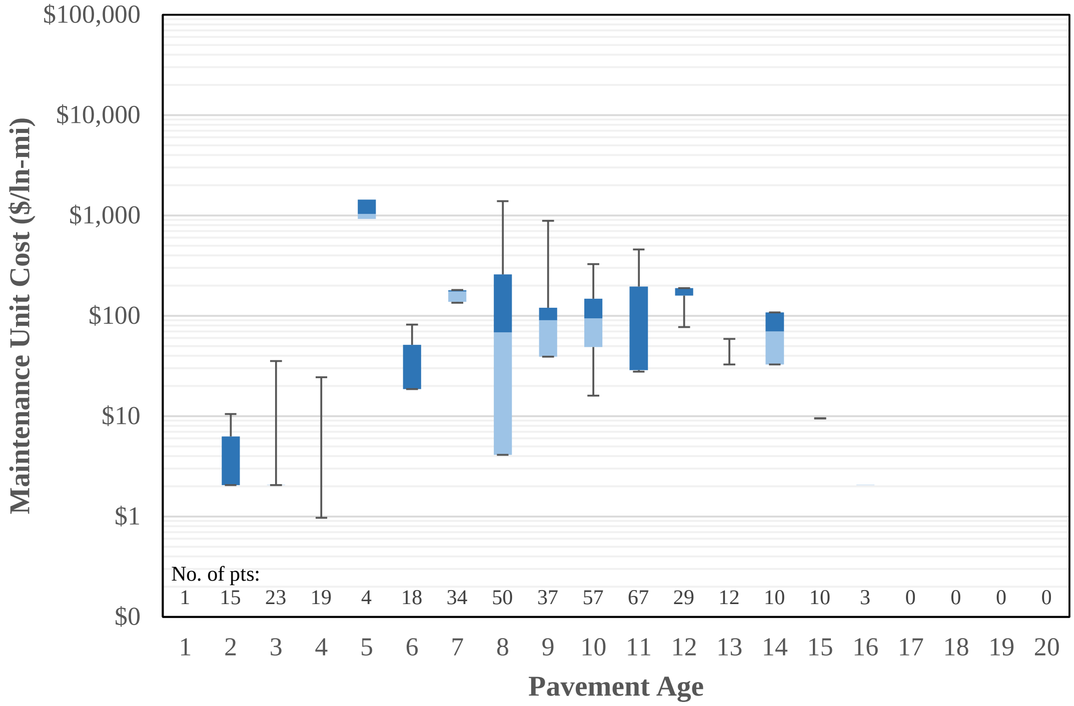

Figure B1: Maintenance Unit Cost Distribution for Coastal-Interstate-Asphalt-Low Roadways

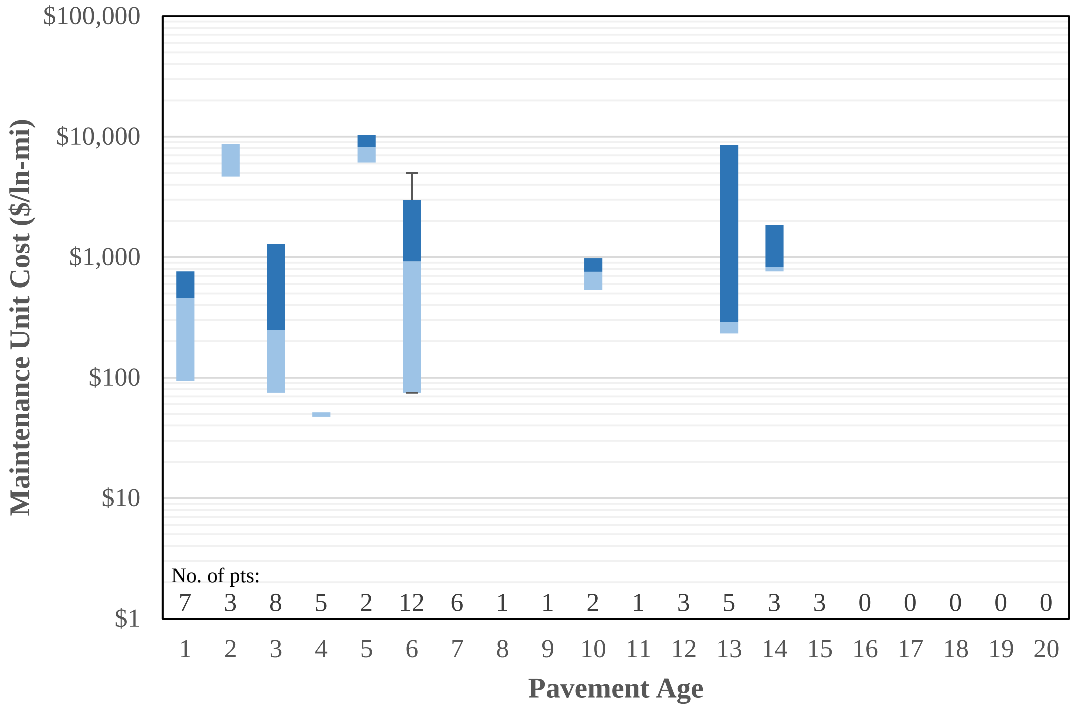

Figure B2: Maintenance Unit Cost Distribution for Coastal-Interstate-Composite-Low Roadways

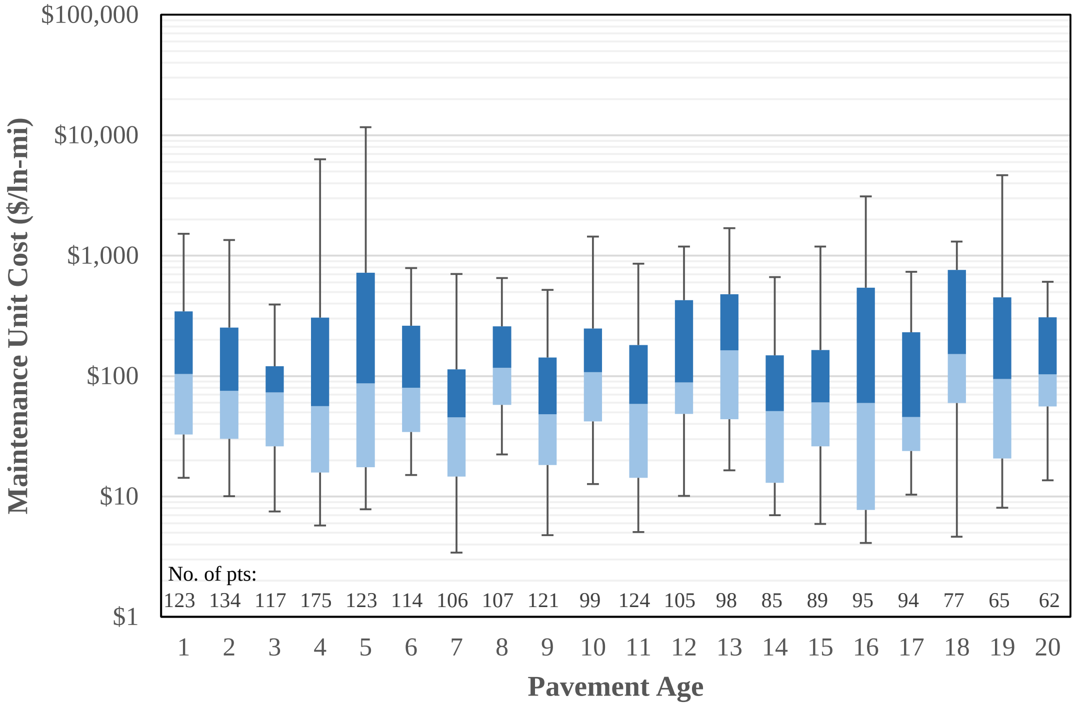

Figure B3: Maintenance Unit Cost Distribution for Coastal-Primary-Asphalt-High Roadways

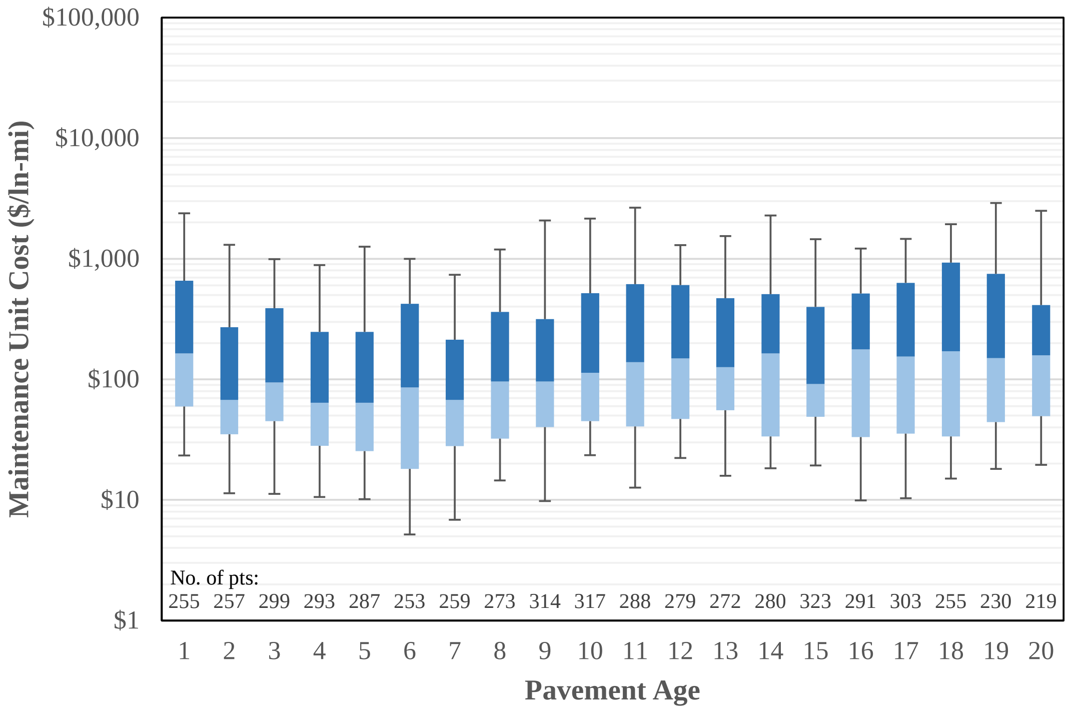

Figure B4: Maintenance Unit Cost Distribution for Coastal-Primary-Asphalt-Low Roadways

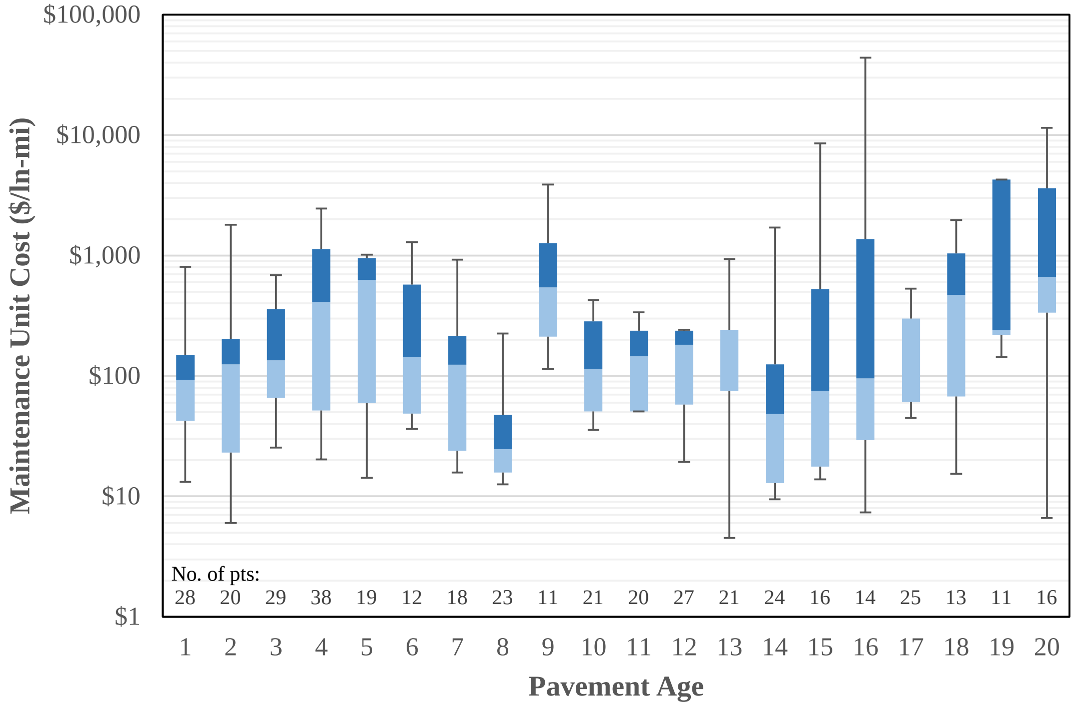

Figure B5: Maintenance Unit Cost Distribution for Coastal-Primary-Composite-High Roadways

