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16. ABSTRACT

This research examines the vehicle equipment replacement decision-making methodologies available to the California Department of Transportation (Caltrans) and other agencies with similar vehicle fleet operations. The goal of these methodologies is to optimize the replacement timing of aging vehicle equipment in a way that minimize total costs while maintaining certain fleet characteristics such as fleet preparedness. This report presents the information and findings gathered during the conduct of this research. These include an overview and discussion of key factors that drive the decision on vehicle equipment replacement and various Fleet Replacement Methods (FRM) utilized by Caltrans and other state Departments of Transportation (DOTs). Also, methodological aspects of several FRMs in three different FRM categories are compared and summarized.

To determine which vehicle equipment to be replaced, at the time of this reporting, Caltrans' Division of Equipment (DOE) is using a method based on a set of criteria referred to as Vehicles Meets Criteria (VMC). VMC consider equipment age, usage, and repair costs to identify candidate vehicle equipment for replacement. The percentage of the pre-defined standard for each criteria is calculated for each piece of equipment and equipment is placed into groups with varying levels of replacement priority. Equipment with higher priority are preferred candidates for replacement.


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UCR | College of Engineering- Center for Environmental Research & Technology

# Fleet Replacement Method: Evaluation and Refinement

## FINAL REPORT

**Prepared for:**

**Caltrans Division of Equipment**

**By:**

*College of Engineering – Center for Environmental Research and Technology*
*University of California at Riverside*

**April 2017**

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# Executive Summary

This research examines the vehicle equipment replacement decision-making methodologies available to the California Department of Transportation (Caltrans) and other agencies with similar vehicle fleet operations. The goal of these methodologies is to optimize the replacement timing of aging vehicle equipment in a way that minimize total costs while maintaining certain fleet characteristics such as fleet preparedness. This report presents the information and findings gathered during the conduct of this research. These include an overview and discussion of key factors that drive the decision on vehicle equipment replacement and various Fleet Replacement Methods (FRM) utilized by Caltrans and other state Departments of Transportation (DOTs). Also, methodological aspects of several FRMs in three different FRM categories are compared and summarized.

To determine which vehicle equipment to be replaced, at the time of this reporting, Caltrans' Division of Equipment (DOE) is using a method based on a set of criteria referred to as Vehicles Meets Criteria (VMC). VMC consider equipment age, usage, and repair costs to identify candidate vehicle equipment for replacement. The percentage of the pre-defined standard for each criteria is calculated for each piece of equipment and equipment is placed into groups with varying levels of replacement priority. Equipment with higher priority are preferred candidates for replacement. Figure ES-1 shows the relationship between repair cost, age, usage and priority for replacement.

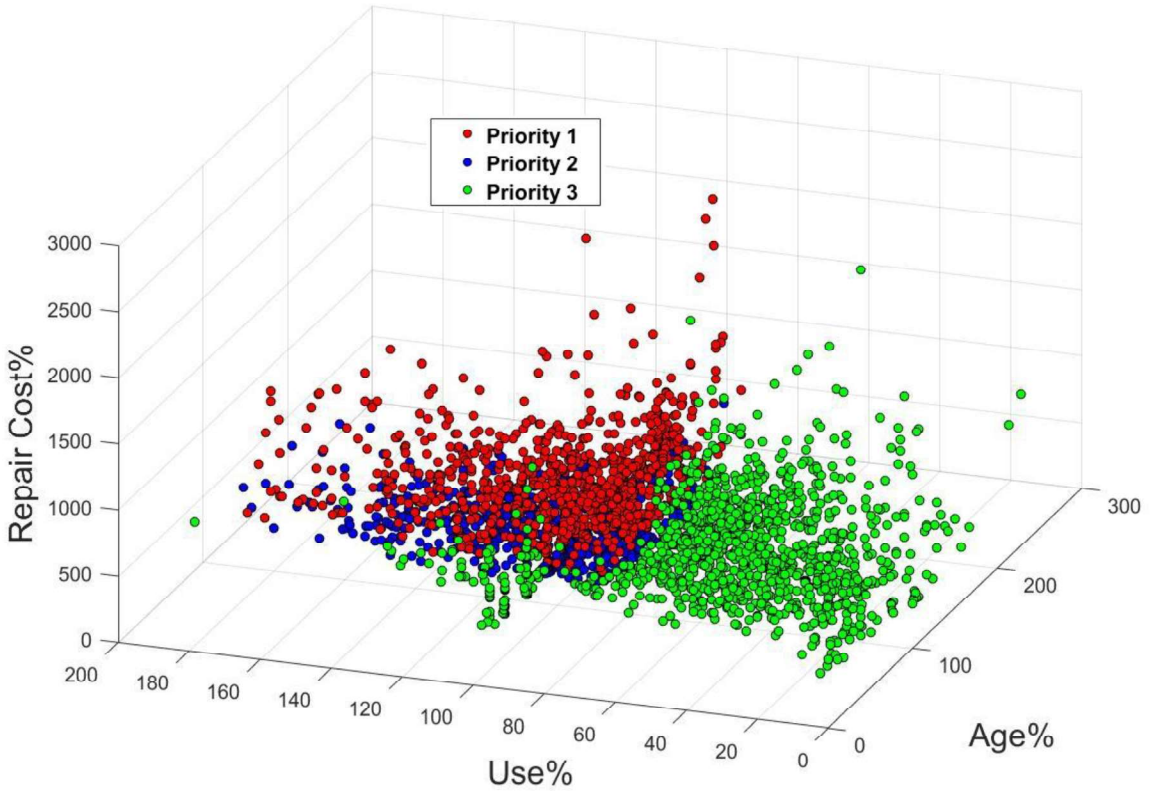



**Figure ES-1: Caltrans VMC priority 1-3.**

In this report, three FRM categories--Pre-Defined Threshold, Life Cycle Cost Analysis (LCCA), and Mathematical Ranking Method--are summarized; and several FRMs previously used or currently being used by state DOTs were described in detail. Following the evaluation of each replacement method, the LCCA method was found to be very data-driven with known life-cycle theory to support it and it was chosen as the most applicable alternative to Caltrans' current FRM. Thus, another major part of this research is focused on developing an alternative FRM based on LCCA. The major tasks in this work include building a LCCA Model, obtaining Caltrans' fleet data, processing and visualizing fleet data, modeling cost trends to predict future costs, evaluating the feasibility and constraints, and applying an enhanced method to optimize the model. The primary objective of this part of the research is to develop a tailored FRM and facilitate the decision making process for replacing equipment within Caltrans' vehicle fleet.

Utilizing the LCCA model to analyze vehicle cost reveals numerous patterns and trends. The life cycle cost analysis of the Caltrans fleet data shows that there is a wide range in the ratio of cumulative cost by age, even within a given equipment category as seen in Figure ES-2 for passenger vehicles. In Figure ES-2, the top 10% costly vehicles in the passenger vehicle category are plotted in red and the bottom 10% costly vehicles in the passenger vehicle category are plotted in green. To show the differences between these vehicles more clearly,

the research team plotted operating costs for individual vehicles in the bottom and top 10%, as shown in Figure 4-8 ES-3.

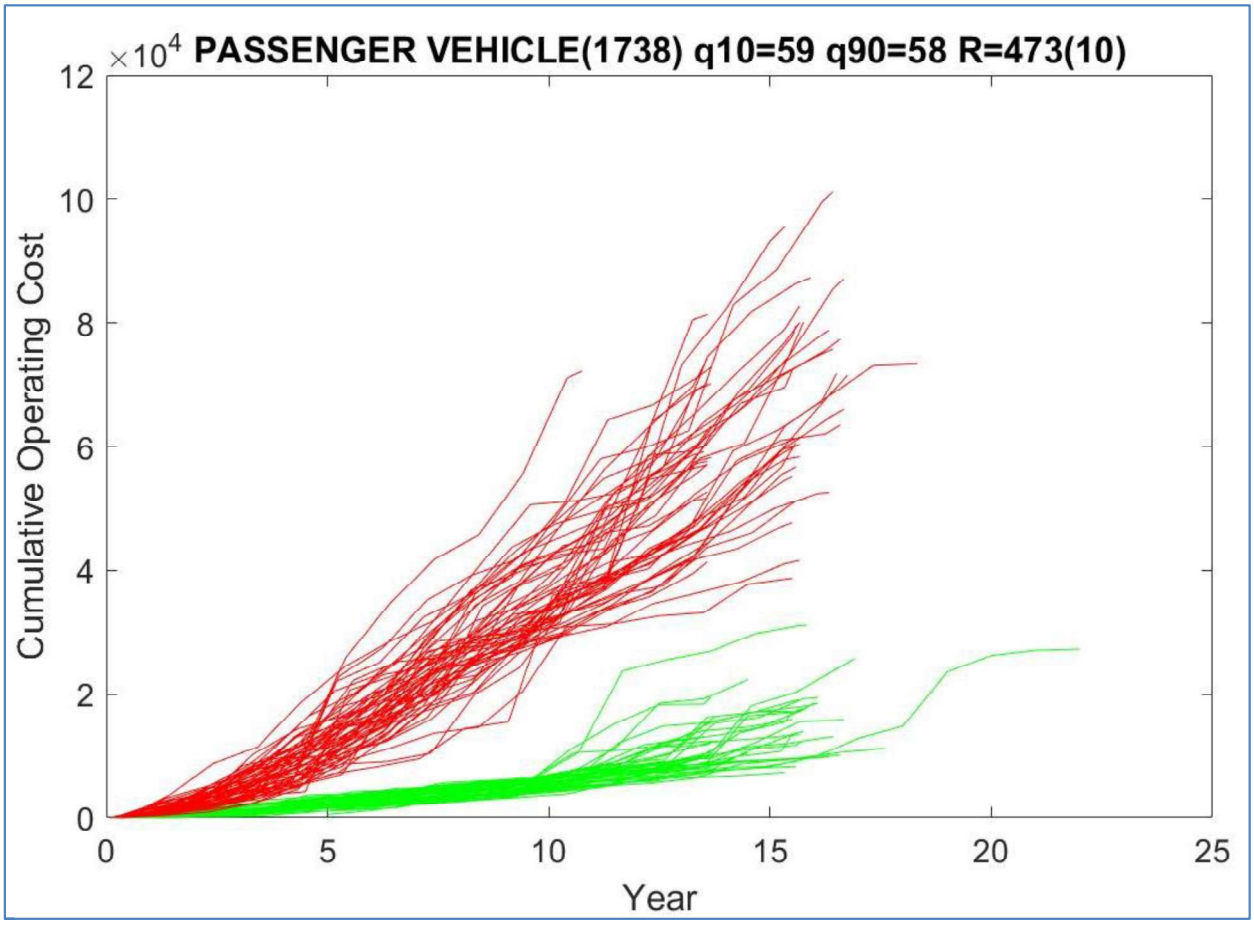
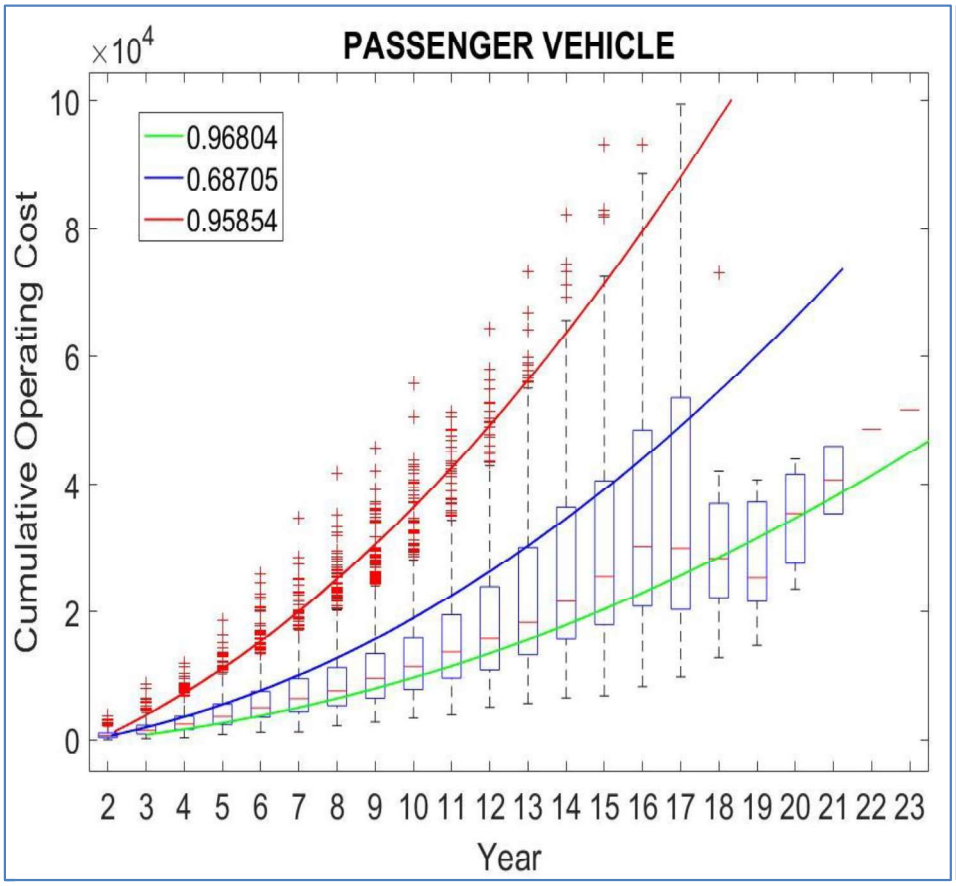



**Figure ES-2: Percentile plot for passenger vehicle category consisting of 1738 vehicles is shown. Only the top 10% costly vehicles are shown in red and the bottom 10% costly vehicles are shown in green.**




| Second Order Coefficient | Optimal Life Cycle |
|---|---|
| | Sedan Compact |
| 20 | 30 |
| 30 | 24 |
| 40 | 20 |
| 50 | 17 |
| 60 | 16 |
| 70 | 14 |
| 80 | 13 |
| 90 | 12 |
| 100 | 12 |
| 110 | 11 |
| 120 | 11 |
| 130 | 10 |
| 140 | 10 |
| 150 | 9 |
| 160 | 9 |
| 170 | 9 |
| 180 | 8 |
| 190 | 8 |
| 200 | 8 |
| 210 | 8 |
| 220 | 8 |
| 230 | 6 |
| 240 | 6 |
| 250 | 6 |
| 260 | 6 |
| 270 | 5 |
| 280 | 5 |
| 290 | 5 |
| 300 | 5 |

**Figure ES-3: Enhanced LCCA model**

The development of the LCCA model presented challenges and opportunities. Considering the characteristics of the life cycle cost and the thorough analysis of Caltrans data, an enhanced LCCA model and a new terminology, Composite Operating Cost (COC), were introduced. These two components help to enhance the basic LCCA, addressing some of the limitations that are characteristic of the LCCA, and providing a more realistic result for the fleet replacement decision-making process.