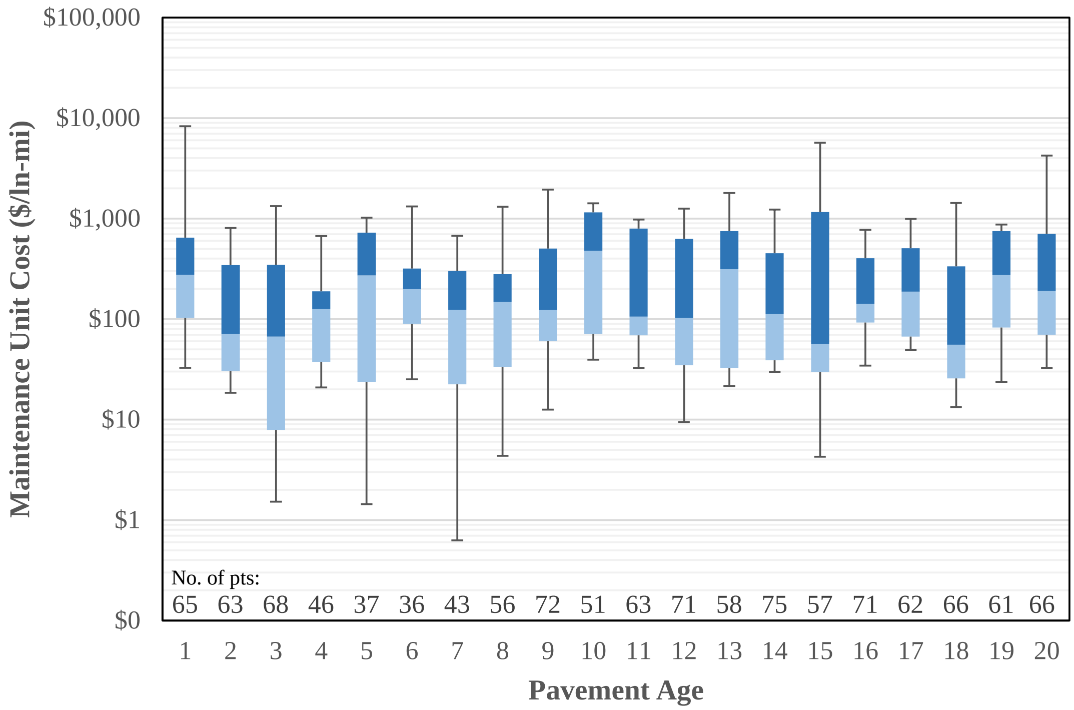

Figure B6: Maintenance Unit Cost Distribution for Coastal-Primary-Composite-Low Roadways

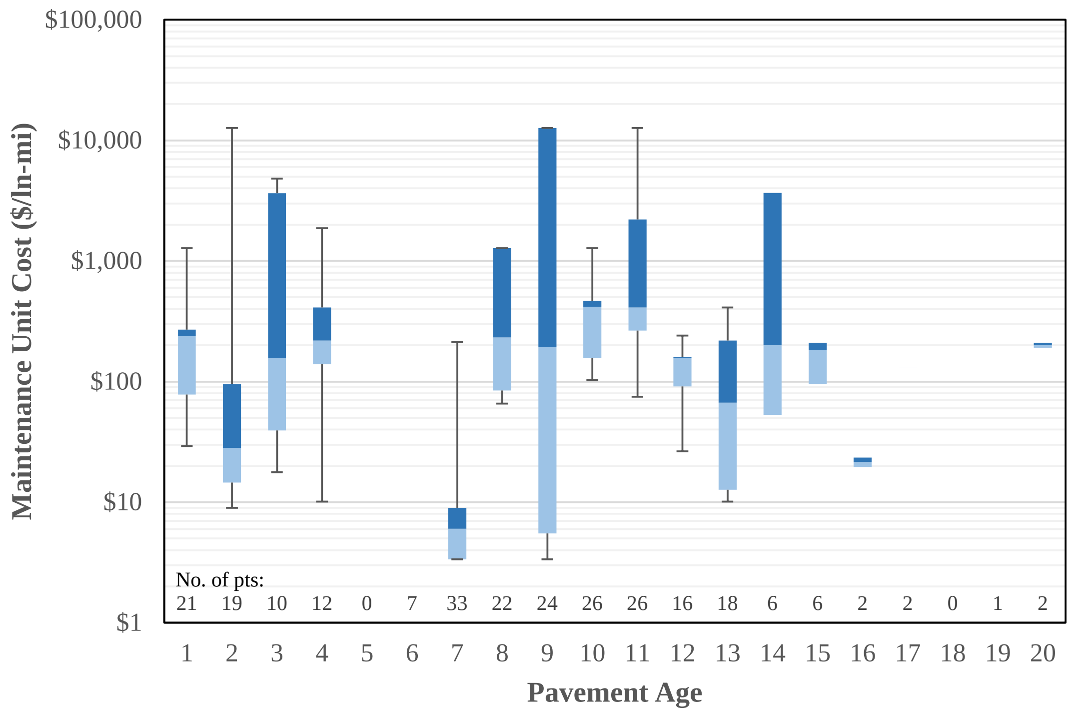

Figure B7: Maintenance Unit Cost Distribution for Mountains-Interstate-Asphalt-Low Roadways

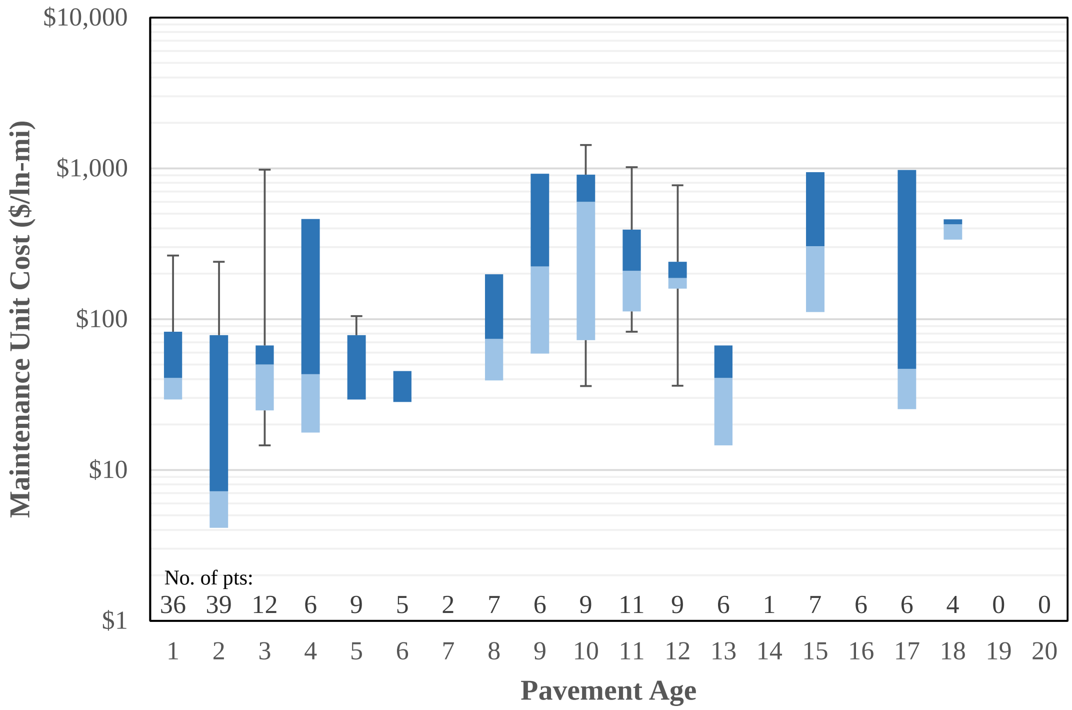

Figure B8: Maintenance Unit Cost Distribution for Mountains-Interstate-Composite-Low Roadways

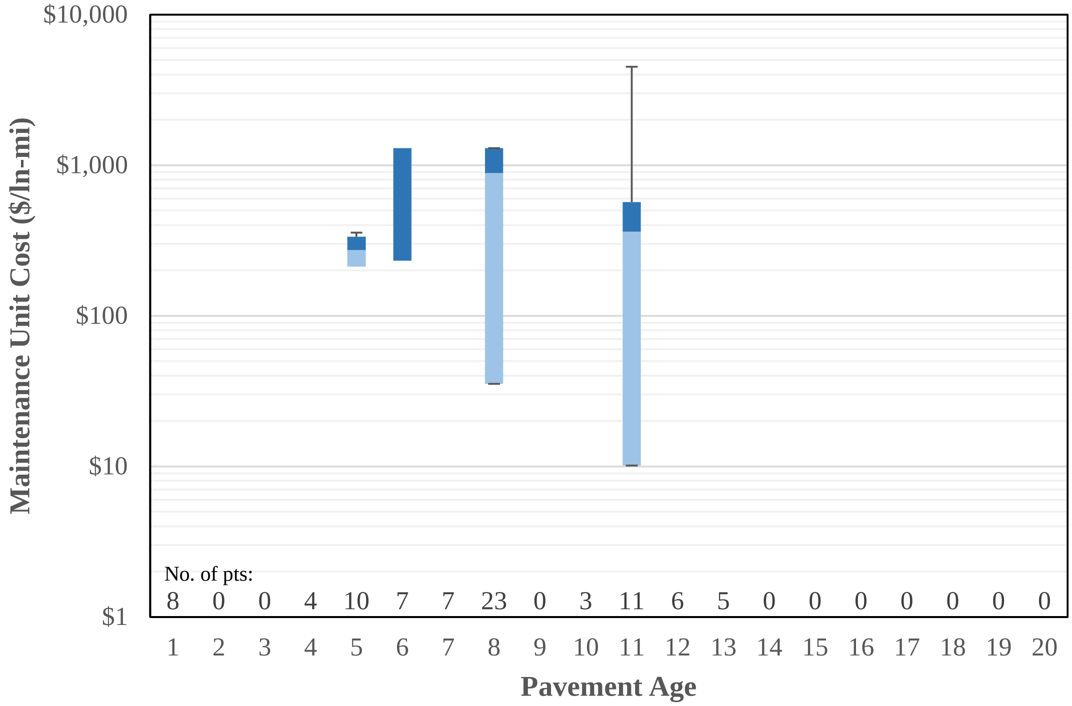

Figure B9: Maintenance Unit Cost Distribution for Mountains-Interstate-Concrete-Low Roadways

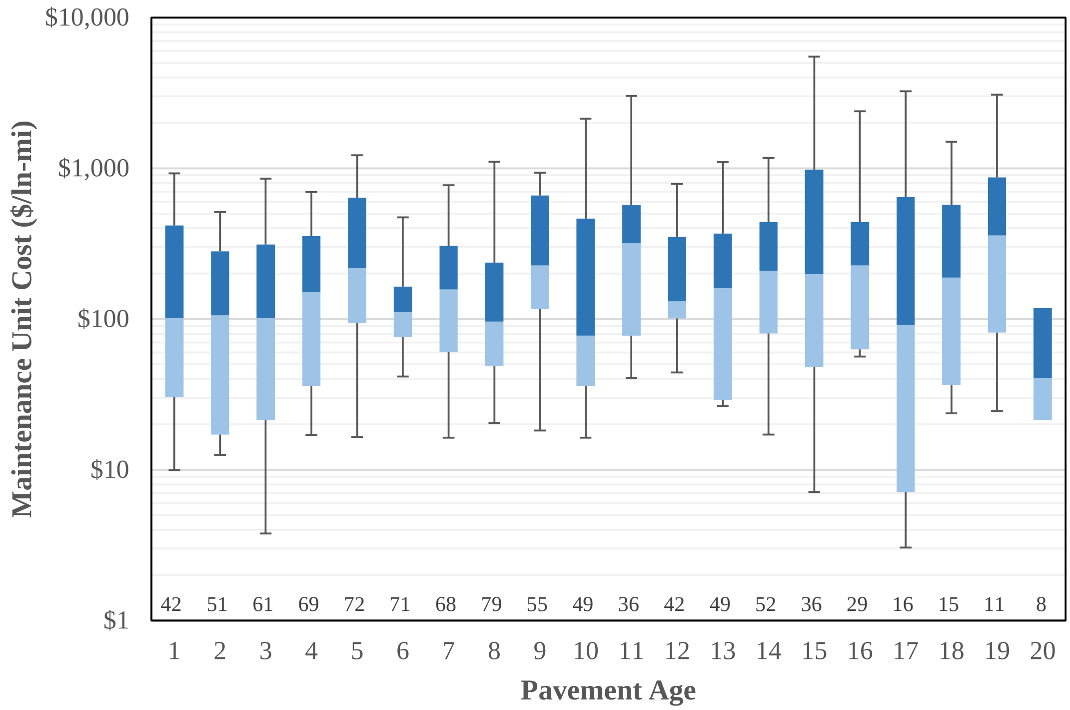

Figure B10: Maintenance Unit Cost Distribution for Mountains-Primary-Asphalt-High Roadways

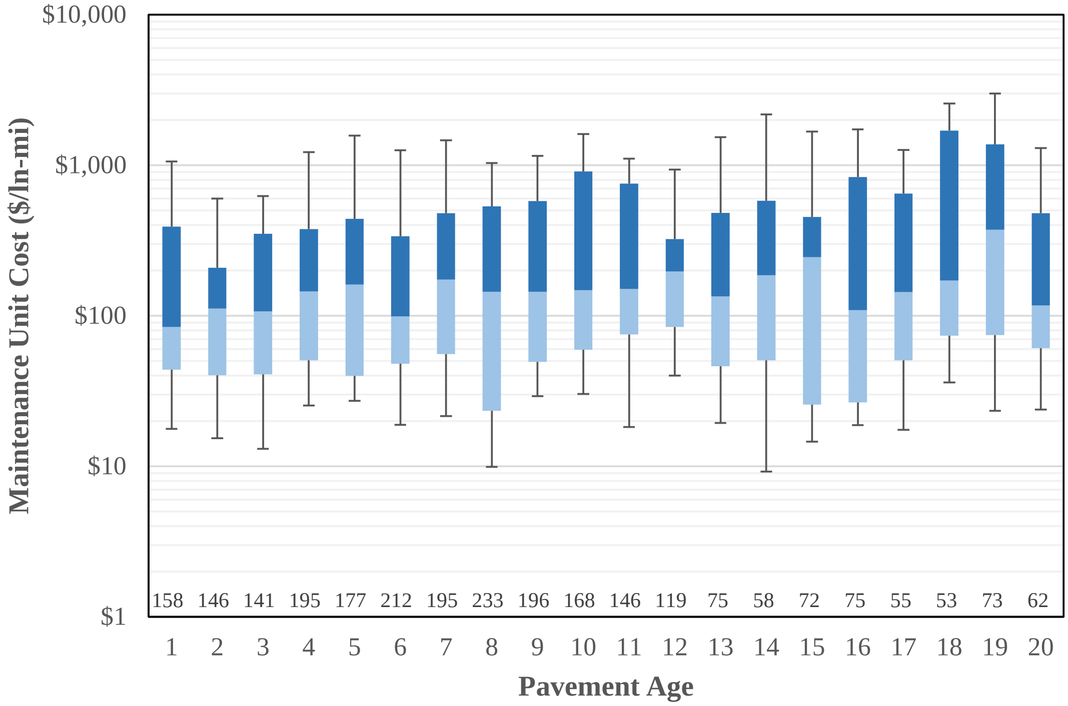

Figure B11: Maintenance Unit Cost Distribution for Mountains-Primary-Asphalt-Low Roadways

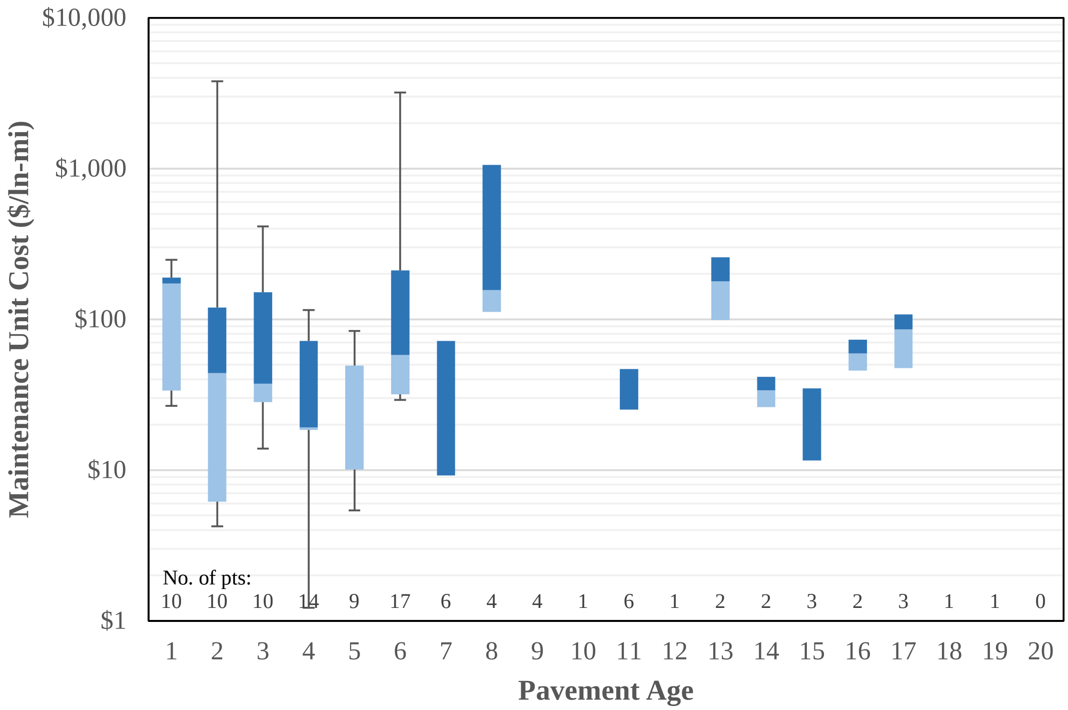

Figure B12: Maintenance Unit Cost Distribution for Mountains-Primary-Composite-High Roadways

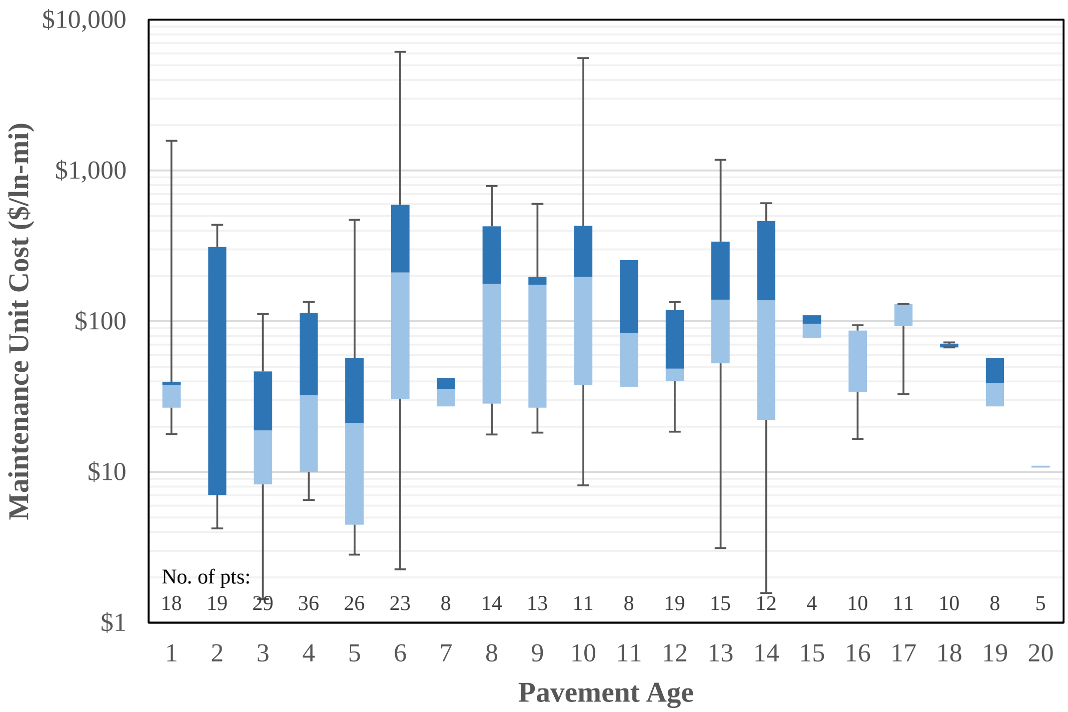

Figure B13: Maintenance Unit Cost Distribution for Mountains-Primary-Composite-Low Roadways

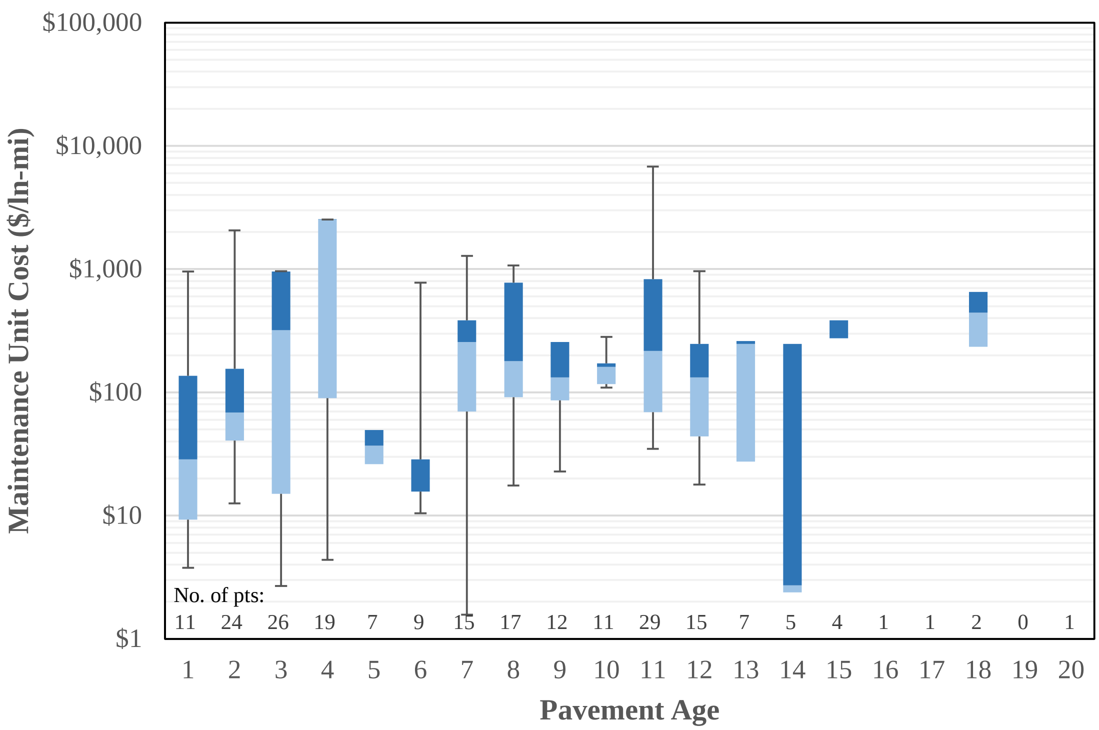

Figure B14: Maintenance Unit Cost Distribution for Piedmont-Interstate-Asphalt-Low Roadways

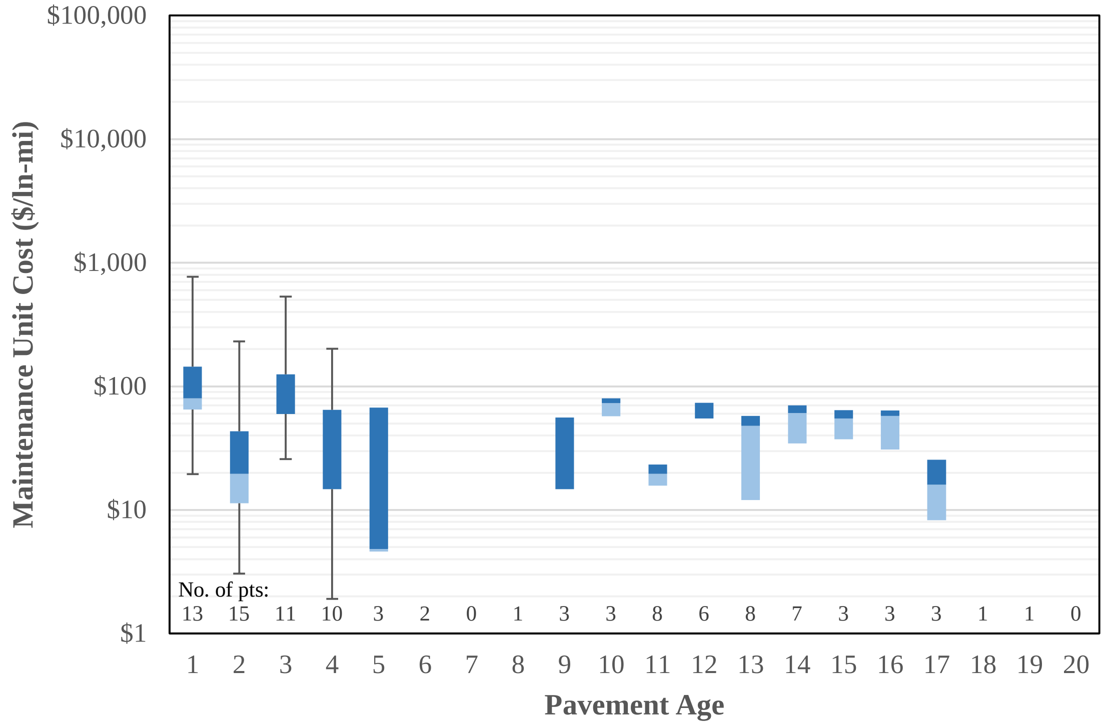

Figure B15: Maintenance Unit Cost Distribution for Piedmont-Interstate-Composite-High Roadways