In additional analysis, the life-to-date cumulative cost for vehicles selected for replacement in Caltrans' current 1- and 5-year replacement plans was compared to the top and bottom 10% life-to-date cumulative cost fleet vehicles by vehicle category in order to help identify vehicles whose replacement status may require further review. Figure ES-4 shows this comparison for the 1-year replacement plan vehicles in the super pickup maintenance class (00728). Blue represents vehicles scheduled for replacement, the red are the top 10% costly fleet vehicles and the green are the bottom 10% costly fleet vehicles. Overlap is indicated by blue stars. Figure ES-4 shows that two vehicles scheduled for replacement in this category are low cost vehicles and there are 14 high cost vehicles not scheduled for replacement. The replacement status of both of these groups of vehicles may require further review.

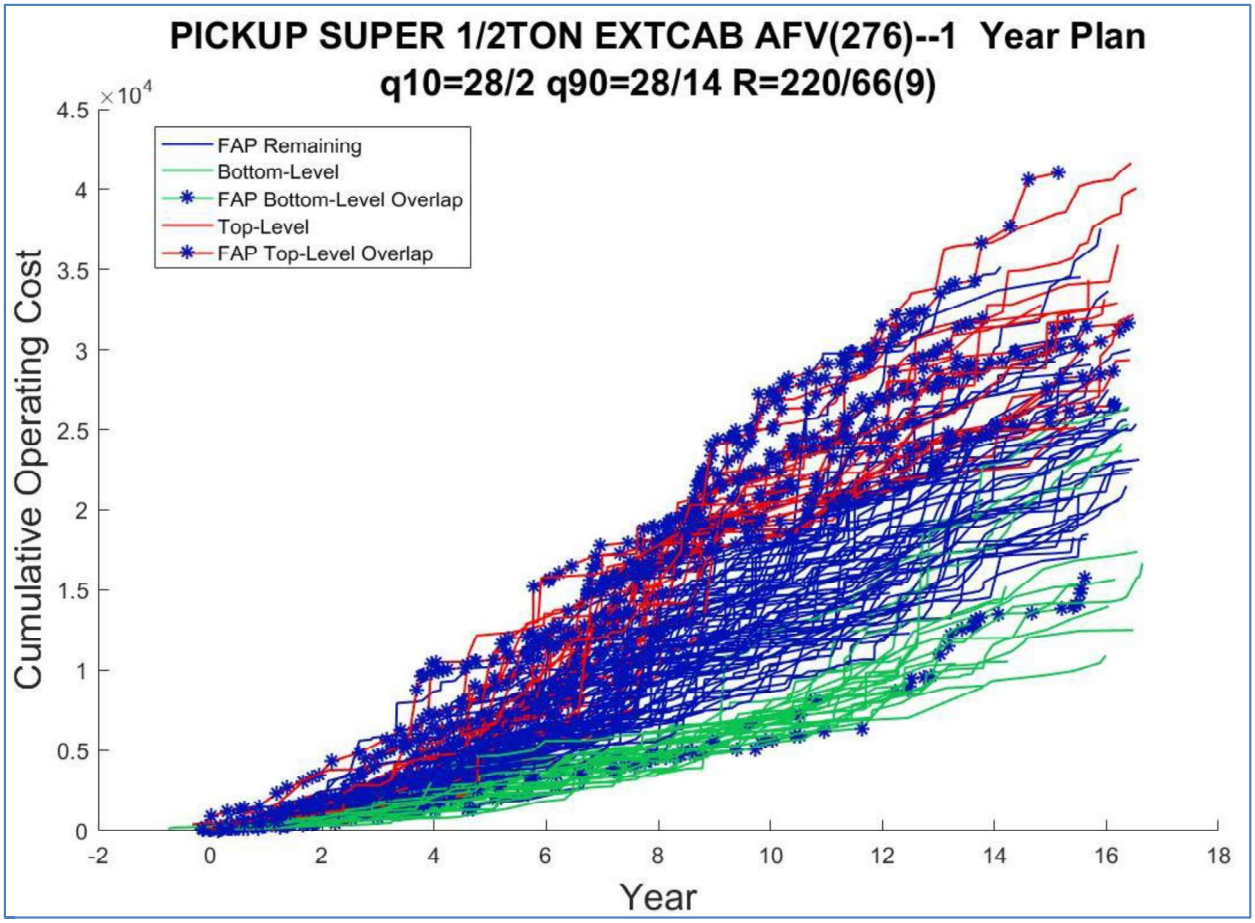



**Figure ES-4: Comparison of Caltrans fleet replacement selections with the top and bottom 10% cumulative cost vehicles**

# 1. Introduction

## 1.1. Background

The California Department of Transportation (Caltrans) manages more than 50,000 miles of California's highway and freeway lanes requiring the acquisition, maintenance and deployment of a broad range of vehicle based equipment. Caltrans' Division of Equipment (DOE) is responsible for approximately 13,000 vehicles, which range from light vehicles such as passenger cars and utility vehicles to heavy-duty on-road vehicles, such as dump trucks to off-road equipment such as loaders (1). Each year, DOE determines vehicle equipment to replace. At the time of this reporting, DOE is using a method using a set of criteria referred to Vehicles Meets Criteria (VMC). VMC considers equipment age, usage, and life-to-date repair costs to identify candidate vehicle equipment for replacement. The percentage of the pre-defined standard for each criteria is calculated for each piece of equipment and equipment is placed into groups with varying levels of replacement priority. Equipment with higher priority are preferred candidates for replacement. Due to budgetary constraints, replacing all of the candidate vehicles is not an option and as a result, a subsequent assessment of vehicle condition and fleet requirements is made by DOE staff to select the top candidates for replacement.

Since such a decision-making process involves many subjective factors, a more data-driven method to prioritize vehicle equipment for replacement is desired. In this research, various Fleet Replacement Methods (FRMs) are identified and evaluated. Several methods have been evaluated by applying the methodology to Caltrans' fleet data. Additional components have been incorporated into the analysis in order to enhance the selected FRM.

## 1.2. Objectives

The basic objectives of this project are listed as follows:

1. Evaluate and characterize Caltrans current Fleet Replacement Method
2. Compare and contrast the FRMs of other state DOTs and similar fleets
3. Analyze potential alternatives to Caltrans FRM
4. Propose and evaluate potential improvements to Caltrans FRM

## 1.3. Report Organization

To achieve the project objectives, the research team at the University of California Riverside (UCR) investigated the FRM of Caltrans and other state DOT's, obtained fleet inventory data from Caltrans, and investigated several FRM methods using this data. The research activities and results are presented in this report, which is organized as follows:

- Chapter 2– presents an overview of Caltrans current fleet replacement practices.

- Chapter 3 – describes various fleet replacement methods used by other state DOT's and found in literature.
- Chapter 4 – describes acquisition, processing and analysis of Caltrans fleet data.
- Chapter 5 – presents the evaluation of selected FRMs using Caltrans fleet data.
- Chapter 6 – provides conclusions to this research and recommendations for future research.

# 2. State DOT Fleet Replacement Practices

This research summarizes replacement practices used by various state DOTs, including: replacement factors/criteria, replacement models, software, and other methodologies. The following sections describe all of the parameters currently used by various fleets, and defines three FRM categories that group different replacement methods based on their characteristics.

## 2.1. Summary of State Replacement Practices

As part of this work, UCR researched the fleet replacement practices of 50 state DOTs and eight Canadian provinces as well as those found in literature. Information regarding fleet replacement practices was collected from different sources, including previous research reports, the American Association of State Highway and Transportation Officials (AASHTO) conference records, in-depth interviews, etc. All 50 states were reviewed and the following 8 Canadian provinces: Alberta, Saskatchewan, Prince Edward Island, Nova Scotia, New Brunswick, Manitoba, British Columbia, and Ontario. Based on this review, 17 major parameters utilized in the fleet replacement decision-making process were identified and the quantity of DOTs utilizing each parameters is presented in Table 2-1.

**Table 2-1: Parameters used in the fleet replacement decision-making process across 50 states and 8 Canadian DOTs.**

| Parameter | Definition | DOTs |
|---|---|---|
| Age/Equipment Life | Equipment age/time in service | 43 |
| Usage (Mileage/Hours) | Life-to-date usage, based on different meter types (mileage/hours) | 39 |
| Repair Costs/Maintenance Costs/Operating Costs | Life-to-date repair costs, maintenance costs or operating costs | 34 |
| Manual Evaluation/ Inspection/Condition of Equipment/Safety | Condition/reliability/safety assessment, reviewing operational expenditures or physical inspection | 16 |
| Budgetary Constraints | Budget limitation | 9 |
| Acquisition Value/Capitalized Value | Purchase price and may include up-fitting cost | 8 |

| | | |
|---|---|---|
| Downtime | Idle hours | 7 |
| Full Amortization/ Expected Useful Life | Life expectancy based on experience or historical data in mileage or years. | 5 |
| Remaining Asset Value/Depreciated Value | Current market value, which is the subtraction of life-to-date depreciation from the initial capitalized value | 5 |
| Parts Availability | Availability of repair parts | 3 |
| Replacement Cost | The purchase price of replacement equipment | 2 |
| Rental Income | Value of equipment as rental | 2 |
| Future Trends, Needs and Plans | Usually used to consider alternative equipment that are more efficient or environmental-friendly. | 2 |
| Mandate/Emission | Official policy/Executive Order/Zero Emission Vehicle Action Plan/Emission Criteria | 2 |
| Lead Time | The time between the placement of an order and delivery of a new equipment. | 1 |
| Service Activities Occurrences | The occurrences of the most common maintenance and repair activities for different equipment classes | 1 |

Equipment age, usage (mileage/hours) and repair costs were found to be the most frequently utilized replacement decision-making factors. These results are in agreement with a report prepared for Caltrans by CTC & Associates which states that when rating various equipment replacement criteria by importance, usage is the most important, followed in order by equipment age/time in service, condition assessment and repair cost (2).

On October 24th, 2013, a Governors' Memorandum was signed by 8 states to ensure the successful implementation of a zero-emission vehicle (ZEV) program, which seeks to have at least 3.3 million ZEVs by 2025 (3). Thus, there may be an increase in the impact of emission standards or other mandates on fleet management practices and increasingly more state DOTs may take such non-economic factors into consideration when they make vehicle replacement decisions.

## 2.2. FRM Classification

Fleet replacement decisions typically utilize the parameters considered the most influential by each DOT. Some parameters like equipment age, usage and cost can be determined directly from the fleet database or can easily be quantified, but other factors such as the condition of the equipment or future trends are more subjective. In order to account for various replacement factors, DOTs have developed unique and specialized FRMs. According to the findings from state DOTs and related literature, FRMs can be categorized into the following three categories: Pre-Defined Threshold method, Life Cycle Cost Analysis (LCCA), and Mathematical Ranking Model. These categories are described in more detail in the remainder of this section.

### 2.2.1. Pre-Defined Threshold

The Pre-Defined Threshold method compares equipment parameters to threshold values and equipment with parameters exceeding the threshold value become candidates for replacement based on that parameter. Thresholds or standards may be determined based on experience, manufacturer's information and/or historical data. After identifying candidates for replacement, some states prioritize all the candidate equipment based on physical inspection or the discretion of the maintenance engineer, while other states rank candidates based on the number of thresholds that were exceeded and by what extent.

After looking into the states' replacement practices, UCR found that 38 state DOTs chose to select specific parameters and set threshold values to trigger the equipment replacement process. For example, Caltrans' previous replacement method, Vehicles Meets Criteria (VMC) 15 Priorities (4), shown in Table 2-2, falls into this category.

**Table 2-2: Caltrans' VMC 15 Priorities.**

| | Priority | Priority Parameters | Count* |
|---|---|---|---|
| **Critical Replacement** | 1 | >=400% Repair Cost and 80% Age and 80% Use | 890 |
| | 2 | 300%-399% Repair Cost and 80% Age and 80% Use | 711 |
| | 3 | >=300% Repair Cost | 1181 |
| | 4 | 100% Age and 100% Use and 200% Repair Cost | 493 |
| | 5 | 80% Age and 100% Use and 200% Repair Cost | 110 |
| | 6 | 100% Age and 80% Use and 200% Repair Cost | 280 |
| | 7 | 200%-299% Repair Cost | 1133 |
| | 8 | 100% Age and 100% Use and 100% Repair Cost | 264 |
| | 9 | 80% Age and 100% Use and 100% Repair Cost | 183 |
| | 10 | 100% Age and 80% Use and 100% Repair Cost | 176 |
| **Remaining Replacement** | 11 | 100% Age and 100% Use | 31 |
| | 12 | 100%-199% Repair Cost | 1871 |
| | 13 | 80% Age and 100% Use | 96 |
| | 14 | 100% Age and 80% Use | 6 |
| | 15 | 80% Age and 80% Use | 15 |

* As of 6/30/2015

Caltrans' VMC uses equipment age, usage, and life-to-date repair cost as key parameters for determining replacement candidates. Thresholds are set as percentages of the actual value relative to standard values based on historical data. UCR applied Caltrans' VMC to Caltrans' fleet data, which is presented in greater detail in Chapter 4, and assigned priority replacement levels to each vehicle in the fleet. The Caltrans' fleet contained 890 units that qualified as priority 1, 711 units that qualified as priority 2 and 1181 units that qualified as priority 3. The first three priority groups are presented in the scatterplot in Figure 2-1. The plot shows the importance of repair cost in Caltrans' replacement criteria, which is the leading factor that affects replacement prioritization.