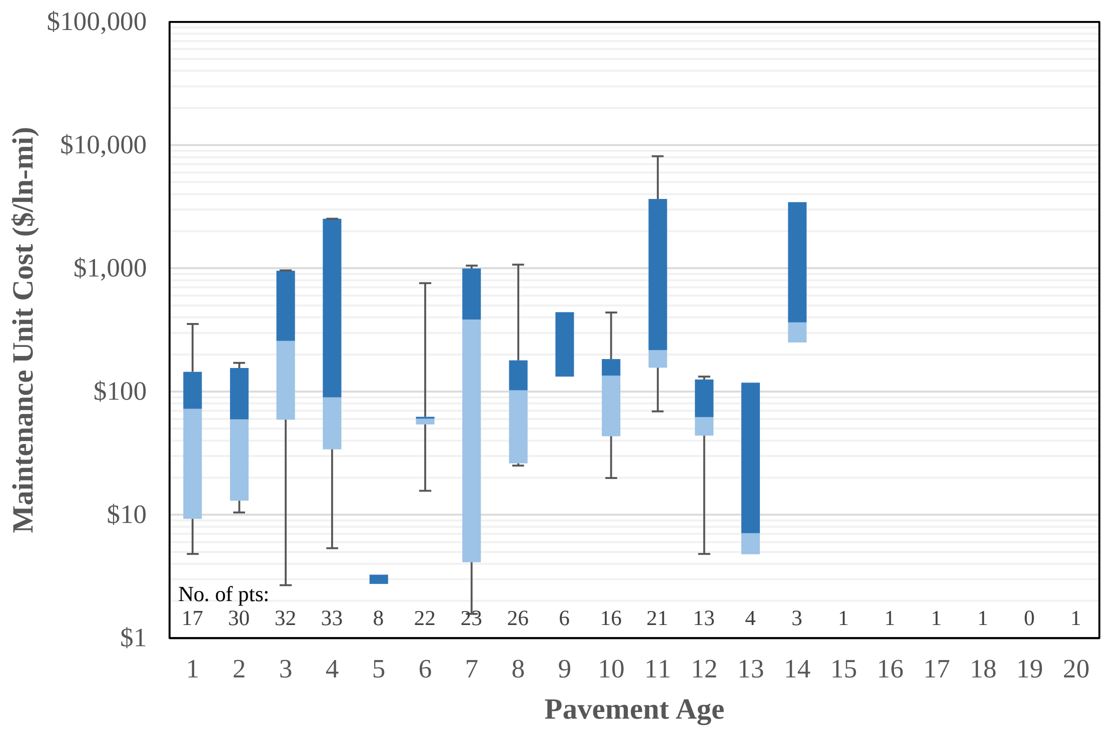

Figure B16: Maintenance Unit Cost Distribution for Piedmont-Interstate-Composite-Low Roadways

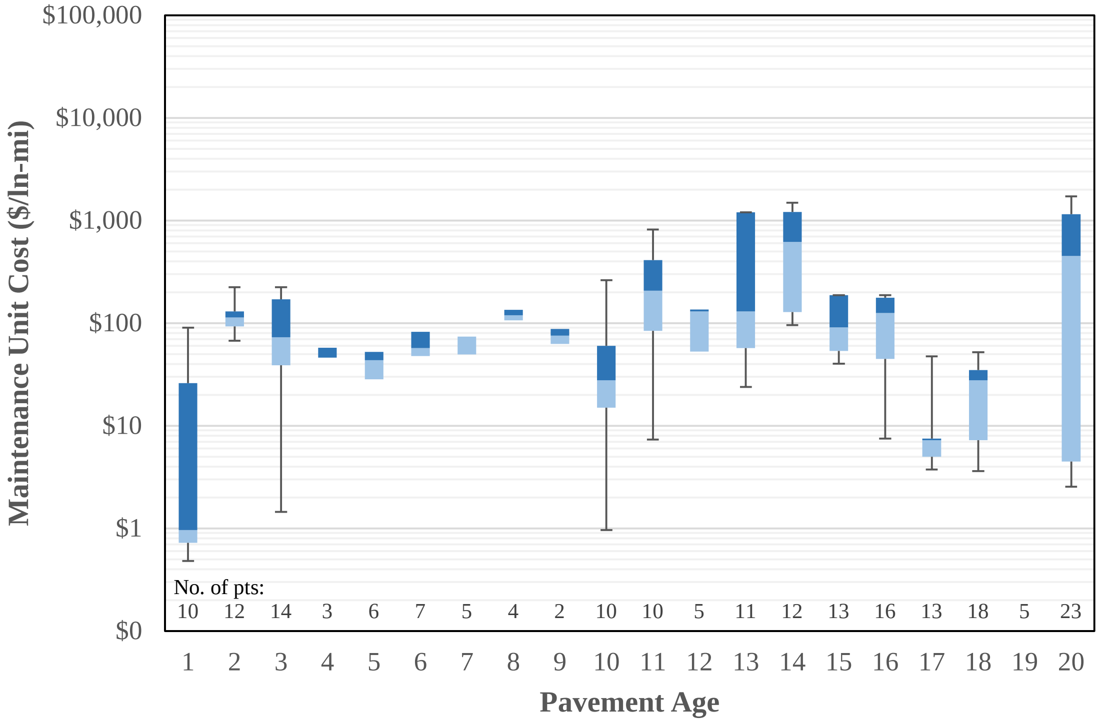

Figure B17: Maintenance Unit Cost Distribution for Piedmont-Interstate-Concrete-High Roadways

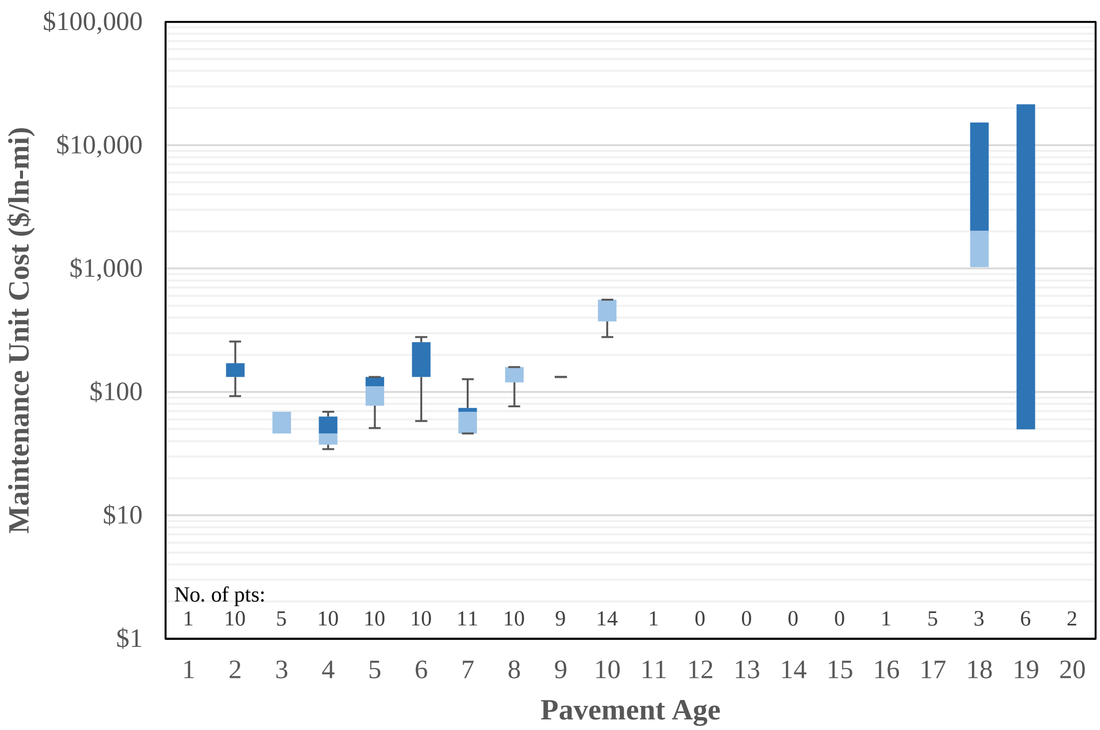

Figure B18: Maintenance Unit Cost Distribution for Piedmont-Interstate-Concrete-Low Roadways

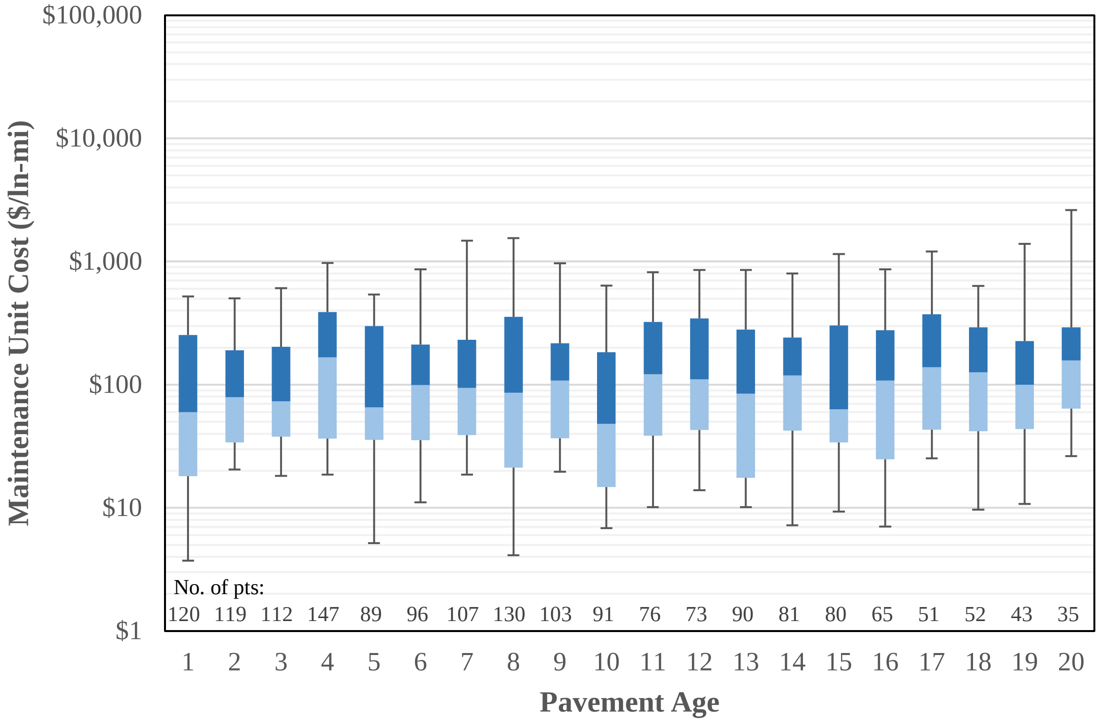

Figure B19: Maintenance Unit Cost Distribution for Piedmont-Primary-Asphalt-High Roadways

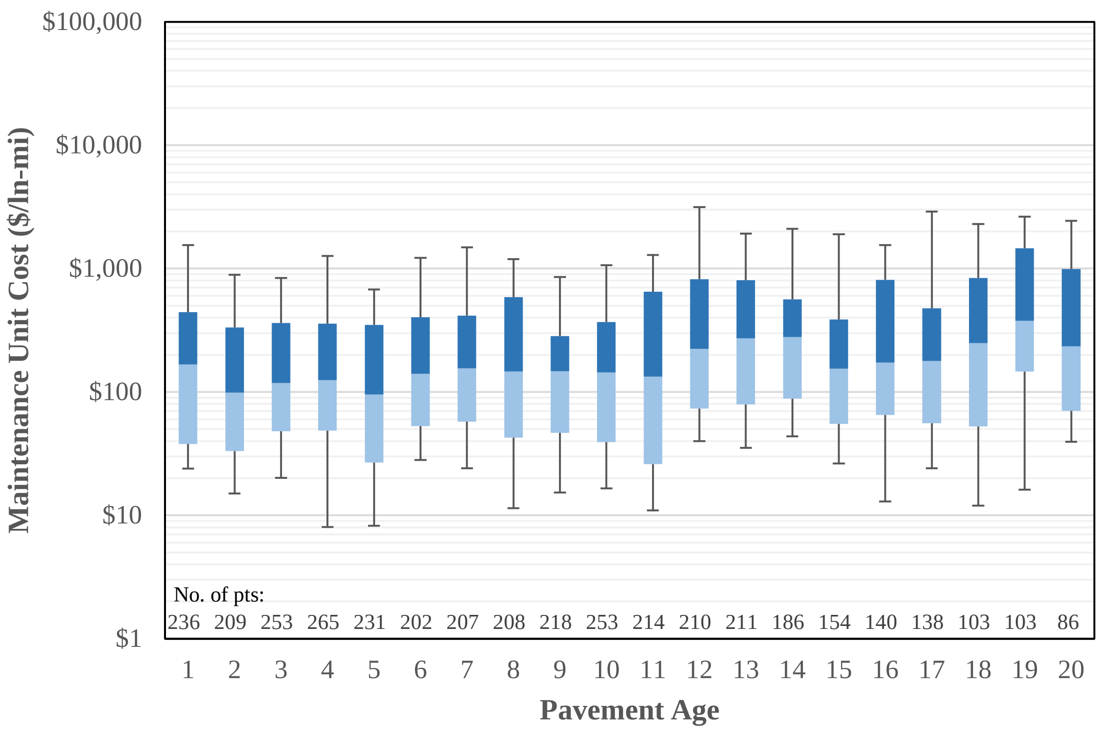

Figure B20: Maintenance Unit Cost Distribution for Piedmont-Primary-Asphalt-Low Roadways

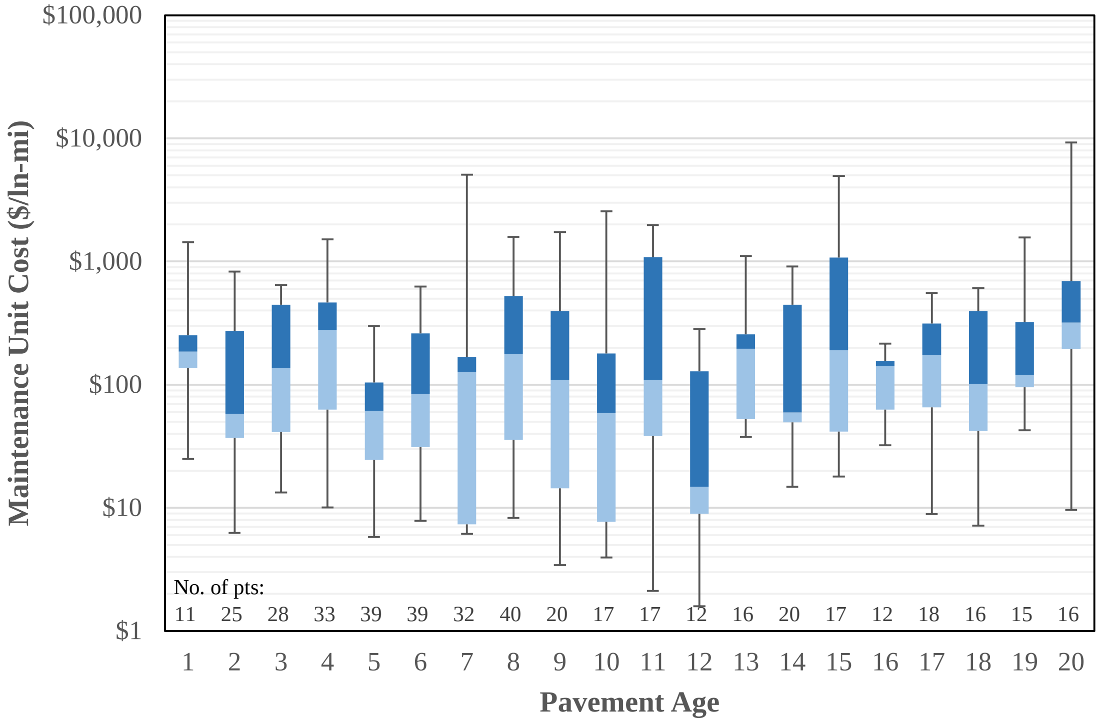

Figure B21: Maintenance Unit Cost Distribution for Piedmont-Primary-Composite-High Roadways

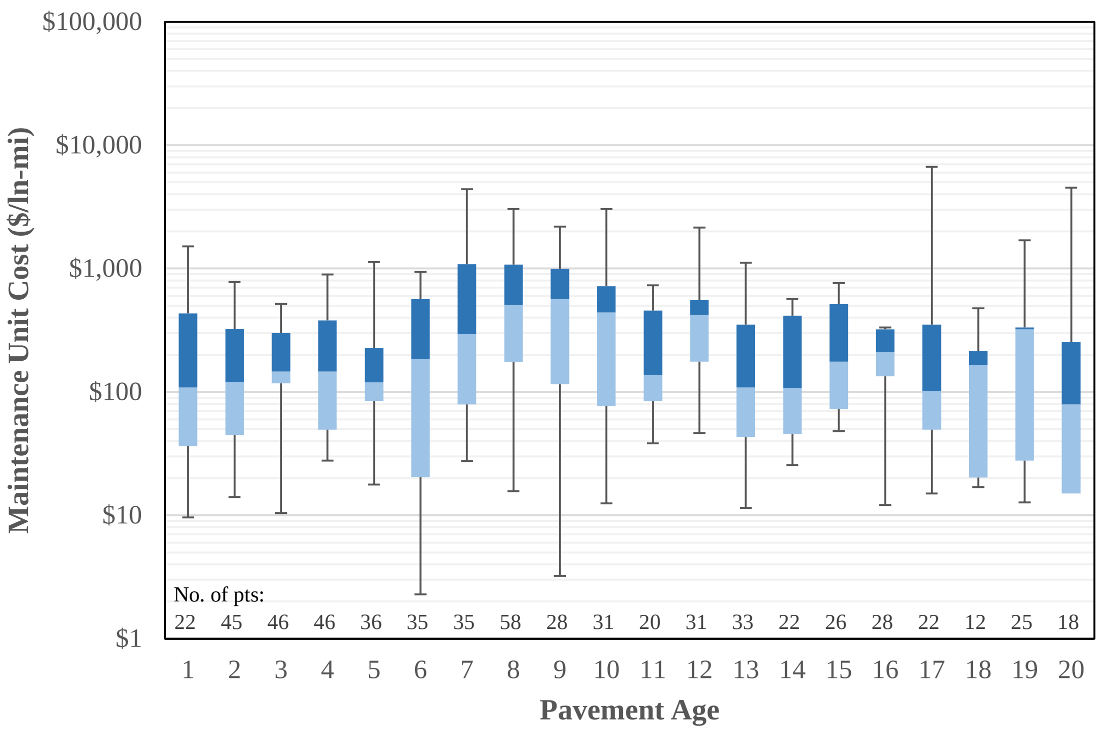

Figure B22: Maintenance Unit Cost Distribution for Piedmont-Primary-Composite-Low Roadways

APPENDIX C – SIMULATED COST STREAMS OF MAINTENANCE UNIT COST FROM COMPREHENSIVE DATA

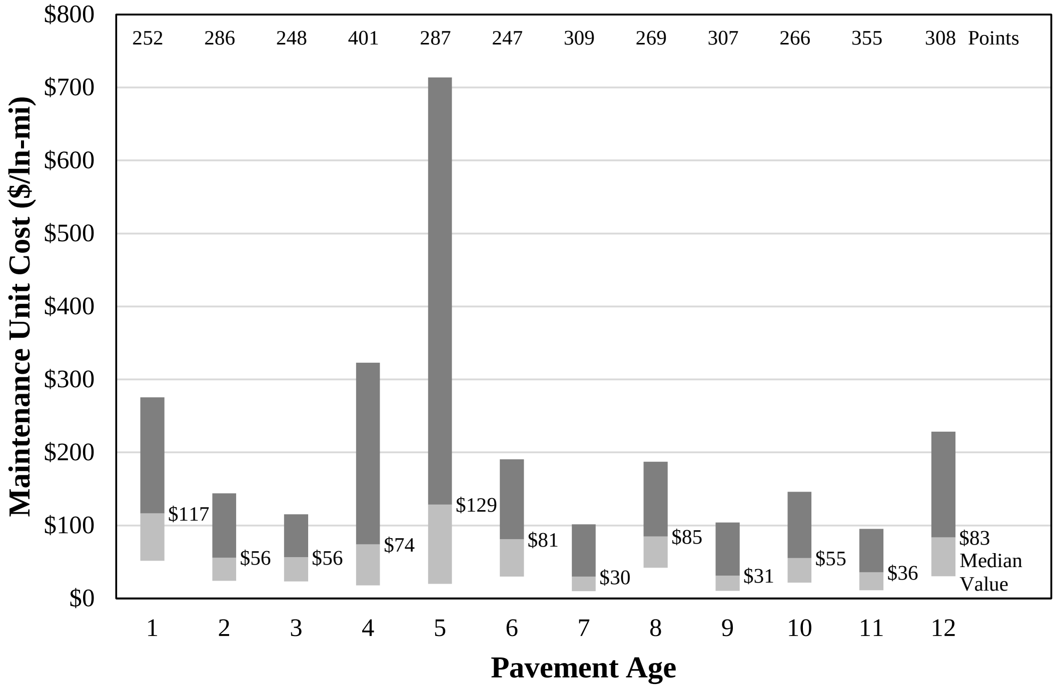

Figure C1: Present Value of Annual Maintenance Unit Cost Stream for Coastal-Primary-Asphalt-High Roadways

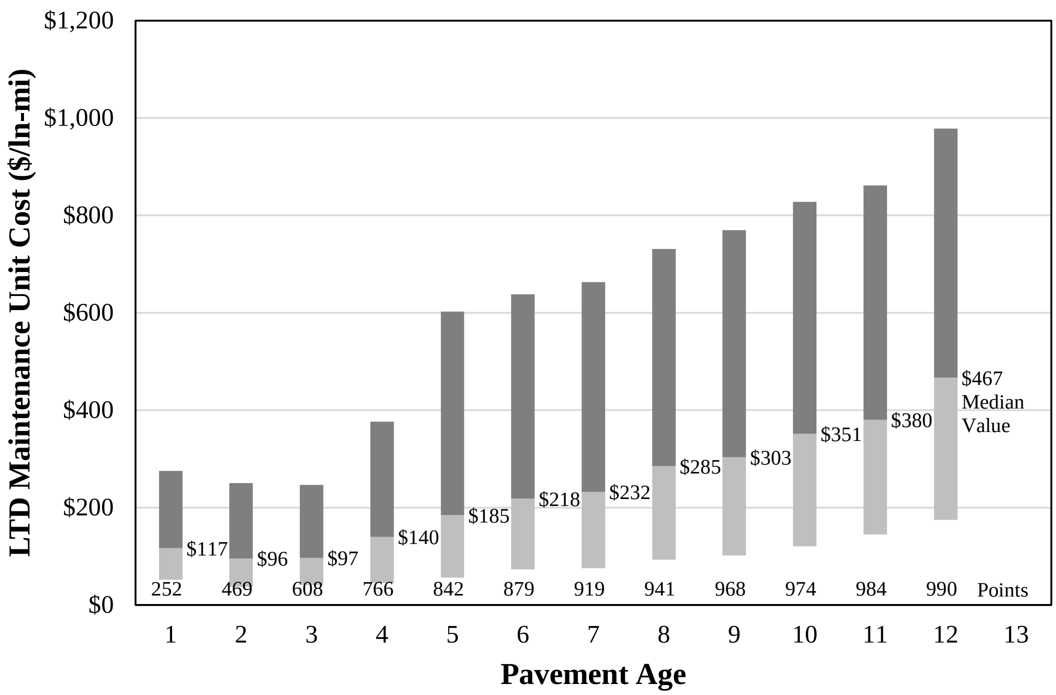

Figure C2: Present Value of Life-to-Date Maintenance Unit Cost Stream for Coastal-Primary-Asphalt-High Roadways

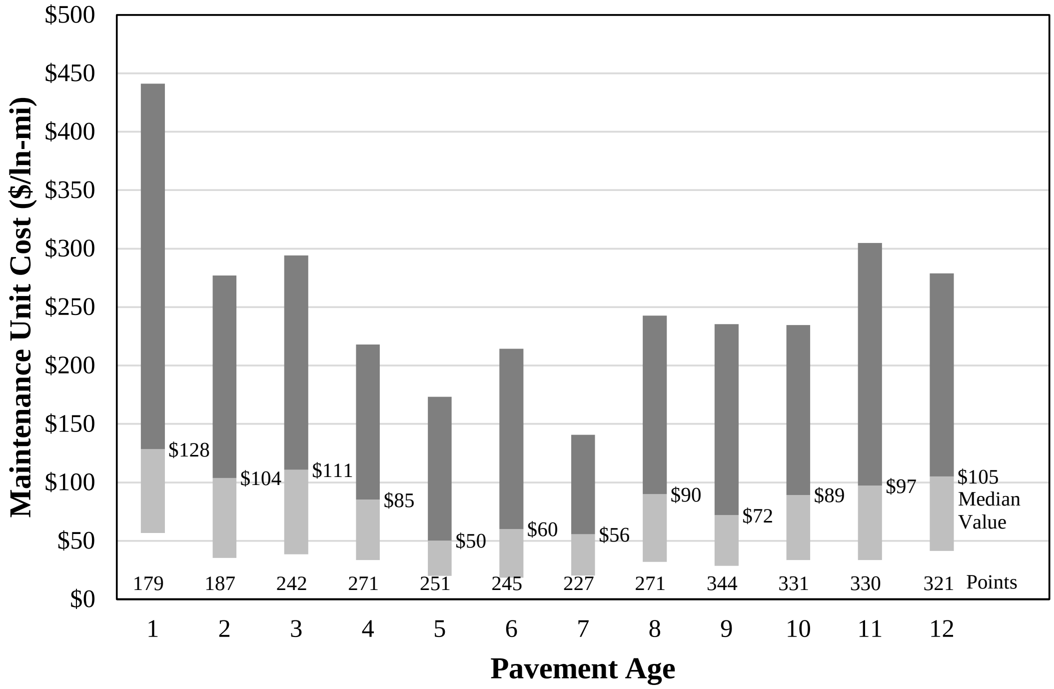

Figure C3: Present Value of Annual Maintenance Unit Cost Stream for Coastal-Primary-Asphalt-Low Roadways

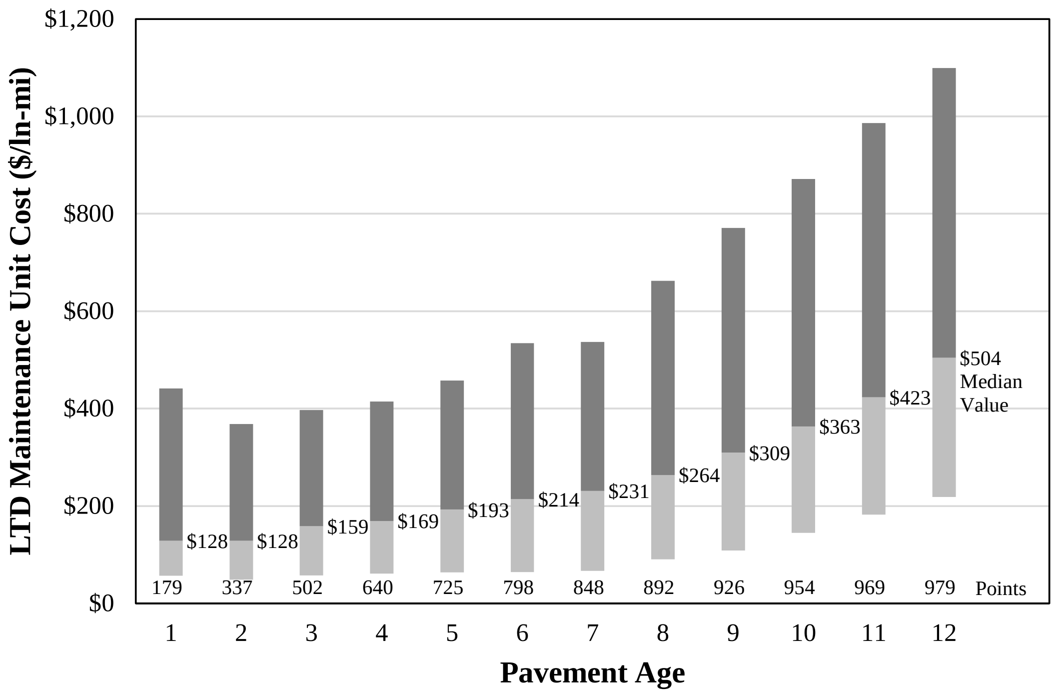

Figure C4: Present Value of Life-to-Date Maintenance Unit Cost Stream for Coastal-Primary-Asphalt-Low Roadways