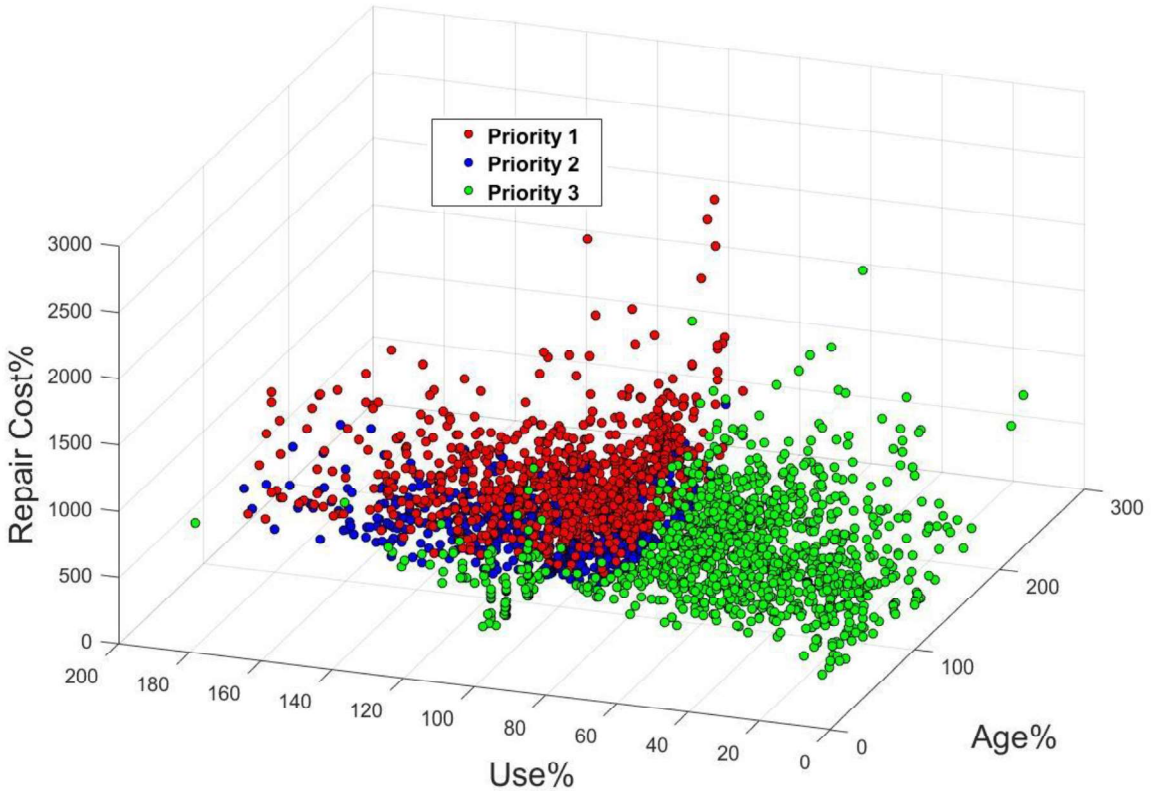



**Figure 2-1: Caltrans VMC priority 1-3.**

Another example of the pre-defined threshold method is the Naval Facilities Engineering Command (NAVFAC) published cost factors. These factors define an upper limit for the yearly maintenance and repair cost for a piece of equipment in each year (5). The upper limit is the percentage that the maintenance and repair cost is of the equipment's residual value, and when that percentage is over 30%, that equipment is evaluated for replacement.

The biggest advantages of the pre-defined threshold method are that it is very straightforward, easily implemented, and understandable. The most commonly used parameters for state DOT fleets are equipment age, usage, and repair cost. Fleet data is typically stored in fleet management information systems and can be easily quantified. The downside of the pre-defined threshold method is that setting thresholds can be subjective and compares all equipment categories similarly. In addition, if a piece of equipment is already in bad condition before it reaches the threshold, it may not be cost effective to retain until the threshold is triggered.

### 2.2.2. Life Cycle Cost Analysis (LCCA)

Life Cycle Cost Analysis (LCCA), also known as Economic Life-cycle Analysis, determines the most economic life of an asset which is defined as "… the operating interval which minimizes the equivalent uniform annual cost (EUAC) of the asset" (6). EUAC can be used to compare the total life-to-date costs of equipment alternatives as well as determining the most

economic life of a single piece of equipment. In addition to reflecting the life-to date costs of an asset, EUAC, which is adjusted by the capital recovery factor and normalized over year to date, provides a reasonable way to compare two pieces of equipment with different cash flow and different years in service (7). The capital recovery factor converts a present value into equal annual values over a given time range and interest rate. Typically, the total lifetime cost of a piece of equipment consists of two parts, the owning cost and the operating cost. (Figure 2-2)

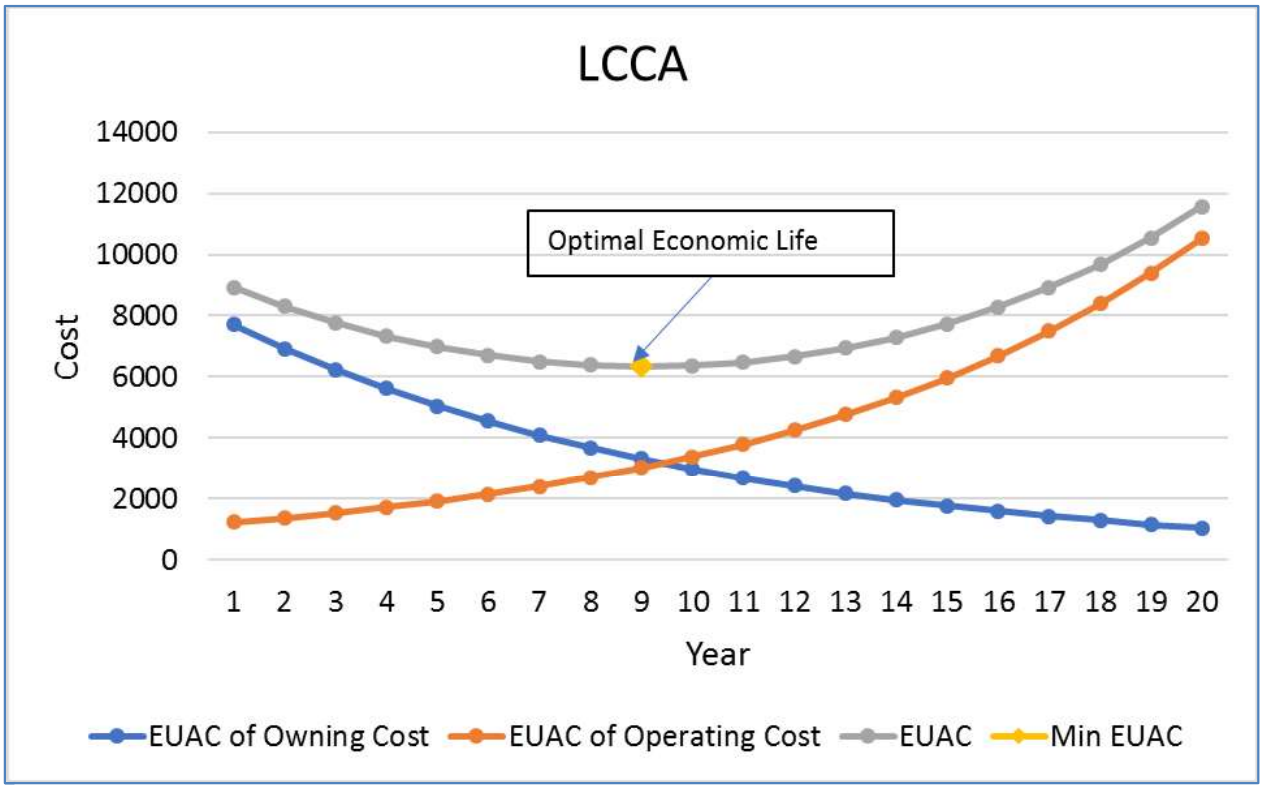



**Figure 2-2: Life Cycle Cost Analysis**

The owning cost includes opportunity loss due to market value depreciation, and the interest charge associated with the salvage value, as well as other costs such as insurance, up fitting, etc. The operating cost consists of various expenditures that occur during an equipment's lifetime, such as routine preventative maintenance, periodic inspections, repair, upgrades, refueling, and the cost of changing parts, etc. As seen in Figure 2-2, the EUAC operating cost increases with equipment age and the EUAC owning cost decreases with equipment age. The point where the total EUAC reaches a minimum is considered the optimal economic life of the asset and is the point at which the equipment should be replaced.

UCR found that the following 6 US state DOTs and 2 Canadian provinces are using a LCCA method: Indiana, Iowa, Minnesota, North Carolina, North Dakota, Texas, Alberta (CAN), and Ontario (CAN). The LCCA conducted in these states and provinces follow the basic LCCA principles with various nuances. The analyses vary in the parameters that are included or in the different methods used to calculate the operating cost. Overall, LCCA is a fairly comprehensive method since it considers most vehicle related costs. However, LCCA

requires extensive amounts of data and can be complicated to implement. In reality, not all the parameters needed in LCCA will be recorded in a DOTs' database. Another challenge faced by state DOTs is that, in the theoretical LCCA model, the EUAC curve is a U-curve and will always have a valley point, which indicates the optimal life cycle. However, in practice, the pattern of EUAC may not be as clear as indicated by theory, which often results from decreasing operating costs in later years due to lower usage. In this case, the EUAC will never reach a minimum point or the lowest EUAC reflects an extremely long life cycle.

### 2.2.3. Mathematical Ranking Method

Some state DOTs create specific algorithms to account for multiple factors and quantify selected factors to prioritize replacement candidates. This type of replacement practice is categorized as the Mathematical Ranking Algorithm Method. For example, Michigan uses eight weighted factors to rank candidates for replacement. These factors include retention time, mileage, engine hours, operating hours, preventive maintenance (PM), equipment condition, equipment function, and region priority (2). The first four factors each account for 21% of the total weight, PM is given a weight of 7%, and the other three factors are given a weight of 3%. Using weighted factors is very common in this type of analysis, and the weights are usually given based on the importance of each selected factor as determined by each state DOT. Another example is from the Oregon DOT, which developed the algorithm [(age/age standard) + (usage/ use standard) + (life-to-date cost/acquisition cost)] to rate each equipment in the fleet. Equipment with a higher score will have a higher priority (2). Giving a score to each equipment is another common approach. The parameters, parameter weighting and formula to calculate scores vary from state to state, by the composition of vehicles in the fleet, and also based on which factors are important to the department. Although this type of replacement practice accounts for various factors at the same time, these special algorithms cannot be used universally and often require being adjusted depending on future trends, needs or plans.

## 2.3. Software and Information Systems

Almost every DOT will use a type of fleet management system or software to store fleet information and/or to perform analysis to assist in the replacement decision-making process. Based on an extensive literature review, some commonly used software/information systems are summarized in Table 2-3. This software is either currently being used or has been previously used by state DOTs.

**Table 2-3 Software/Information Systems**

| Software/Information System | DOTs | Features |
|---|---|---|
| AgileAssets | AK, ID, KY, MT, NM, OH, WV | -Mobile Data Entry<br>-Global Positioning System (GPS) Tracking & Graphical Information Systems (GIS)<br>-Browser Based<br>-Multi-Period/Constraint Life Cycle Analysis |
| AssetWorks/FleetFocus | AZ, CA, DE, GA, MI, MN, | -Comprehensive asset tracking, automatic reports<br>-Browser based |

| | | |
|---|---|---|
| | NH, UT, VT, VA | -Track all functions related to the maintenance of vehicles and equipment (repair, preventative maintenance and operating expenses)<br>-Offer billing and tracking of vehicle and equipment usage |
| Arkansas State Highway and Transportation Department (AHTD) Equipment Mgmt. System | AR | -Uses Verizon's NetworkFleet to track vehicles w/ GPS<br>-Roadside assistance, vehicle diagnostics<br>-Analyze records to optimize life cycle management |
| Chesapeake Computer Group (CCG) Faster | MO | -Improve life cycle costing<br>-Real-time data<br>-Reports emphasis on customer service<br>-Web platform available<br>-For fleet and fuel management |
| Enterprise Asset Mgt. System (EAMS) | NE | -Generic moniker |
| Financial Mgmt. System/ Wennsoft-Based Mgmt. System (Protégé) | MS | -Protégé maintained by Mississippi Management & Reporting System. |
| Fleet Management Information System (Customized Computer Application) | Saskatchewan (Canada) | -Homegrown |
| Highway Maintenance Management System (HMMS) Customized Module | SC | -Homegrown<br>-Database |
| Mainframe Program | OK | -Track equipment usage |
| Maximo | MA, MD | -Data analysis/reports<br>-Total life cycle analysis<br>-Contract & service management |
| Maintenance Management Information System (MMIS) | IL | -In-house system<br>-Maintenance management and information system |
| SAP/Plant Maintenance | CO, LA, NC, PA | -Enterprise Asset Management Software<br>-Manage the entire asset lifecycle<br>-Enterprise Resource Planning Software<br>-Download listing<br>-Excel-load date into spreadsheets and manually manipulate |
| Sprint Geotab GO6 | HI | -GPS Tracking<br>-Focus on predictive maintenance over lifecycle analysis<br>-Monitor driving habits of personnel |
| Synergen | CT | -Bought by SPL WorldGroup in 2004<br>-SPL WorldGroup bought by Oracle in 2006<br>-Oracle transportation has lifecycle management |
| VUEWorks | RI | -Mobile Data Entry<br>-GPS Tracking & GIS<br>-Web enabled<br>-Multi-Period/Constraint Life Cycle Analysis |

# 3. Discussion of Selected Fleet Replacement Models

This chapter provides comparison of eight selected Fleet Replacement Models (FRMs): Basic Life Cycle Cost Analysis, Texas Equipment Replacement Model, Equipment Life Cycle Prediction Tool, Capital Asset Management (CAM), and Caltrans' VMC 15 Priorities. These FRMs are either used by state DOTs, developed by software companies, or just a theoretical

model. This chapter covers detailed description of each FRM, including background, concepts, input parameters and model implementation. Applicability of the models and specific constraints are also discussed.

## 3.1. Basic Life Cycle Cost Analysis (LCCA)

One of the fundamental issues for fleet management is determining the optimal point at which to replace old equipment with new. The life cycle cost analysis model provides a way to find the most economic life of a piece of equipment, taking into consideration multiple economic factors which may impact the cost of ownership such as salvage value, operating costs, rate of inflation, etc. LCCA using equivalent uniform annual costs (EUAC) provides an annualized value with which to compare different operating intervals. The most economic operating life occurs when the EUAC is minimized.

The term EUAC or EAC (Equivalent Annual Cost) appears in many university research projects, sponsored by state DOTs, starting in 2002. For example, in 2002, the University of Texas at San Antonio, sponsored by Texas Department of Transportation, developed a computerized system named Texas Equipment Replacement Model (TERM), which included a specific module that implemented a life cycle cost analysis. In 2010, East Carolina University, sponsored by North Carolina Department of Transportation, used LCCA model to calculate disposal points for six major equipment classes. In both 2012 and 2014, Professor John C. Hildreth from University of North Carolina at Charlotte discusses the Cumulative Cost Model in the National Equipment Fleet Management Conference, and this model actually is the transformation from LCCA just without considering money value.

To determine EUAC, which is ultimately converted from total marginal cost, the annual marginal cost should first be calculated. The annual marginal cost can be separated into two parts: annual owning cost and annual operating cost. The owning cost, also called capital recovery cost, is equivalent to the sum of the annual loss in value and the annual interest charge. The owning cost consists of the initial capital cost (purchase price and up-fitting cost), estimated market value at year end, loss in value for the year/depreciation, annual interest charge, salvage value, and some other owning costs. The annual operating cost consists of the annual constant operating cost and variable repair costs, which may include preventive maintenance costs, fuel consumption, labor costs, repair parts, mechanic/technician salary, overhaul, downtime costs, etc. In summary, the general steps of LCCA model are:

1) Annual Owning Cost = Annual Loss in Value + Annual Interest Charge
2) Annual Operating Cost = Annual Constant Operating Cost + Variable Repair Cost
3) Annual Marginal Cost = Annual Owning Cost + Annual Operating Cost
4) Annual Marginal Cost → Present Value of Marginal Cost → Total Present Value → EUAC

The present value of marginal cost is obtained by multiplying the annual marginal cost by present to future factor: $(P/F, i, n) = \frac{1}{(1+i)^n}$. Total present value is the cumulative present

value of annual marginal cost. In order to convert the total present value of marginal cost to EUAC, it should be multiplied by factor: $(A/P, i, n) = \frac{i(1+i)^n}{(1+i)^n-1}$.