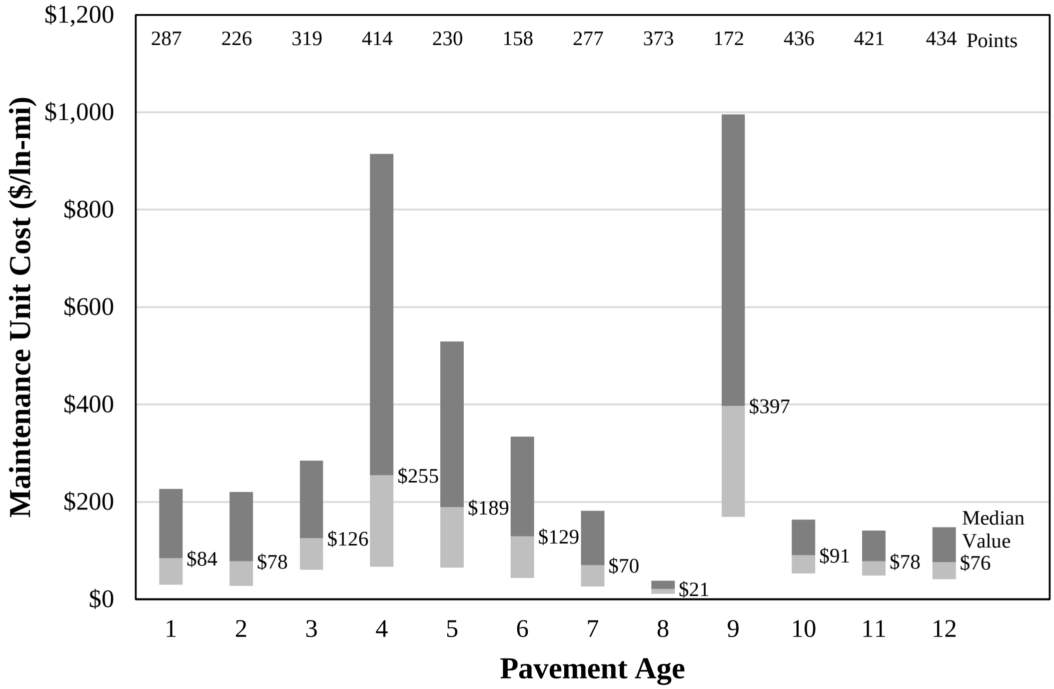

Figure C5: Present Value of Annual Maintenance Unit Cost Stream for Coastal-Primary-Composite-High Roadways

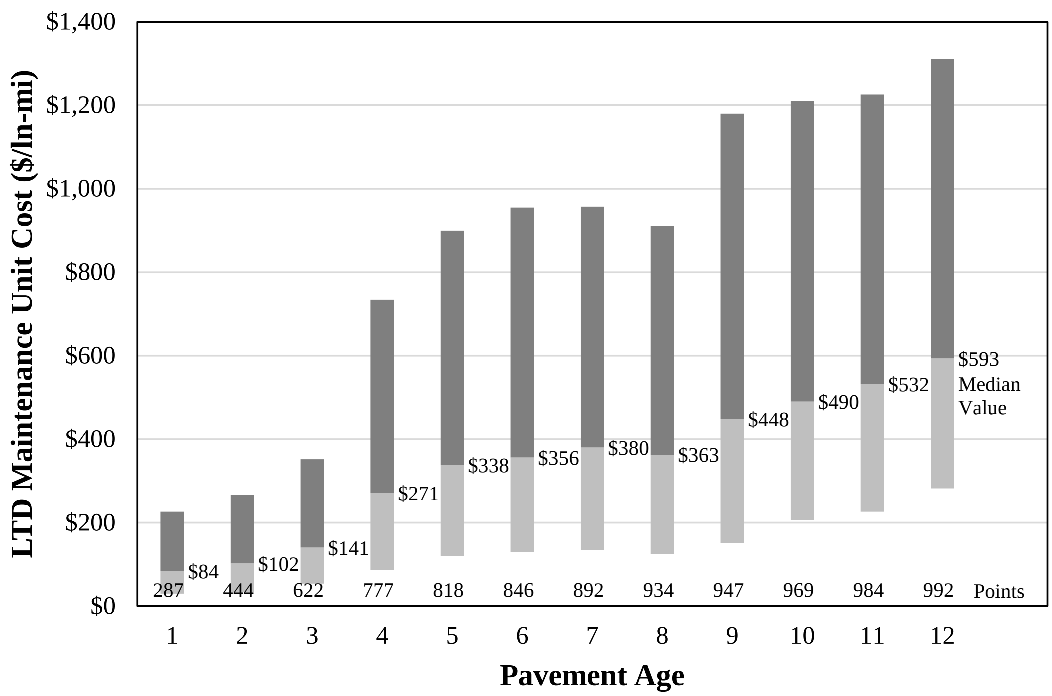

Figure C6: Present Value of Life-to-Date Maintenance Unit Cost Stream for Coastal-Primary-Composite-High Roadways

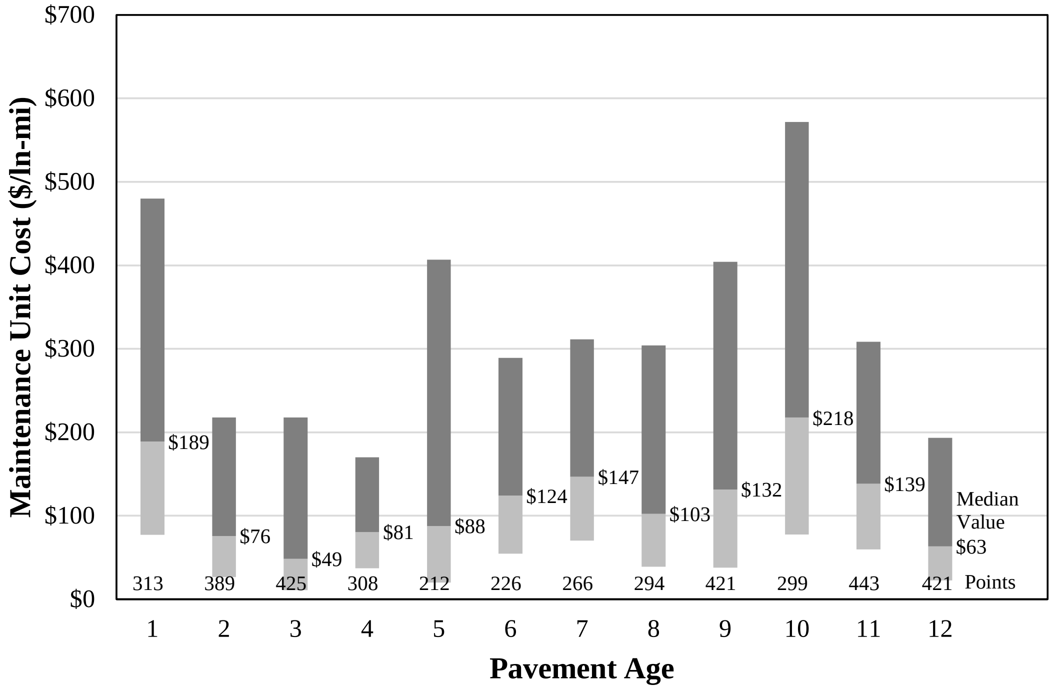

Figure C7: Present Value of Annual Maintenance Unit Cost Stream for Coastal-Primary-Composite-Low Roadways

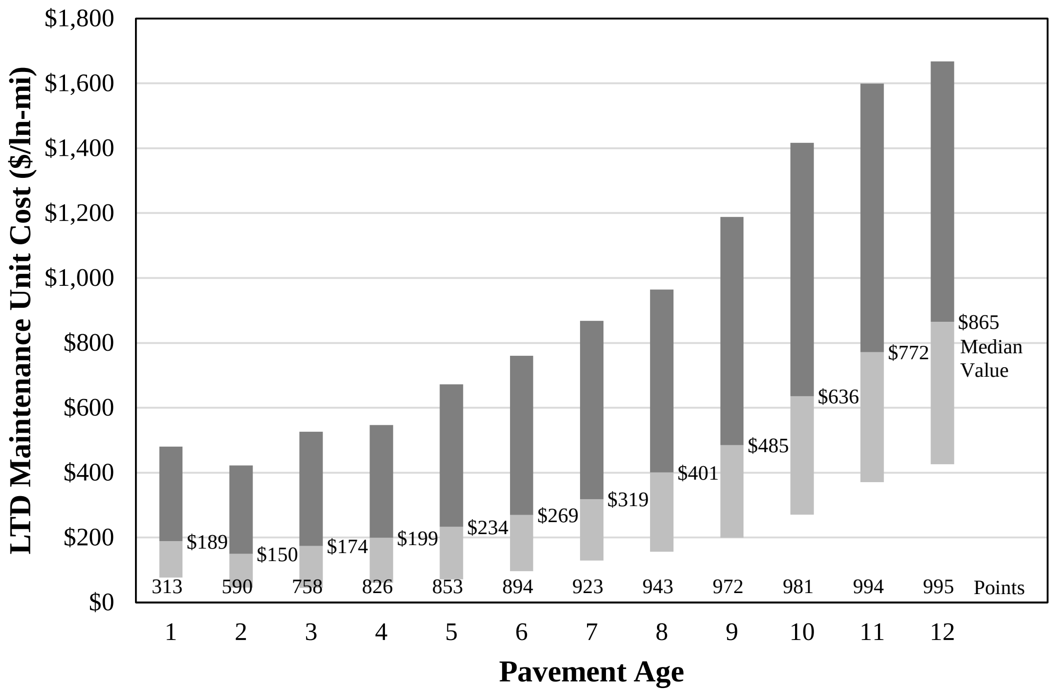

Figure C8: Present Value of Life-to-Date Maintenance Unit Cost Stream for Coastal-Primary-Composite-Low Roadways

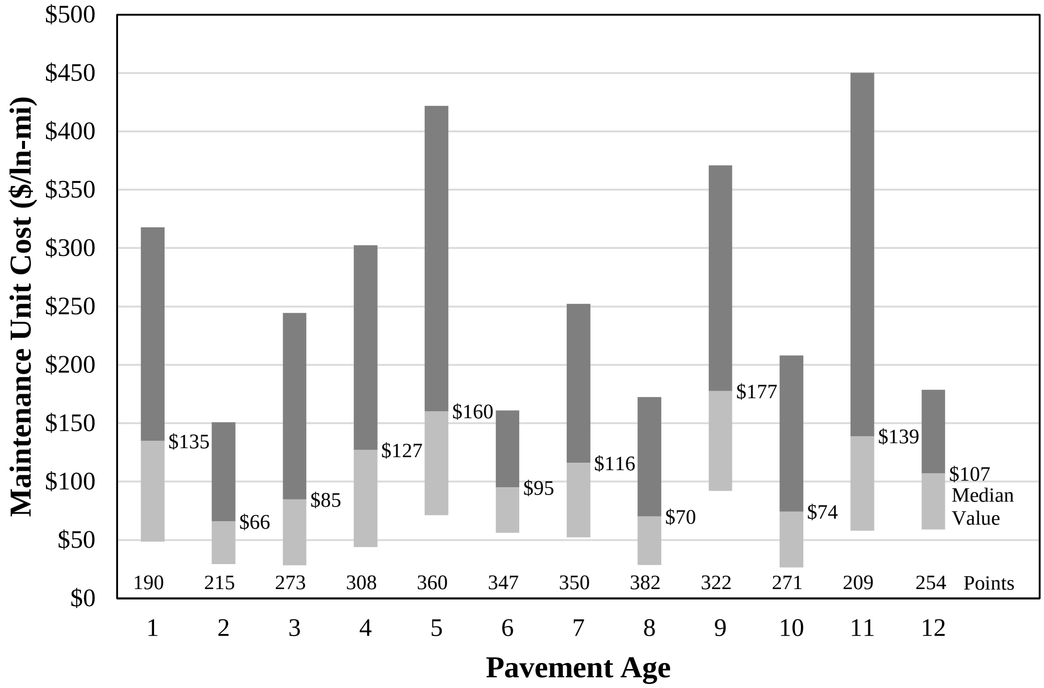

Figure C9: Present Value of Annual Maintenance Unit Cost Stream for Mountain-PrimaryAsphalt-High Roadways