Where:

P = Present value
F = Future value
A = Annuity of present value
i = Annual discount rate
n= Number of years

In practice, state DOTs usually have some type of database or information system to record and track equipment information, but not all the parameters mentioned above will be recorded. For example, instead of having separated cost components, some DOTs may only have a general designation as repair cost in their records, which is the sum of different subdivided costs. Some DOTs may only have a subset of the cost components, which will require that assumptions be made during analysis. For example, most DOTs will not record equipment's annual market value. Thus, this parameter is usually estimated by using historical data or based on personal experience. Another example is downtime. Some DOTs may have records of the idle hours for vehicles, but the cost of these idle hours is hard to quantify. The most common quantification for idle hours uses the rental rate retrieved from the car rental market. Further review of the LCCA method is discussed in Chapter 5.

## 3.2. Caltrans Fleet Utilization Score

In chapter 2, Caltrans' fleet replacement standard was introduced and grouped under the Pre-defined Threshold methodology. Recently, Caltrans has started using another replacement practice referred to as Fleet Utilization Score. The Fleet Utilization Score is a method developed by Caltrans to evaluate how a fleet unit is utilized over its lifetime. Initially developed for usage management and primarily used for that purpose, the Utilization Score is used to somewhat prioritize replacement of vehicles meeting VMC. The scoring criteria for this method defines 4 digits to represent the equipment's age, total life usage (mileage/hours), usage for the last 12 months, and the amount of repair costs spent compared to its repair standard, which is half of its capital cost. The score digit value is based on the percentage of the actual utilization to the pre-defined standard. If the actual value is 0% to 20% of the standard, then the score value will be zero; similarly, 1 = 20% to 40%, 2 = 40% to 60%, 3 = 60% to 80%, 4 = 80% to 100%, 5 = over 100%. After the utilization score has been determined, Caltrans will order their fleet based on the score to decide which fleet unit has the higher priority to be replaced.

## 3.3. Texas Equipment Replacement Model (TERM)

The Texas Equipment Replacement Model (TERM) is a replacement model based on LCCA. The model software was developed using the SAS (Statistical Analysis System) statistical programming language using SAS/AF (Frame Entry Application) and consists of a Graphical User Interface (GUI). TERM has three separate modules: Data Update Module, Programming and Implementing System Upgrades Module, and Replacement Ranking Module. Instead of

setting thresholds to make replacement decision, TERM will generate equipment replacement priority lists for each class code by using two ranking modules. The first one uses Life Cycle Cost Analysis (LCCA) as the only priority criterion, while the second one uses weighted criteria. The research team obtained information about the implementation of the TERM model through a phone discussion with one of the developers of the model and corresponded via email with TxDOT. TxDOT began using the TERM model in 1991, but in recent years has been gradually transitioning from TERM to FNAV (in house name for the AssetWorks software). TERM is still used from time to time, but will be completely abandoned in the near future. The modules and theoretical methodology used in TERM are discussed below.

### 3.3.1. Life Cycle Cost Module

The Life Cycle Cost Module contains the basic life cycle cost analysis and trendscore calculation. The basic life cycle cost analysis helps determine the most economic life cycle for each piece of equipment and determines which piece of equipment has passed the optimal point and qualifies as a replacement candidate. The life cycle cost analysis, however, does not prioritize the replacement candidates. In order to address this issue, the TERM model uses a numerical method called Trendscore, which indicates which region of the life cycle cost curve the equipment is in, how long it has been there and how steep the upward slope is. A steeper upward trend slope or longer upward trend will generate a higher trendscore, and a higher replacement priority.

The three steps operation process of TERM's Life Cycle Cost Module can be summed up as followed:

#### *Perform Basic LCCA*

The life cycle cost analyzed in TERM is the practical application of the LCCA theory. The time value of the sum of all costs incurred during equipment's entire life is calculated and then the minimum equivalent uniform annualized cost, which determines the most economic life cycle, is determined. The parameters included in TERM's LCC module are age, equipment status, purchase cost, resale value, repair expenses, fuel consumption, miles or hours of usage, hours of downtime, rental, and other indirect costs. In TERM, depreciation value, discount rate and downtime cost are estimated.

In order to calculate the annual loss in market value of each piece of equipment, the resale value at the end of each year is estimated using the recorded purchase cost and resale price. The methodology TERM uses to estimate the resale value is based on depreciation factors, which are the ratios between the present value of the resale price and the initial purchase cost. Since only a portion of equipment will be sold after their service life, only that equipment having actual resale price will have a depreciation factor. To get the function representing the relationship between depreciation factors and equipment ages, TERM calculated the median depreciation factor of same-age equipment and then fit these factors to either an exponential or a power function of age, depending on which one has the higher R-squared value. The final function is used to estimate the resale value. As to the discount

rate and downtime cost, the default setting in TERM is 3% discount rate and $20.00 per downtime hour, which can be adjusted by the fleet manager if necessary. Sensitivity analyses were also conducted to see the impact of different discount rate (3%-6%) or downtime cost ($20.00-$80.00) on the LCCA.

### *Determine Time Series Trend*

The time series trend is retrieved from the life cycle cost curve using Bayesian Trend Modeling. The basic time series contains the following three components: trend component, seasonal component and irregular component. To simplify the following step, the TERM model only considers the trend component and filters the other two factors. To calculate trends, TERM calls a SAS/IML subroutine that performs Bayesian time series adjustments.

### *Determine EUALCC Trendscore*

The TERM project team developed a numerical method called "Trendscore" to prioritize the whole fleet. The Trendscore is defined as:

$$\mathbf{Trendscore} = \mathbf{100} \sum_{t=3}^{n} \frac{T_{t+1} - T_t}{T_t}$$

Where:
T = Equivalent Uniform Annual Life Cycle Cost trend component
n = equipment age
t = time

The Trendscore represent an equipment's EUAC tendency between year 3 and the total years in service. The longer the equipment has experienced an upward trend or a steeper slope in the upward trend, the higher the Trendscore. If equipment has been in an upward trend for a long time, this indicates that the equipment is past its optimal replacement point. Equipment with higher Trendscore will cost more to keep and will have higher replacement priority.

## 3.3.2. Multi-attribute Priority Ranking Module

The second module in TERM is the Multi-Attribute Priority Ranking Module, which ranks each piece of equipment based on the weighted percentiles of different attribute relative to other equipment. The percentile is the position of equipment being evaluated relative to other equipment for a given parameter. For example, in a list of replacement candidates, if there are 5 pieces of equipment with a higher downtime value and 6 pieces of equipment with a lower downtime value, then the percentile ranking of that equipment will be 7 out of 12 or 58.33% with respect to downtime. In TERM, the Multi-Attribute Priority Ranking Module only considered four attributes: cumulative downtime, repair costs, cumulative usage and Trendscore. The relative weights are decided by the fleet manager. Equipment that have higher scores will have higher replacement priority.

## 3.4. Equipment Life Cycle Prediction Tool

The Equipment Life Cycle Prediction Tool was introduced in the 2014 National Equipment Fleet Management Conference and is the current replacement practice for the Pennsylvania DOT (PennDOT). This tool helps PennDOT fulfill three main tasks: maintenance cost predictions, prioritizing equipment replacement, and equipment budget allocation. All the calculations and analyses are run within Microsoft Access.

To compare the efficiency of each equipment's life cycle, PennDOT defined two cost ratios. Cost ratio 1 is cumulative maintenance and repair costs to cumulative personnel hours, and cost ratio 2 is cumulative maintenance and repair costs to cumulative fuel usage. The cumulative maintenance and repair costs are estimated using linear prediction.
Similar to TERM, PennDOT's equipment life cycle prediction tool has a replacement priority quotient to quantify all replacement parameters and prioritize the whole fleet. Equipment with the higher quotient will have the higher replacement priority.

$$\textbf{Priority Quotient} = (\textbf{Age in Years} - \textbf{Life Cycle}) + (\textbf{Cost Ratio} - \textbf{Ave Cost Ratio}) + \textbf{40}$$

Where:

Age in years = equipment's age from start-up date to present
Life cycle = the pre-determined life cycle in years for this type of equipment
Cost ratio = either cost ratio 1, cost ratio 2 or (cost ratio 1+cost ratio 2)/2
Average cost ratio = the average cost ratio for all the equipment of the same type and age
40 = a constant that adjusts Priority Quotients to be positive

According to PennDOT, the equations used in this tool are based on the analyses of data recorded from July 2007 through September 2012, which means that the equations will gradually lose their predictive value as equipment and/or maintenance practices change (11). To fix this issue, data needs to be reevaluated and equations need to be reestablished periodically.

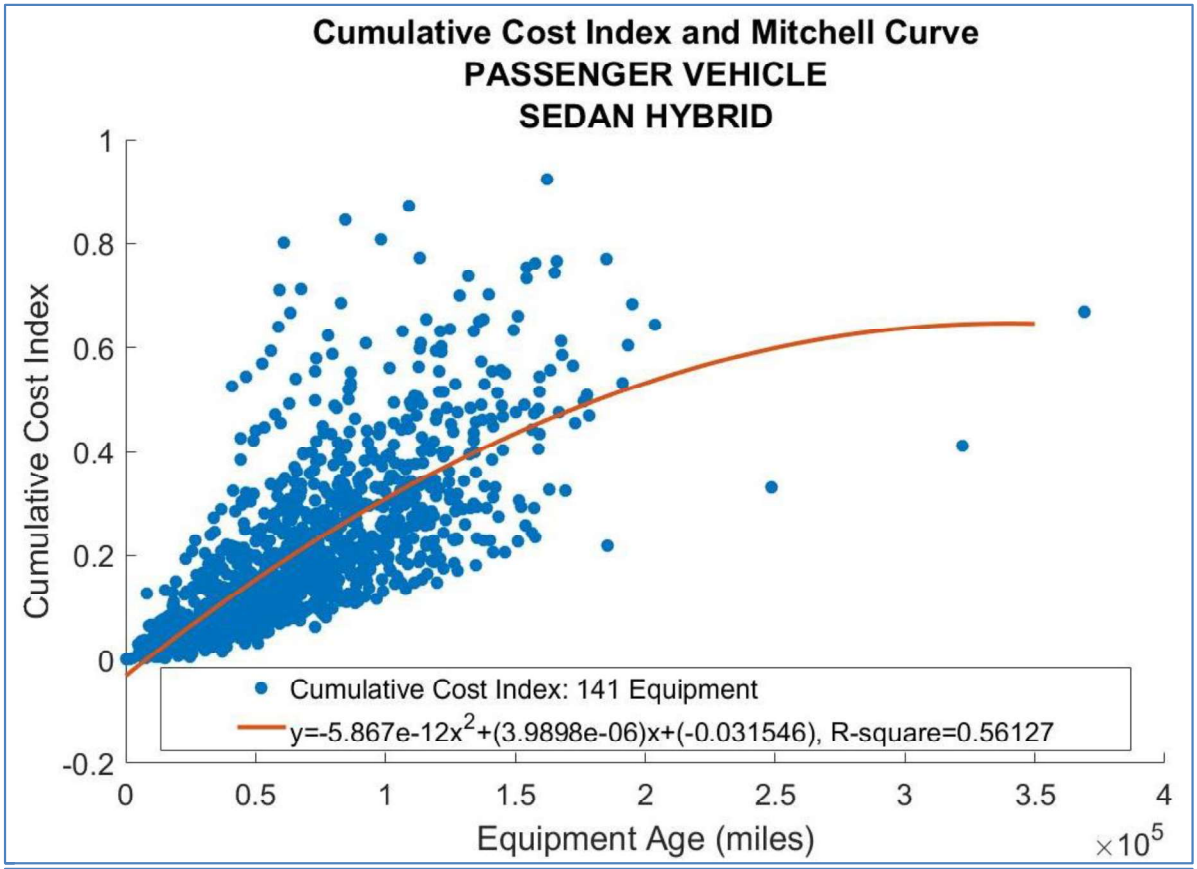
## 3.5. Cumulative Cost Model (CCM)

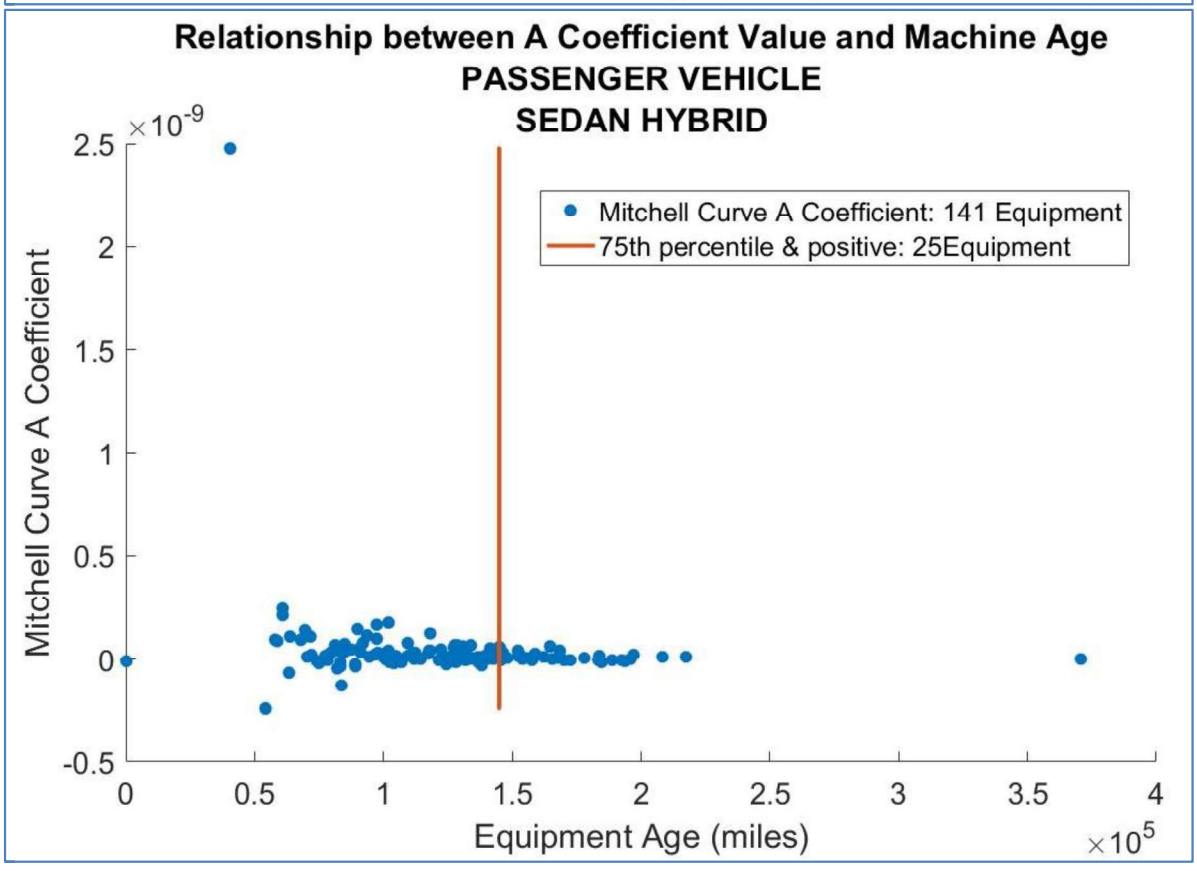
North Carolina's Cumulative Cost Model (CCM) is another implementation of the LCCA concept. Differing from NCDOT's previously developed annual cost models (14), the CCM uses a second order polynomial Mitchell curve to fit the cumulative cost index, which represents the inflation adjusted cumulative cost as a fraction of adjusted purchase price (15). When determining the Mitchell curves for equipment classes, negative second order coefficient values are observed, which indicates an unreasonable decrease in the cumulative cost, and a relatively large variability usually occurring with young equipment in that class. To avoid such downtrends, the CCM only fits Mitchell curve above the 75th percentile of equipment age and it also neglects equipment with negative second order coefficients. The fixed Mitchell curve is used in calculating the life to date (LTD) total rate, which equals to LTD owning charge/age plus LTD operating cost/age. The most economic life is the point at which the LTD total rate reaches a minimum.