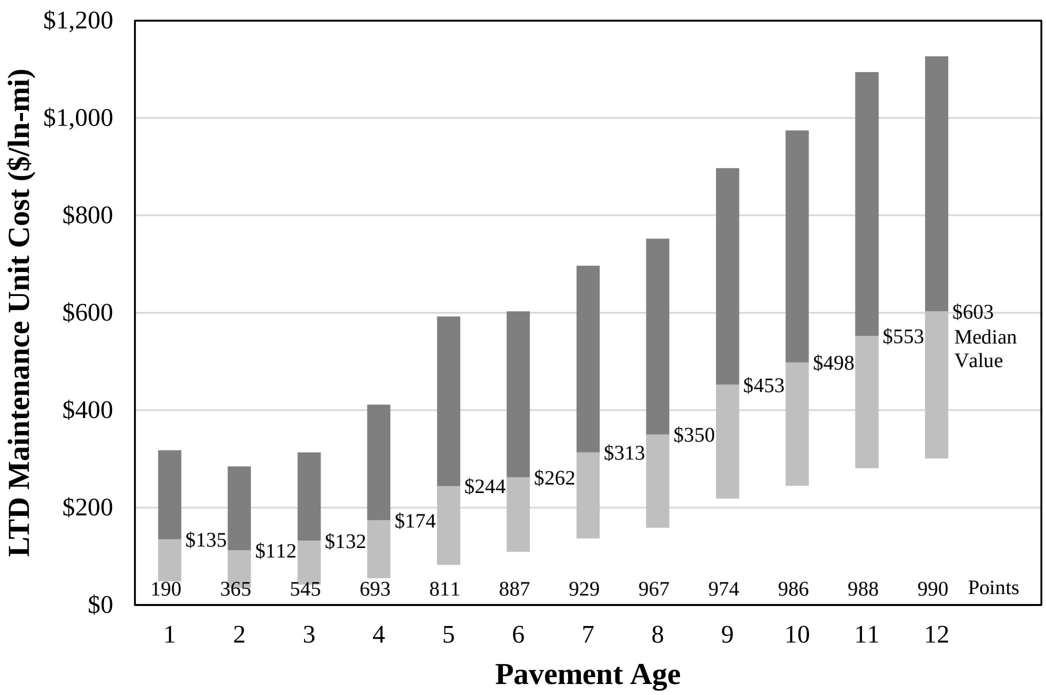

Figure C10: Present Value of Life-to-Date Maintenance Unit Cost Stream for Mountain-Primary Asphalt-High Roadways

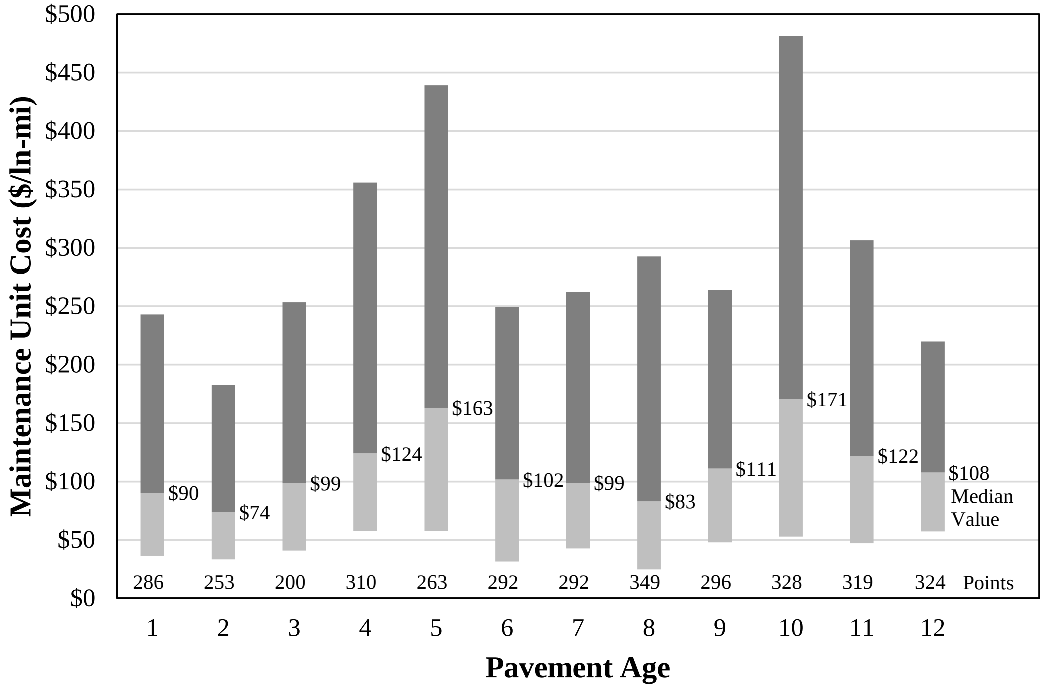

Figure C11: Present Value of Annual Maintenance Unit Cost Stream for Mountain-Primary-Asphalt-Low Roadways

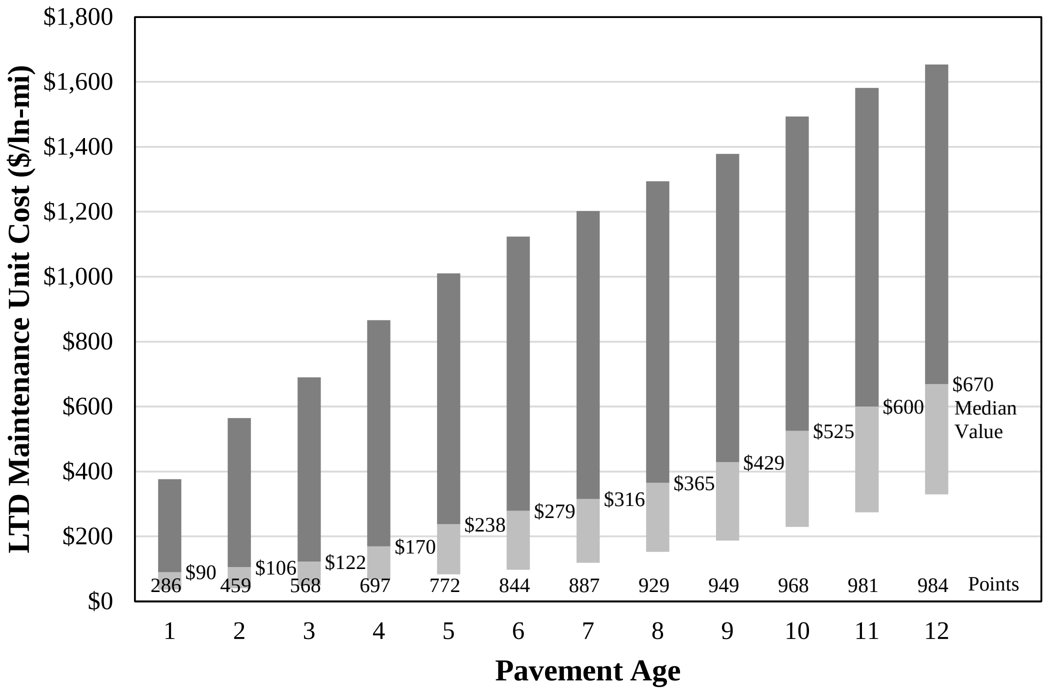

Figure C12: Present Value of Life-to-Date Maintenance Unit Cost Stream for Mountain-Primary-Asphalt-Low Roadways

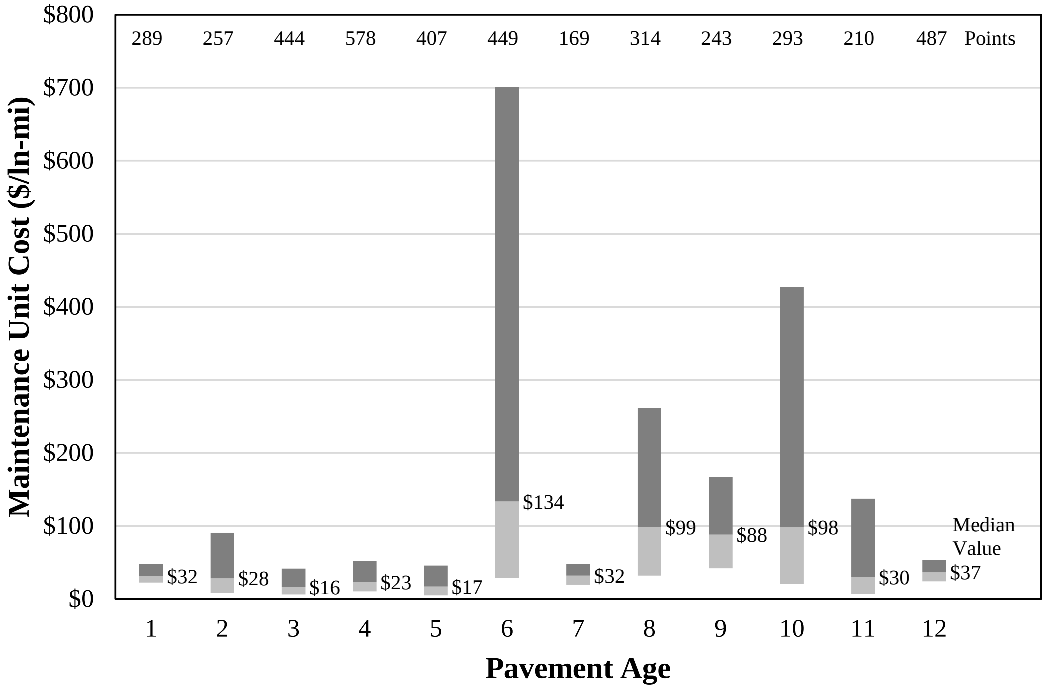

Figure C13: Present Value of Annual Maintenance Unit Cost Stream for Mountain-Primary-Composite-Low Roadways

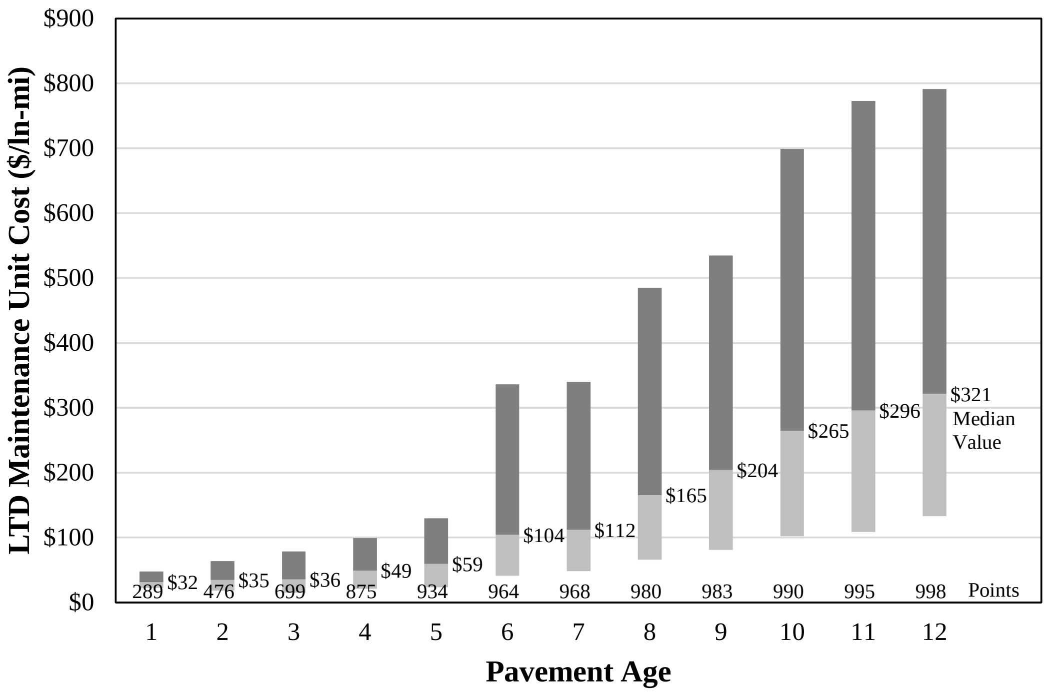

Figure C14: Present Value of Life-to-Date Maintenance Unit Cost Stream for Mountain-Primary-Composite-Low Roadways

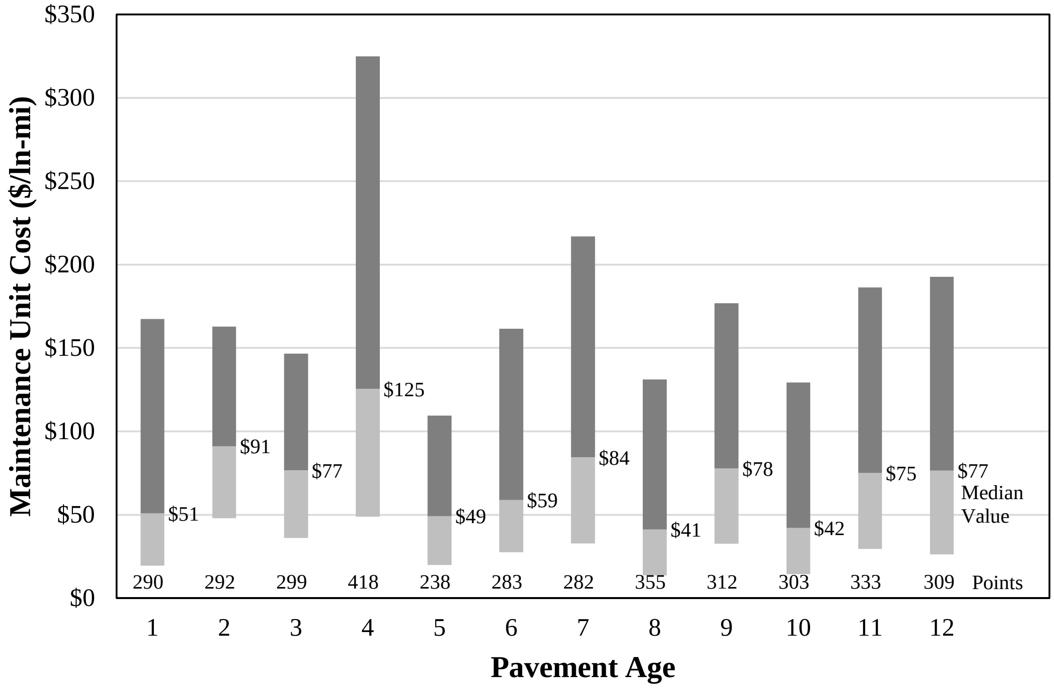

Figure C15: Present Value of Annual Maintenance Unit Cost Stream for Piedmont-Primary-Asphalt-High Roadways