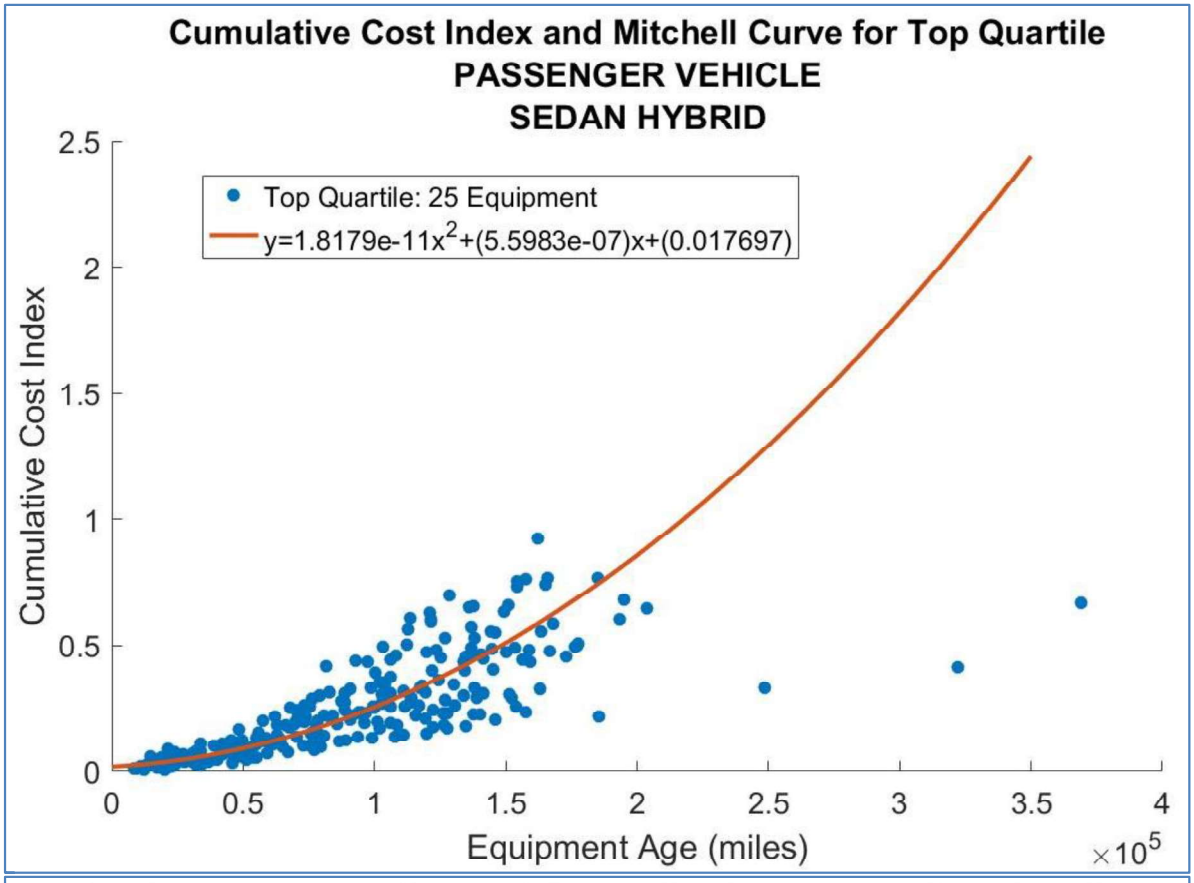
Estimates of economic life developed by the University of North Carolina using the CCM and the NCDOT fleet dataset are the following:

Pickup Trucks - 197,800 miles at an average life to date total rate of $0.38/mile
Single Axle Dump Trucks - 105,000 miles at an average life to date total rate of $1.32/mile
Loader-Backhoe - 5,865 hours at an average life to date total rate of $29.43/hour
Motor Grader - 6,020 hours at an average life to date total rate of $52.27/hour

The research team applied North Carolina's methodology to Caltrans fleet data for several maintenance classes. Figure 3-1 shows the results for the Sedan Hybrid maintenance class (00106), which has 141 pieces of equipment. Plots 1 through 4 show separate steps in the CCM method. In the first plot, at a certain mileage, there shows one dot representing the cumulative cost as a fraction of equipment's capitalized value, aka cumulative cost index. After fitting with the Mitchell Curve, the regression shows a downtrend, which results in a negative second order coefficient. The second step in the process is fitting the Mitchell Curve to each piece of equipment, and plotting the second order coefficient for each unit. Since each equipment has different life total usage, so plot 2 is showing the relationship between the second order coefficient and equipment's life total usage. Plot 2 shows that the younger equipment units' coefficients are having a more spread out distribution and increased negative values. After the 75$^{th}$ percentile line, most coefficients are positive, which contains 25 pieces of equipment. If the Mitchell curve is only fit above the 75th percentile of equipment usage and neglects equipment with negative second order coefficients, it gives us a reasonable increasing trend in plot 3. The fixed Mitchell curve is used in calculating cumulative operating cost by multiplying the equipment's capitalized value. Plot 4 shows the graphical economic model of different costs. By normalizing both cumulative owning costs and operating costs by usage, we can get the life-to-date owning rate and life-to-date operating rate, which are represented by the blue line and red line in plot 4. Subsequently, adding these two rates together provides the life-to-date total rate, which shows a U-curve in yellow. The most economic life of Caltrans' Sedan Hybrid is the point at which the life-to-date total rate reaches the minimum, i.e. at 218,698.8203 miles and 15 years.


Cumulative Cost Index and Mitchell Curve
PASSENGER VEHICLE
SEDAN HYBRID
Cumulative Cost Index
Equipment Age (miles)
×10^5
Cumulative Cost Index: 141 Equipment
y=-5.867e-12x^2+(3.9898e-06)x+(-0.031546), R-square=0.56127


Relationship between A Coefficient Value and Machine Age
PASSENGER VEHICLE
SEDAN HYBRID
×10^-9
Mitchell Curve A Coefficient
Equipment Age (miles)
×10^5
Mitchell Curve A Coefficient: 141 Equipment
75th percentile & positive: 25Equipment


Cumulative Cost Index and Mitchell Curve for Top Quartile
PASSENGER VEHICLE
SEDAN HYBRID
Top Quartile: 25 Equipment
y=1.8179e-11x^2+(5.5983e-07)x+(0.017697)
Cumulative Cost Index
Equipment Age (miles)
×10^5

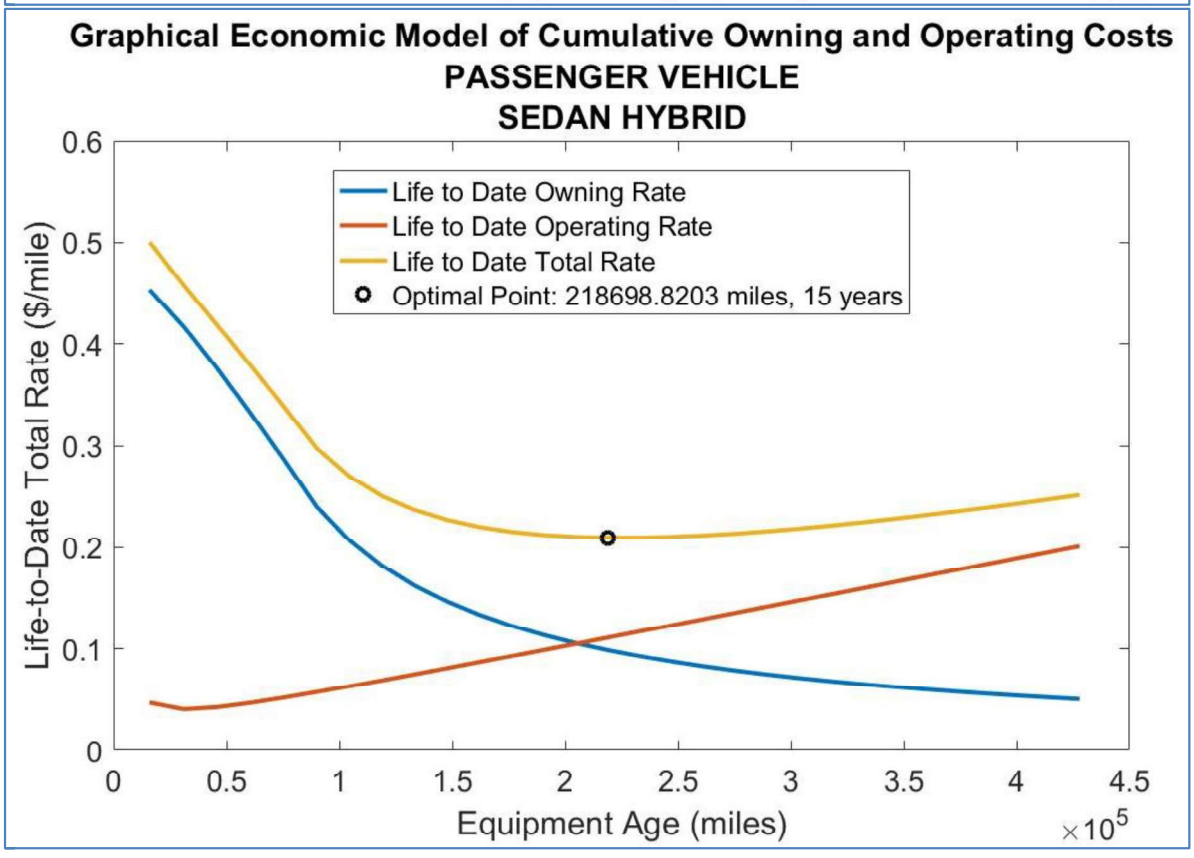

Graphical Economic Model of Cumulative Owning and Operating Costs
PASSENGER VEHICLE
SEDAN HYBRID
Life to Date Owning Rate
Life to Date Operating Rate
Life to Date Total Rate
Optimal Point: 218698.8203 miles, 15 years
Life-to-Date Total Rate ($/mile)
Equipment Age (miles)
×10^5

**Figure 3-1: Cumulative Cost Model (CCM) implementation by using Caltrans' fleet data**

By testing CCM for several classes in Caltrans' fleet, the research team realized that this method does not always identify replacement needs. In some cases, the method still shows downtrends even after neglecting equipment with negative second order coefficients and fitting Mitchell curve above the 75th percentile. In many cases, the optimal life cycle point calculated by CCM was found to be fairly long and the research team concluded that North Carolina's Cumulative Cost Model may not be applicable for Caltrans' fleet.

## 3.6. Ohio Fleet Cycling Methodology

The Ohio Department of Transportation (ODOT) presented a Fleet Cycling Methodology, which recommends some optimized fleet cycling guidelines to promote the operational efficiency for ODOT, in its 2015 performance audit report (12). These guidelines are determined by the occurrences of the top 20 most common service activities (Table 3-1) and the operating cost per mile trend of different equipment types.

**Table 3-1: The top 20 most common service activities**

| | | |
|---|---|---|
| Inspection (a standard inspection after routine maintenance) | Electrical Instruments/Gauges/Meters/ Speedometer | Brake Inspection or Troubleshooting |
| Test Drive (after repair or routine maintenance) | Tire Repair or Replacement (with a used tire) | Parts Pick-up/Research or Ordering |
| Travel To or From Repair Site | Rotors/Drums | New Tire/Replacement |
| Brake Reline/Replace/Complete Brake Job | F Inspection (a standard inspection after repair) | Windshield Wiper/Washer System |
| Battery Charging or Cleaning | Electrical Troubleshooting | Scope/Analysis/Diagnostic |
| Battery Replacement | Deliver/Pickup Equipment | Inspection/Safety |
| Computer/Sensor Repair or Replace | Brakes/Pads/Shoes/ Replacement | |

Since service activities generally increase in both frequency and cost as equipment ages, ODOT believes that equipment should retire before half of the services are performed. As an example, the service activities of ODOT's passenger vehicle for 2013 to 2014 fiscal year are shown in Figure 3-2. In each odometer range, the service occurrences and the cumulative service occurrence percentages are listed. When the mileage is between 84,001 and 96,000, the cumulative percentage is 45.9% and when the mileage is between 96,000 and 108,000, the cumulative percentage is 56.4%. This would indicate that, according to Ohio's fleet cycling methodology, the suggested replacement cycle for passenger vehicles is before a mileage reading of 96,000 miles.

| Odometer Range | Service Occurrences | Avg. Service Occurrences per Vehicle | % of Total Services Occurrences | Cumulative Percentage | Avg. Cost per Service Occurrence |
|---|---|---|---|---|---|
| 0-12,000 | 13 | 0.9 | 0.7% | 0.7% | $74.12 |
| 12,001-24,000 | 49 | 2.9 | 2.5% | 3.1% | $142.15 |
| 24,001-36,000 | 135 | 4.7 | 6.8% | 9.9% | $134.00 |
| 36,001-46,000 | 119 | 5.2 | 6.0% | 15.9% | $159.63 |
| 48,001-60,000 | 126 | 5.0 | 6.4% | 22.3% | $171.79 |
| 60,001-72,000 | 150 | 5.6 | 7.6% | 29.9% | $173.84 |
| 72,001-84,000 | 84 | 6.0 | 4.2% | 34.1% | $154.88 |
| 84,001-96,000 | 234 | 5.3 | 11.8% | 45.9% | $170.91 |
| 96,001-108,000 | 208 | 6.7 | 10.5% | 56.4% | $184.10 |
| 108,001-120,000 | 173 | 5.6 | 8.7% | 65.1% | $169.11 |
| 120,001-132,000 | 190 | 5.8 | 9.6% | 74.7% | $180.62 |
| 132,001-144,000 | 154 | 6.2 | 7.8% | 82.5% | $205.82 |
| 144,001-156,000 | 130 | 6.5 | 6.6% | 89.0% | $196.91 |
| 156,001-168,000 | 115 | 7.7 | 5.8% | 94.8% | $224.84 |
| 168,001-180,000 | 61 | 8.7 | 3.1% | 97.9% | $204.12 |
| 180,001-192,000 | 29 | 7.3 | 1.5% | 99.3% | $130.02 |
| 192,001 or more | 13 | 6.5 | 0.7% | 100.0% | $197.93 |

**Figure 3-2: ODOT passenger sedan service activities FY 2013-14**

In addition to service activities, ODOT reviewed equipment cost-per-mile (CPM) trends, which also helps to determine an odometer range for equipment replacement. The CPM trend is broken down into 3-year ranges, and changes in cost per mile within each 3 years are calculated as percentage increases. The larger increases suggest that the optimal replacement time is within that range. If there are several larger increases, then ODOT chooses the range based on practical purposes. The final combined results are listed below:

4 Years and 48,000 Miles – Passenger Cars, 1/4 Ton SUVs, and 1 Ton Pickup Trucks
5 Years and 60,000 Miles – 1/2 Ton SUVs, 1/2 Ton Pickup Trucks, and 3/4 Ton Pickup Trucks
6 Years and 72,000 Miles – Minivans and 1 Ton Passenger Vans
7 Years and 84,000 Miles – Cargo Vans
10 Years and 100,000 Miles – Light Dump Trucks
11 Years and 132,000 Miles –Utility Trucks (3/4 and 1 Ton)

## 3.7. Major Equipment Life-Cycle Analysis

The Major Equipment Life-cycle Cost Analysis published by Minnesota DOT presents a deterministic and stochastic Equipment LCCA model. The deterministic LCCA model follows the standard LCCA principles found in most LCCA models, but differs in the method of calculating operating cost (13). The stochastic equipment LCCA model is an optimized LCCA with sensitivity analysis. The Major Equipment Life-cycle Cost Analysis model uses equations shown in 3-1 through 3-4 to calculate life cycle costs of equipment (13).

$$\textbf{LCC} = \textbf{Operating Cost} + \textbf{Ownership Cost} \quad (3\text{-}1)$$

$$\textbf{Operating Cost} = \textbf{R\&MC} + \textbf{Fuel Cost} + \textbf{Tire Cost} + \textbf{Tire Repair Cost} \quad (3\text{-}2)$$

$$\textbf{R\&MC} = (\textbf{Repair factor}) \times (\textbf{straight} - \textbf{line depreciation cost}) \quad (3\text{-}3)$$

$$\textbf{Years R\&MC} = \left(\left(\frac{\textbf{Year Digit}}{\textbf{Sum of Years Digit}}\right) \times \textbf{Total repair Cost}\right) + \textbf{R\&MC} \quad (3\text{-}4)$$

Where:

LCC = Life-cycle cost
R&MC = Repair and maintenance costs
Repair factor = Repair factors based on operating condition and equipment type
Year Digit = Year taken in ascending order
Sum of Years Digit = sum of years digit for the depreciation period

Unlike other operating cost models, which generally apply historical data to a preferred regression method, this model proposes a repair factor to model the yearly R&MC. The idea of a repair factor is essentially to apply a synthetic weight, which varies between different equipment types and operating conditions (favorable, average, and unfavorable), and is calculated based on productivity, horsepower utilization, units of gal/fwhp-hr, engine horsepower and fuel price. As in the stochastic LCCA model, "it allows input values for the variables of interest to vary within their historic ranges" (13). In the research, the fuel prices, interest rate, and market value are utilized to conduct the sensitivity analysis, which helps DOT to determine an adjusted replacement period based on confidence levels.

## 3.8. Capital Asset Management (CAM)

Capital Asset Management (CAM), developed by AssetWorks, is a comprehensive asset life-cycle-based management system designed to help minimize capital expenditures and operating expenses by maximizing the useful life of an asset.

The parameters that CAM considers are listed in **Error! Reference source not found.**. Users can decide whether each parameter is required or optional, and some values can be set based on the real situation. This level of flexibility allows for the creation of unique and customizable models.

**Table 3-2: CAM model parameters**

| Description | Value |
|---|---|
| Include Warranty Costs | Yes/No |
| Cost Per Labor Hour | Set value |
| Cost Per Downtime Hour | Set value |
| Cost Per Energy Unit | Set value |
| Depreciation Type | SL/DDB/SOYD |
| Depreciation Term | Set value |
| Maximum Months To Display | Set value |
| Salvage Percentage | Set value |
| Discount Factor | Set value |
| Capitalized Cost | Set value |
| Utilization Meter Type | Distance/Hours |

CAM software generates summary results for selected assets, which contains the average annual capital value and costs through defined years. The costs included in results summary are average yearly maintenance, average yearly downtime, average yearly energy, total operating cost, and cumulative cost. The result summary information is used as input in life-cycle calculator, where the lowest mean equivalent annual cost (MEAC), lowest MEAC year, cumulative utilization in MEAC year is calculated. The CAM model also provides an option to let users look at the life-cycle calculation displayed graphically. In addition, the software shows the quartile grouping of assets based on life-to-date annual usage (low, medium, and high). The plot displays the average maintenance, downtime and fuel costs for each quartiles, which allows users to see the performance of the whole fleet. Additional graphs are also available to provide a visual depiction of output data generated by the model.

# 4. Fleet Data Analysis

One of the main objectives of this work was to examine Caltrans fleet data, to determine characteristics of the dataset, and to determine the suitability of the data for use with different fleet replacement strategies. This chapter discusses data acquisition, data processing and various analysis that were performed on the dataset.

## 4.1. Data Acquisition

Caltrans fleet data is stored and managed using AssetWorks Fleet Focus (FA) fleet management software. The Caltrans version of the software contains a browser based GUI, which allows the user to access data from different screens. In some sections, very detailed information is stored (e.g. work orders) and, without access to FA's backend, can only be retrieved by individual equipment unit. In other sections of the GUI, users can create customized reports, including all fields that are needed for analysis, and summarized data for selected equipment. The interface is shown in Figure 4-1.

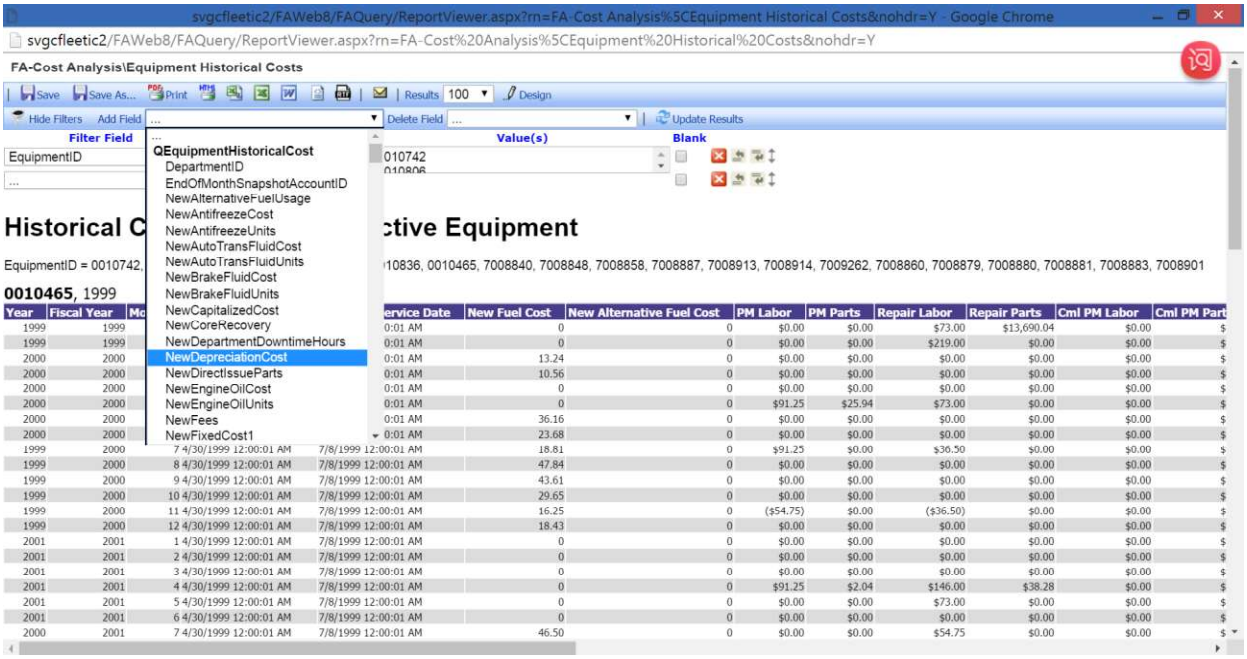



**Figure 4-1: Caltrans FA suite GUI**

The historical data obtained from FA contains 13 categories, which include 514 maintenance classes comprised of 11,106 individual pieces of equipment, ranging from passenger vehicles and light duty trucks to heavy duty vehicles and specialized equipment. In addition to the fleet data obtained from FA, the research team also requested data directly from Caltrans DOE, including fleet cost data from the work order center, Caltrans FAP data, fleet disposal data, etc.

The following four datasets are the primary datasets acquired from Caltrans for fleet data analysis:

1) Fleet Equipment: This dataset provides basic information for each piece of fleet equipment;
2) Equipment-Historical Costs: This is a customized dataset that provides historical cost data for vehicle equipment from the year 1999 to 2016;
3) Fleet Disposal Data: This dataset contains Caltrans previous disposal data; and
4) Work Order Center: This dataset, from the work order center database, contains historical work order cost data for each equipment unit.

The work order dataset is the most recently updated dataset and is newer than the equipment historical costs dataset. Analysis performed after 03/17/2017 uses the work order dataset. The most relevant parameters from each dataset are listed in Table 4-1.

**Table 4-1: Caltrans data acquisition—parameter list**

| | Parameter Name | Description |
|---|---|---|
| **Fleet Equipment** | Equipment ID | Identification for each equipment |
| | Maintenance Class | Equipment type |
| | Category | Each contains numerous maintenance classes |
| | Equipment Description | Detailed description for each equipment |
| | Actual In Service Date | Equipment started in service |
| | Original Cost | Initial purchase price, without any upfitting |
| | Capitalized Value | Equipment value after upfitting |
| | Meter ½ Type | Mile, hour, or none |
| | Life Total Meter ½ | Total usage |
| | Latest Meter ½ reading | The most current meter reading |
| **Equipment -Historical Costs** | Year & Month | Calendar year / month |
| | PM Labor / Parts | Preventative maintenance labor and parts cost |
| | Repair Labor / Parts | Labor and parts cost of repair conducted in-house |
| | Cml PM Labor / Parts | PM labor and parts cost done by outside vendor |
| | Cml Labor / Parts | Labor and parts cost of outsourced repair tasks |
| | End of Month Meter ½ Reading | Total usage up to the end of each month |
| | Current Meter ½ Reading | Monthly usage |
| **Fleet Disposal Data** | Retired Date | The date that one equipment has been retired |
| | Months in Service | Total months in service, the duration between the actual in service date and the retired date |
| | Sale Date | The date that one equipment has been sold |
| | Sale Price | The price at which one equipment has been sold |
| **Work Order Center** | WORK_ORDER_ID | The ID that identifies each opened work order, the number sequence contains 5 digits of work order location, 4 digits of work order year, and last few digits of work order no |
| | JOB_TYPE | Either PM (preventative maintenance) or repair |
| | REAS_REAS_FOR_REPAIR | The repair reason |
| | DATETIME_UNIT_IN | The date and time that equipment is in the shop for PM or repair |
| | DATETIME_FINISHED | The date and time that the work order is finished |
| | TOTAL_COST | Total cost of one work order |

## 4.2. Data Processing

Data processing is an important step when dealing with real-world data. The processing step compiles and organizes data into usable datasets as well as cleaning the data and correcting specific data issues found by the research team during data analysis. To deal with many of these concerns, the research team based corrections on discussion with Caltrans' representatives and acquired knowledge of the dataset. The software used for data processing and some of the data cleaning issues are presented in this section.

### 4.2.1. Data Processing Software

Data processing and analysis were performed using both Excel and Matlab. The datasets were provided as flat .csv files. An implementation of an interactive LCCA was performed using Excel and specific plotting functions were developed for the data set in Matlab. These functions are described in further detail in Appendix A.

### 4.2.2. Negative Meter Usage

Several instances of negative monthly meter usage were found in the data set. According to Caltrans, these values are likely corrections for errors in previous meter readings. These values were typically replaced with corrected values based on odometer readings.

### 4.2.3. Negative Cost

Similar to negative meter usage, negative cost values were also found in the dataset. These values are also thought to be corrections for incorrect entries in previous cost data. In many cases, these were associated with a large cost value in the previous period and applied to the previous period to make an adjustment.

### 4.2.4. Empty Capitalized Value

Empty capitalized values existed in the data set. In these cases, the value was set equal to the original cost, which does not have any empty fields in the dataset.

### 4.2.5. Excessive Costs in Early Years

In some cases, excessive costs in the first few years were observed. These values are likely delayed up-fitting costs and in some cases may already have been added to the capitalized value. The research team removed any costs greater than 1000 in the first 2 years and discarded them.

### 4.2.6. Excessive Monthly Usage

Excessive monthly usage was believed to be incorrect data entry and the value was typically replaced based on values for cumulative usage (odometer reading) and previous values. Thresholds for excessive or unrealistic monthly usage were but in place to identify these points.

## 4.3. Fleet Age Composition

An important factor in the fleet replacement decision-making process is equipment age. The distribution of equipment age by equipment category in the Caltrans fleet is presented in the bar chart in Figure 4-2. In this figure, the x-axis shows the 13 categories in Caltrans fleet, and the y-axis shows the percentage of fleet composition. The bar chart also presents additional information. The numbers in the first row above the chart title are the quantities of

equipment in each fleet category, and the numbers in the second row are the quantities of maintenance classes in each fleet category. For example, for the passenger vehicle category, about 40% of equipment is over 10 years old, which is around 695 pieces of equipment. Looking across the vehicle categories, at least 10% of the fleet or 1110 pieces of Caltrans equipment are older than 20 years. A percentage of these pieces of equipment are older than 25 years. The category with the highest percentage of new equipment is the road maintenance category.