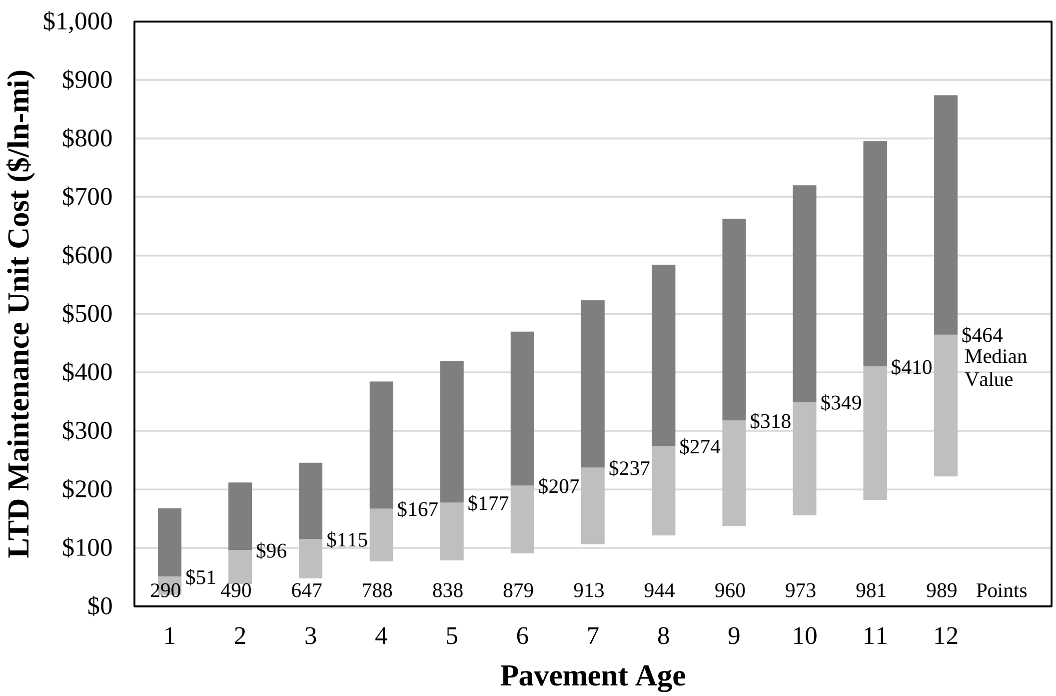

Figure C16: Present Value of Life-to-Date Maintenance Unit Cost Stream for Piedmont-Primary-Asphalt-High Roadways

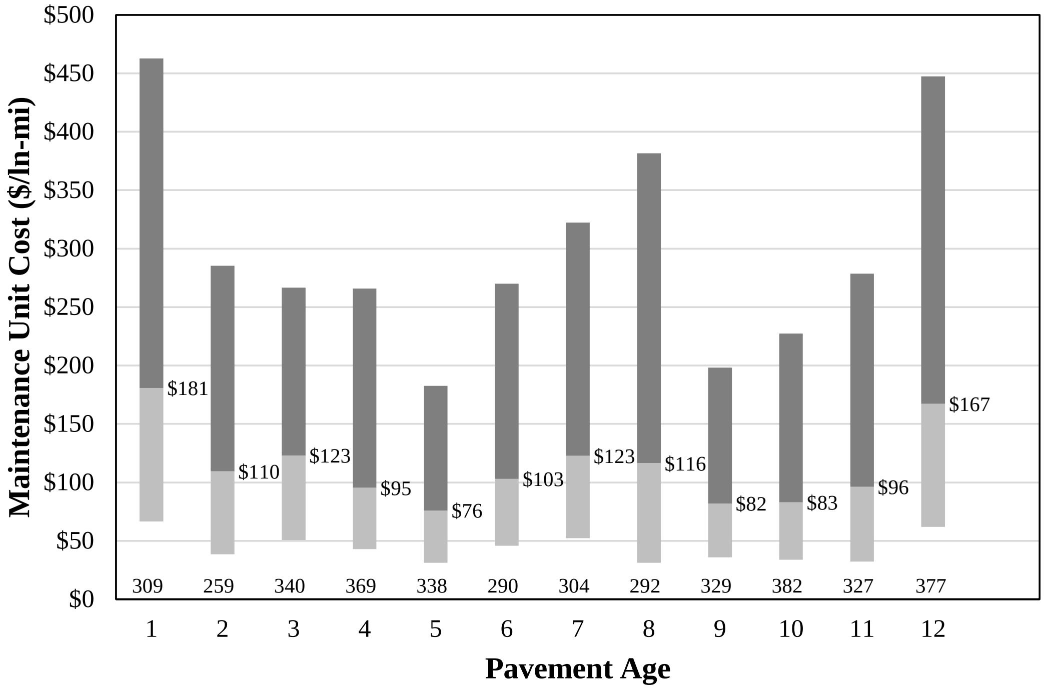

Figure C17: Present Value of Annual Maintenance Unit Cost Stream for Piedmont-Primary-Asphalt-Low Roadways

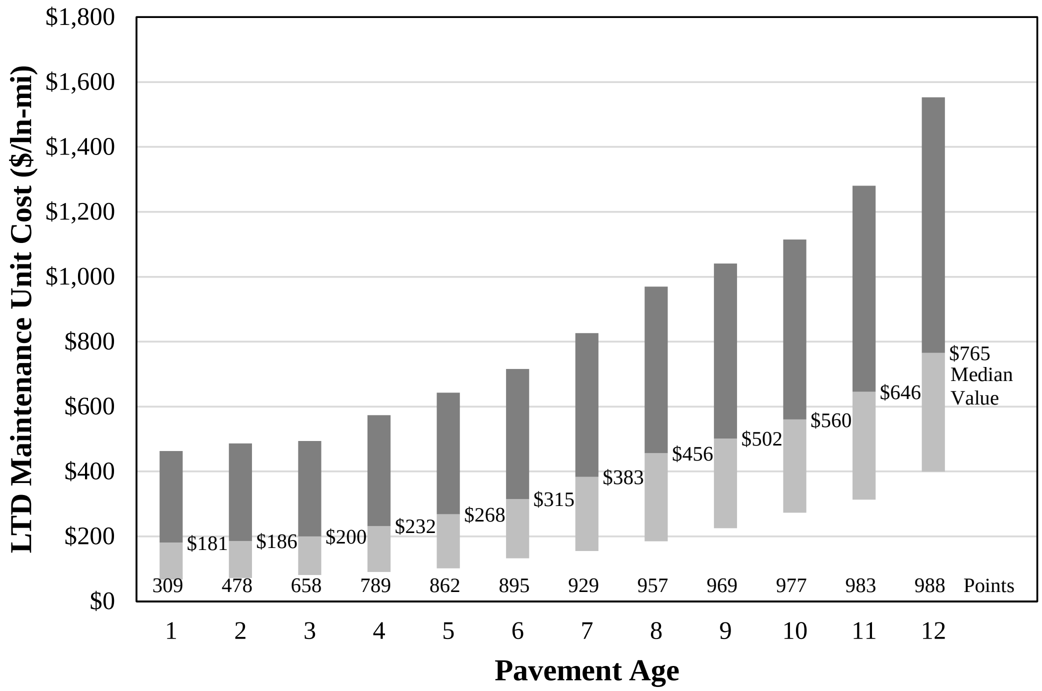

Figure C18: Present Value of Life-to-Date Maintenance Unit Cost Stream for Piedmont-Primary-Asphalt-Low Roadways

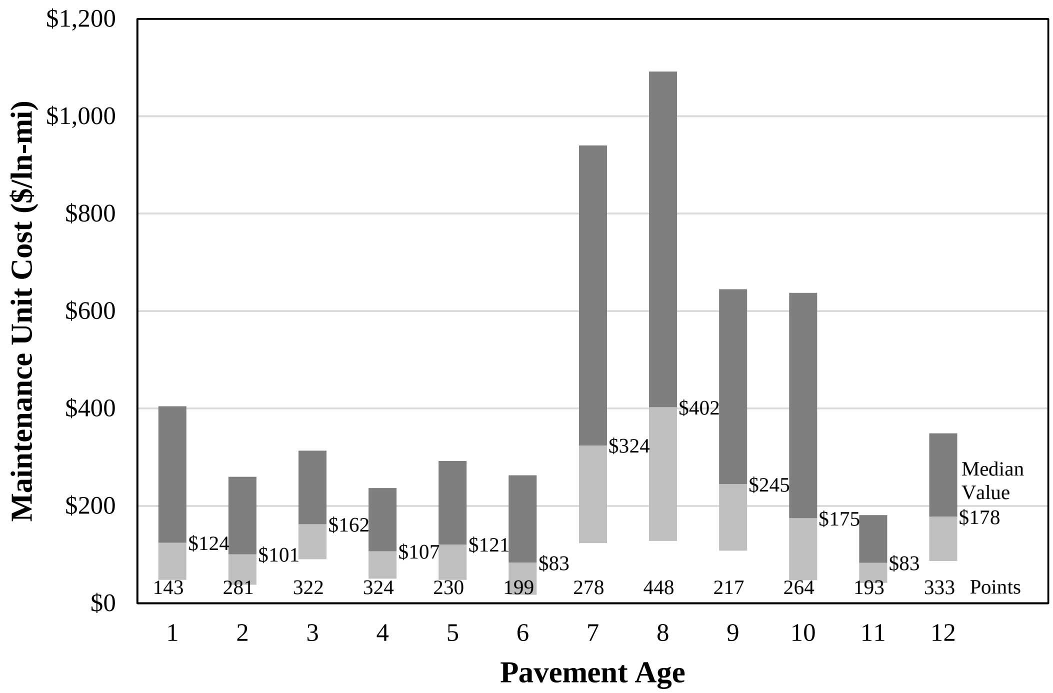

Figure C19: Present Value of Annual Maintenance Unit Cost Stream for Piedmont-Primary-Composite-Low Roadways

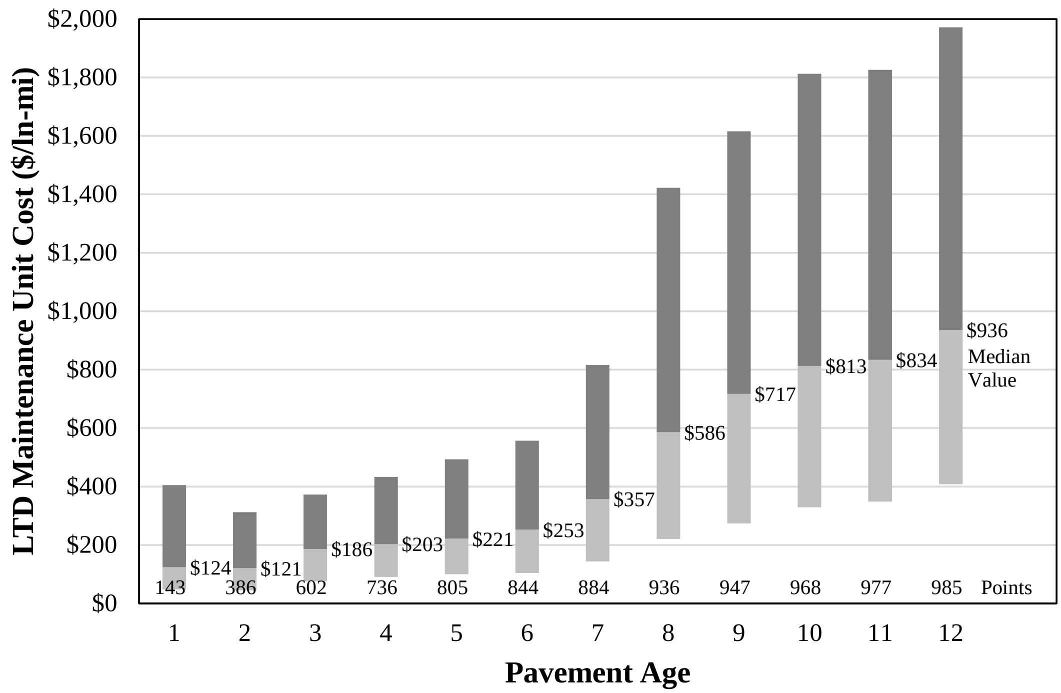

Figure C20: Present Value of Life-to-Date Maintenance Unit Cost Stream for Piedmont-Primary-Composite-Low Roadways