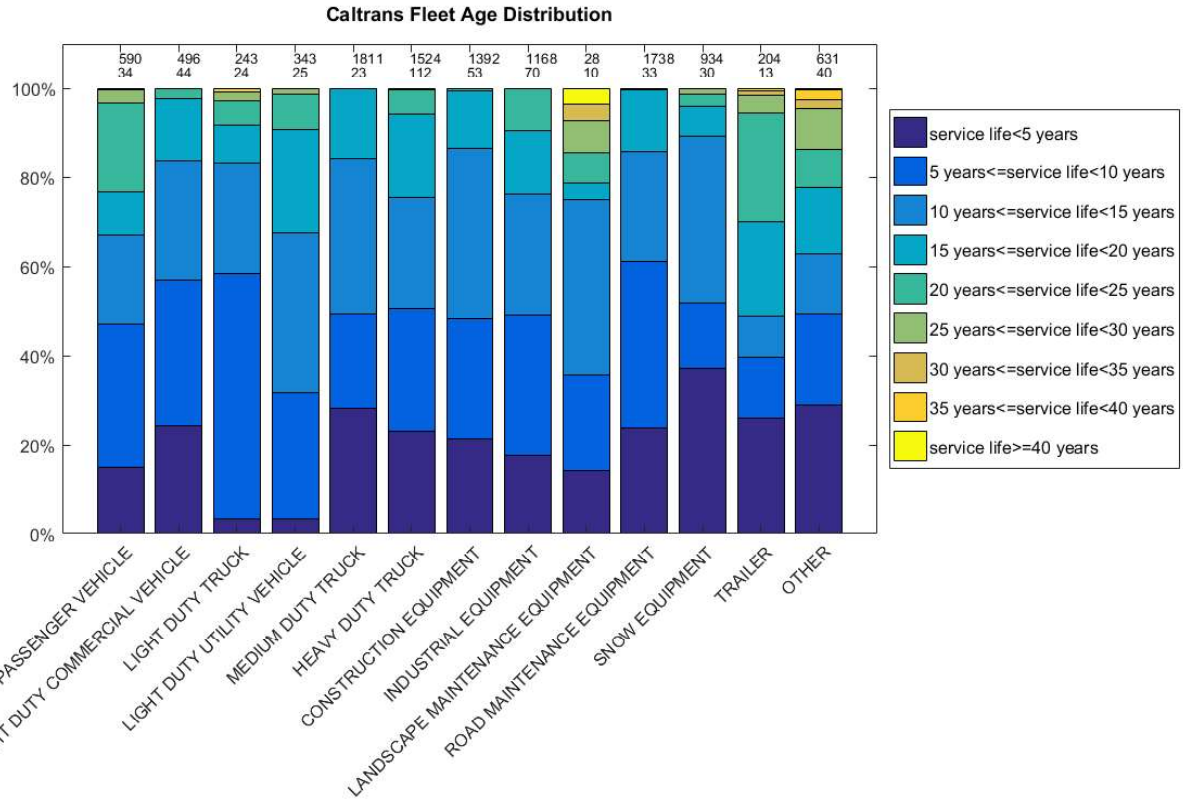



**Figure 4-2: Caltrans fleet age distribution**

## 4.4. Cost Trends

Another important factor in the fleet replacement decision-making process is vehicle cost. As vehicles age and accrue mileage, the costs required to keep vehicles in service are expected to increase. The total costs may be offset by a decrease in vehicle usage under those conditions. Other factors may also affect costs, such as, operating environment or the particular vehicle model.

Figure 4-3 shows boxplots for the cumulative cost of passenger vehicles by mileage and age. In each boxplot, the central red line indicates the median value, and the bottom and top edges of the box indicate the 25th and 75th percentiles. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the '+' symbol. From both sets of boxplots in Figure 4-3, it is evident that there is a wide

range in cumulative costs for vehicles within the passenger vehicle category, and there are numerous outliers labeled by red crosses. The cumulative plot versus mileage shows that for the passenger vehicle category, the average increase in cumulative cost by mileage is nearly linear which indicates a constant annual cost. This is not the case with age where the cumulative cost appears to follow a second order polynomial trend until year 16. This indicates that the average vehicle cost by year is increasing. It is important to note that the trends at higher mileage are biased towards better-behaved vehicles since the poorly behaving vehicles are replaced and drop out of the dataset.

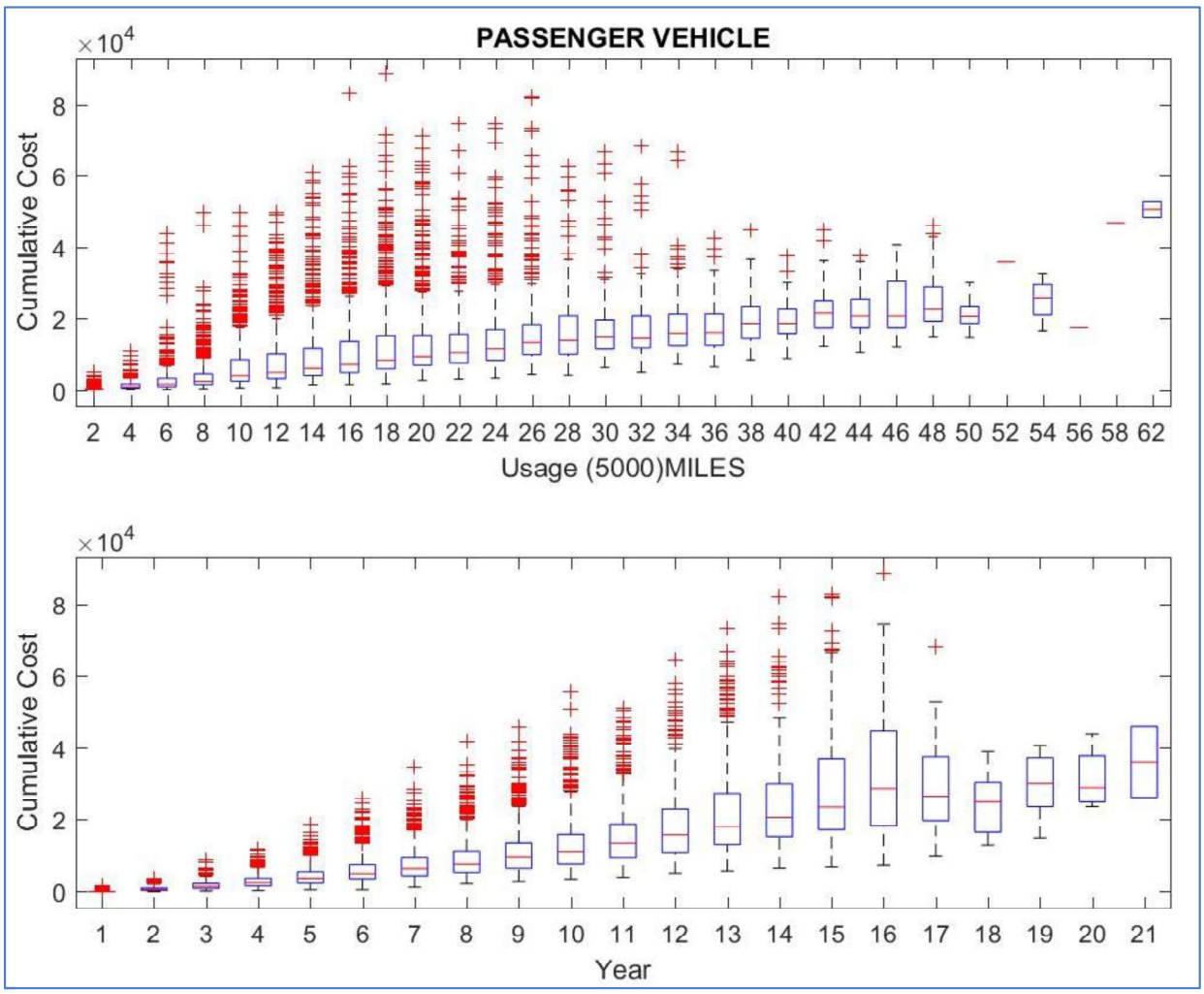



**Figure 4-3: Cumulative cost of passenger vehicle.**

## 4.5. Annual Usage

Annual usage is an important variable when analyzing fleet characteristics. As vehicles deteriorate with age and mileage, their usage has been found to decrease. Figure 4-4 shows cumulative annual usage and annual usage by age for the passenger vehicle category for vehicles purchased prior to 2006 (at least 10 years old). According to the plot, the cumulative

annual usage for passenger vehicles decreases with equipment age until the trend plateaus around 15 years at which point the average vehicle's annual mileage accrual is near zero. This is also evident in the annual usage plot. Similar patterns are observed in other fleet categories and maintenance class levels, such as the medium duty truck shown in Figure 4-5.

**Figure 4-4: Passenger vehicle usage vs age.**

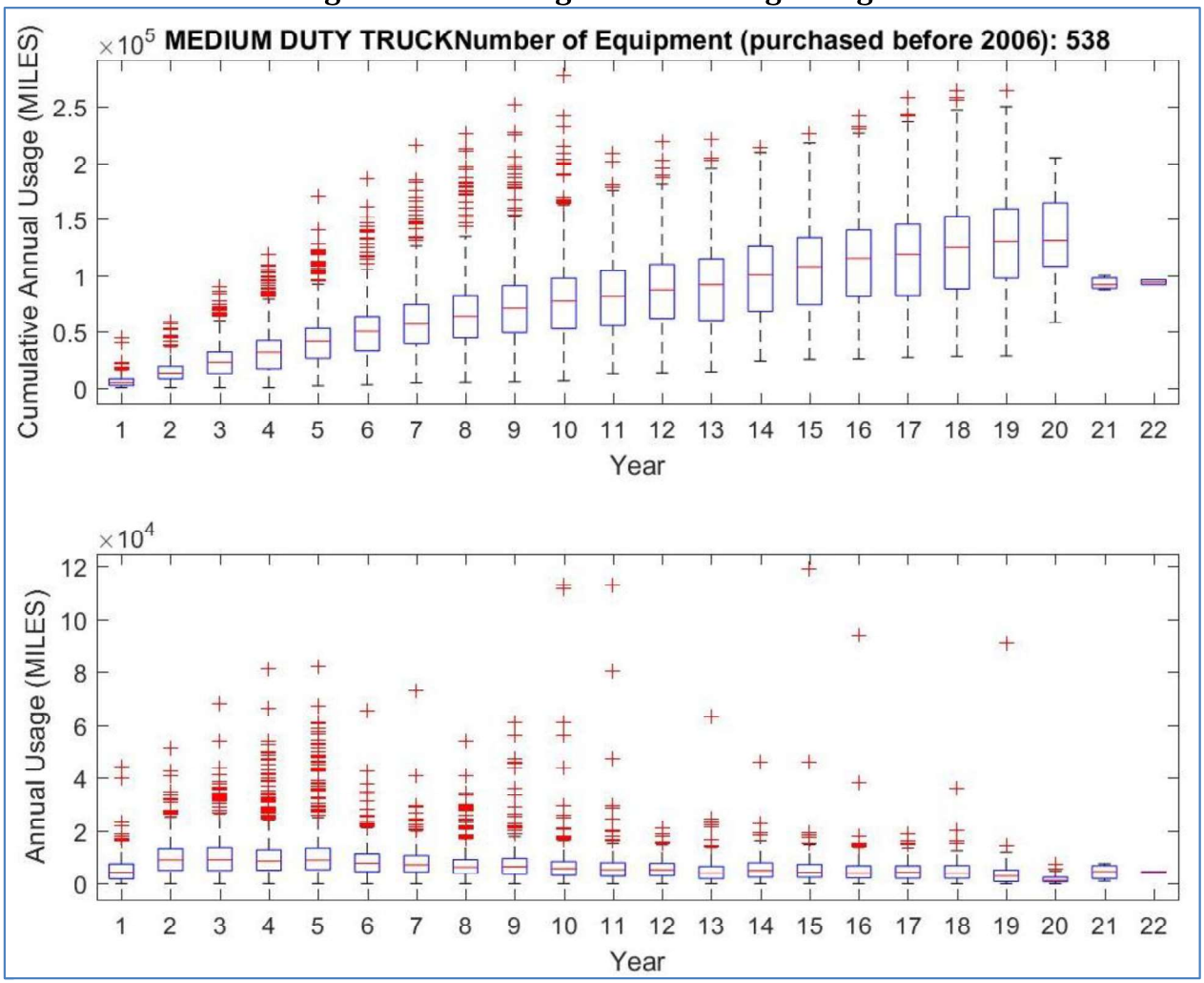



**Figure 4-5: Medium duty truck usage vs age**

## 4.6. Annual Cost per Usage

Since a decrease in usage affects annual vehicle costs, the annual cost normalized by the annual usage is examined. Figure 4-6 and Figure 4-7 show these values for the Dump Body and Mid-size SUV categories. All equipment units used in both figures were purchased before 2006 and are therefore at least 10 years old.

In both figures, the yearly cost per usage versus age show an increase with vehicle age. This is expected since the average vehicle usage decreases with age and vehicles are always likely to incur some type of costs, such as preventative maintenance costs, even when usage is low.

It may also be due to older equipment having higher or more frequent repair and/or maintenance costs.

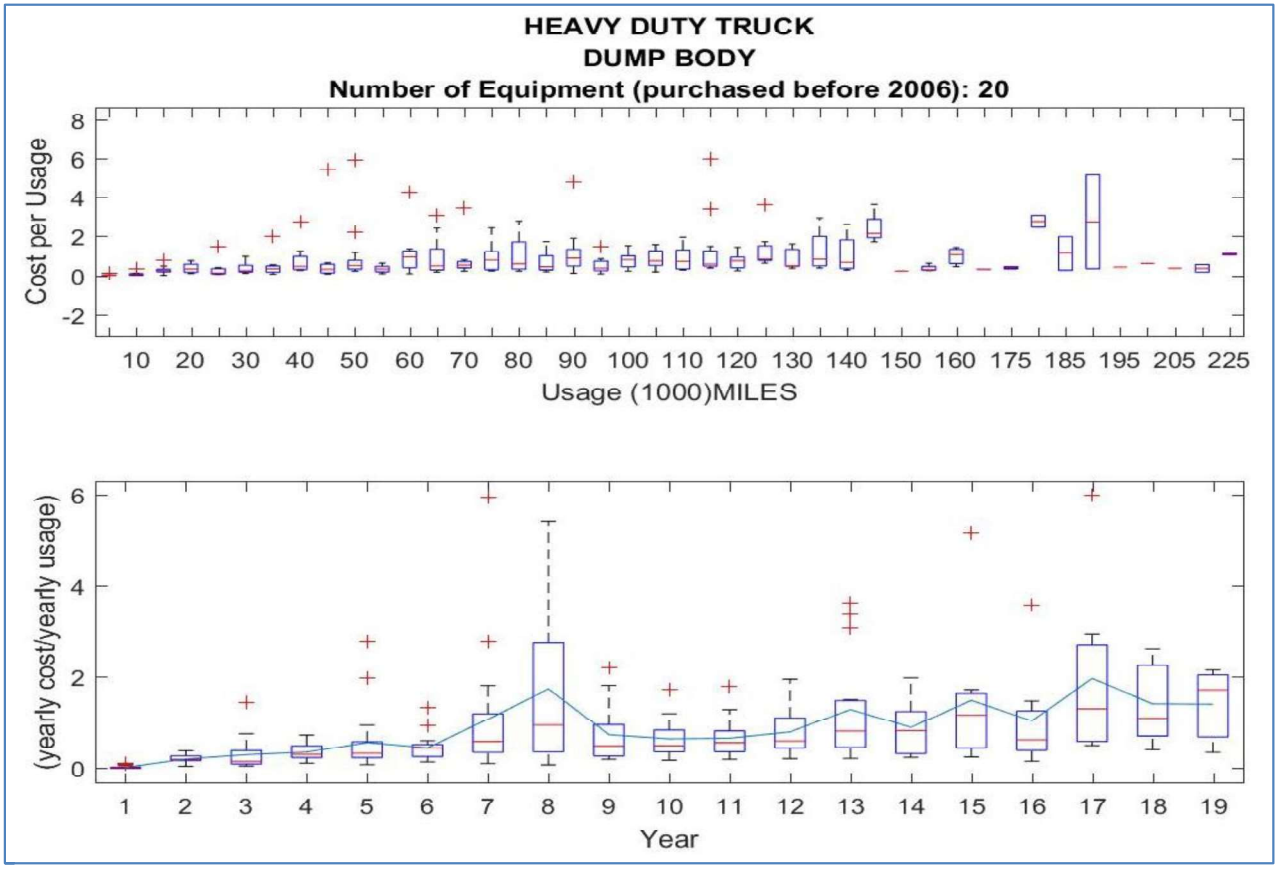



**Figure 4-6: Yearly cost per usage for dump body**

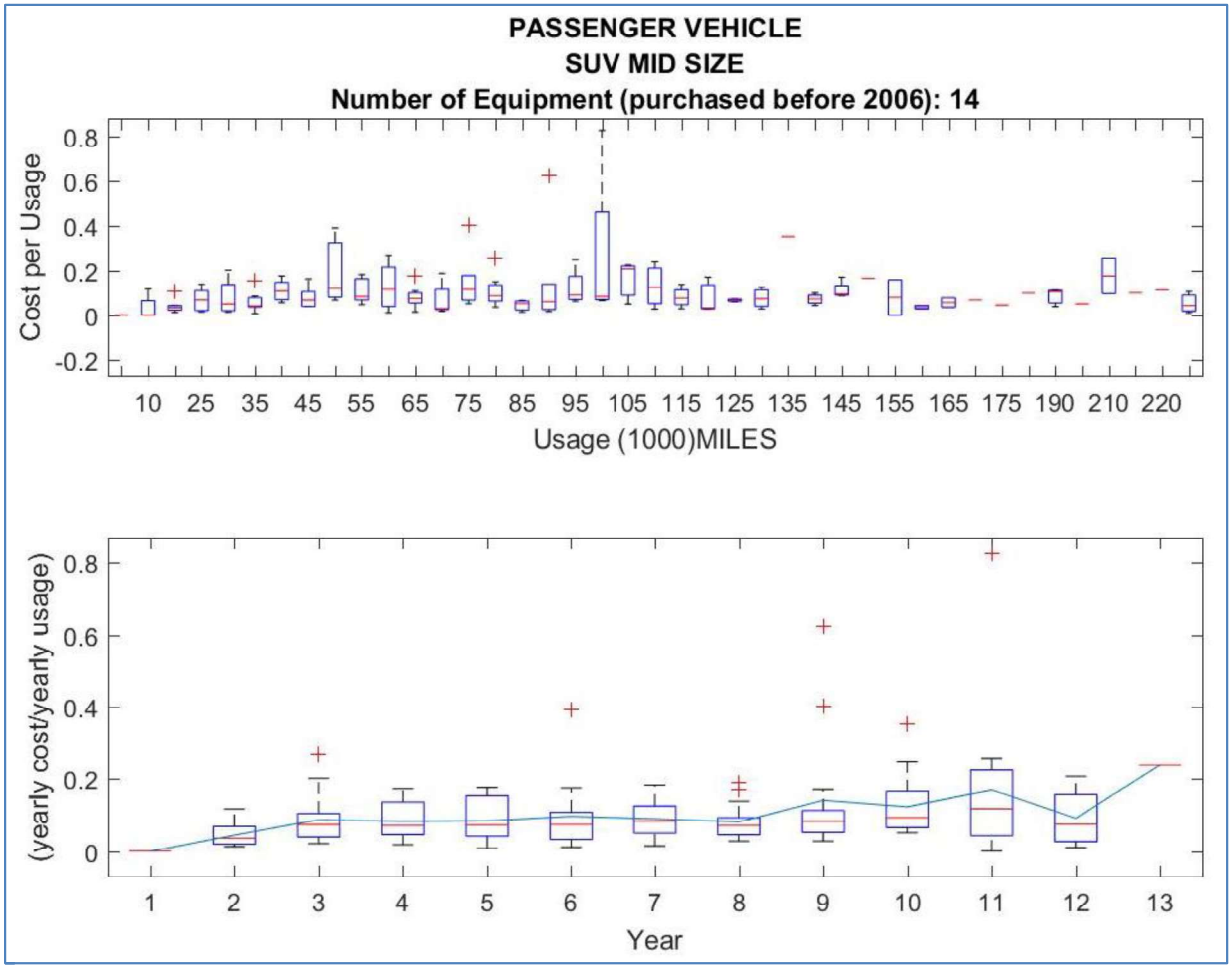



**Figure 4-7: Yearly cost per usage for mid-size SUV**

## 4.7. Evaluating High Cost Vehicles

Analysis of the Caltrans fleet data shows that there is a wide range in the ratio of cumulative cost by age, even within a given equipment category as seen in Figure 4-3 for passenger vehicles. In Figure 4-3, there are numerous outliers. These vehicles are the most costly. To show the difference between these vehicles more clearly, the research team plotted operating costs for individual vehicles in the bottom and top 10%. Figure 4-8 shows this plot for the Passenger Vehicle category. The defined parameters are shown in the plot title and are labeled as follows:

"PASSENGER VEHICLE(1738) q10=59 q90=58 R=473 (10)"

where:

PASSENGER VEHICLE: name of the chosen category
1738: total number of equipment in the category
q10=59: number of equipment in the bottom 10% level
q90=58: number of equipment in the top 10% level
R=473: remaining equipment
10: reference point, year 10

The percentile plots are based on a reference year. Each equipment unit that reached the reference age are grouped based on their total life-to-reference year cost. In this example, if the cumulative operating cost at year 10 is over 90%, then this equipment is grouped into the top 10% level (q90); similarly, if the cumulative operating cost at year 10 is below 10%, then this equipment is grouped into the bottom 10% level (q10). The R parameter in the title shows the number of equipment between top and bottom 10% levels. Surprisingly, there is very little overlap between vehicles in the bottom and top percentiles and the groupings seem to be well defined. Vehicles in the top percentile continue to have a higher slope (higher yearly operating cost) than vehicles in the bottom percentile. This indicates that low cost vehicles tend to stay low and high cost vehicles tend to stay high.

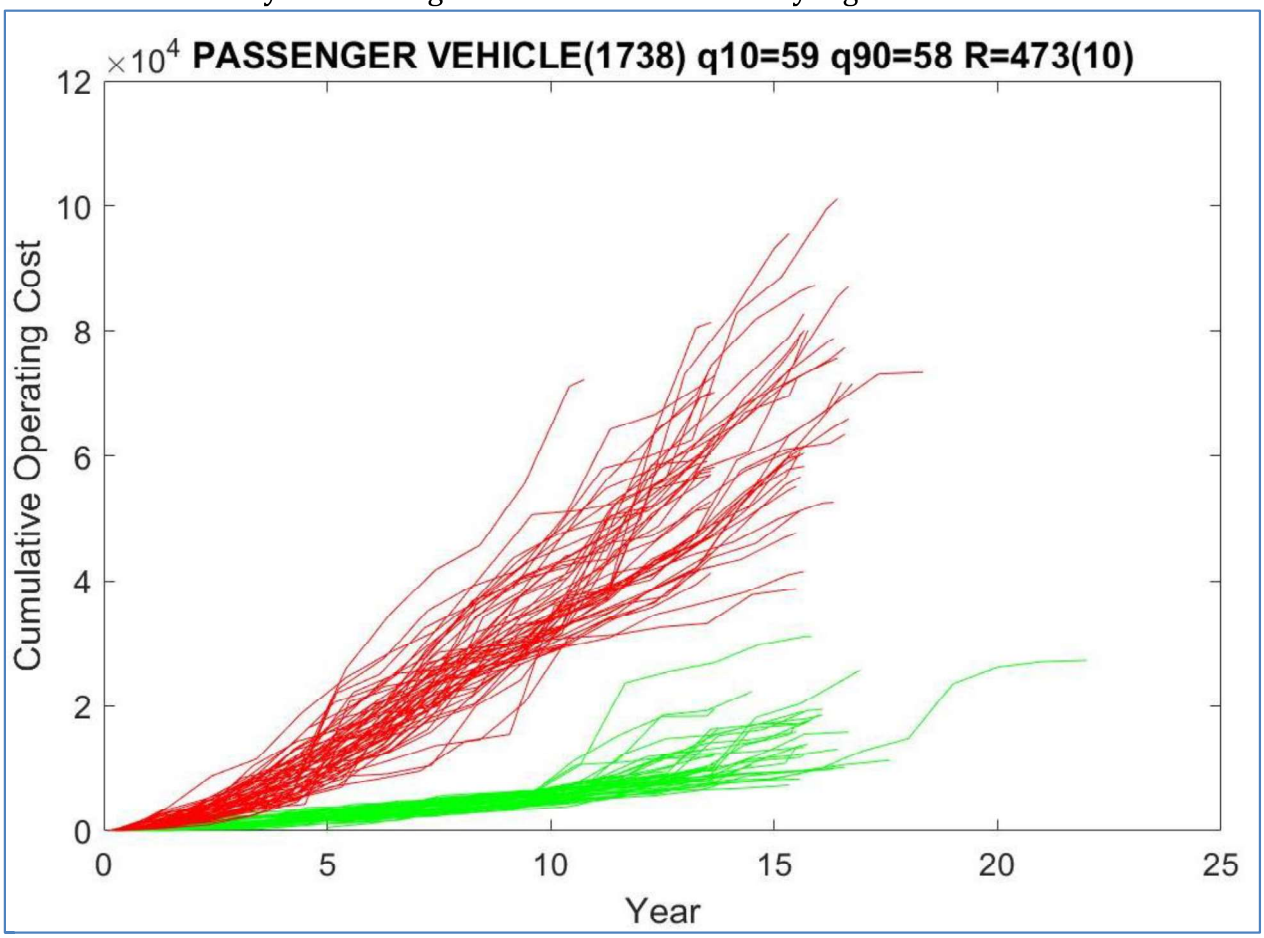



**Figure 4-8: Percentile plot for passenger vehicle class**

To investigate whether a correlation exists between high cost vehicles and individual Caltrans districts, the distribution of high cost and low cost vehicles across districts was graphed and the results are presented in Figure 4-9. Results in Figure 4-9 show that a large number of the high cost vehicles are from district 7 and that district 7 has a high ratio of high cost vehicles to low cost vehicles. This type of information can help identify locations that may require further investigation.

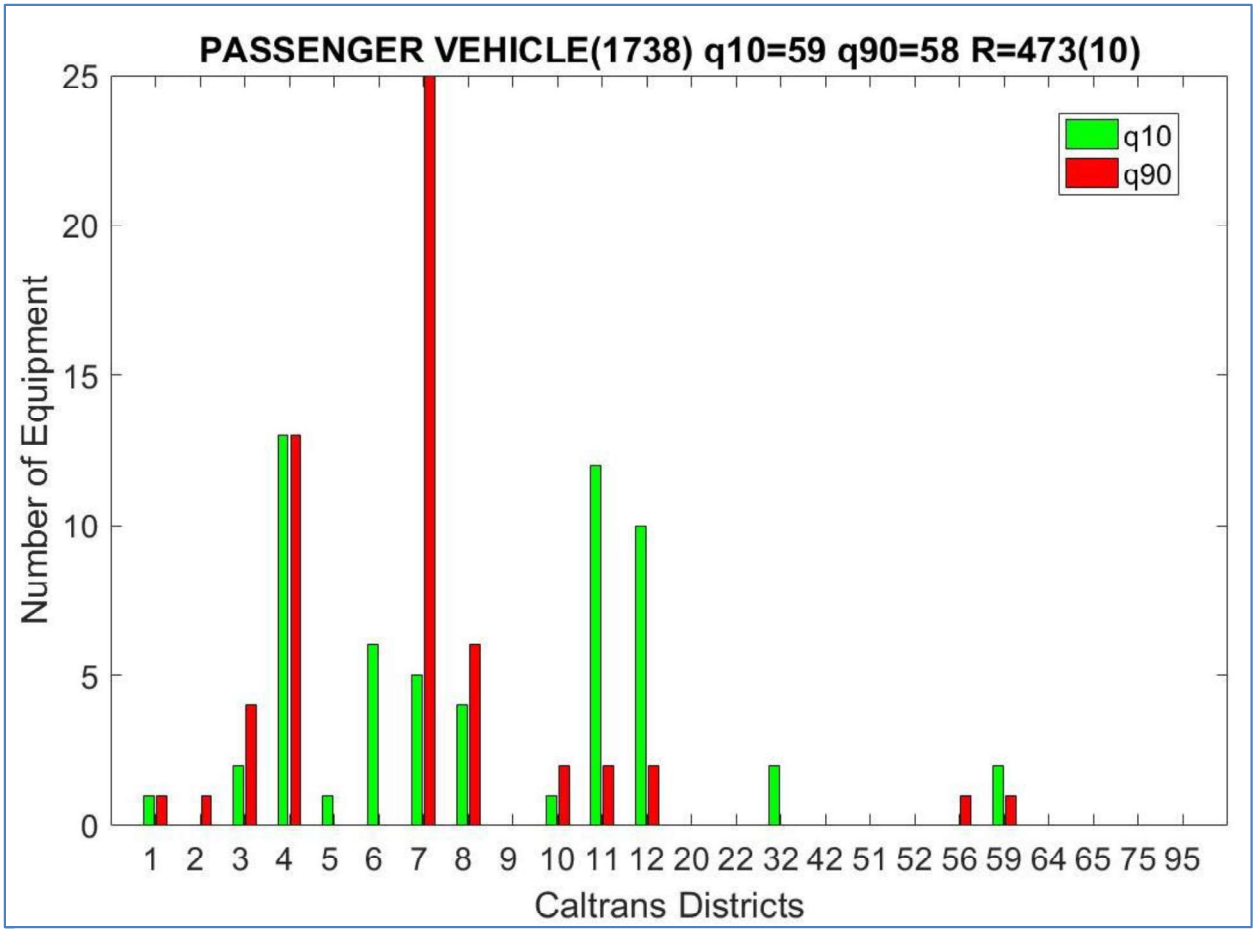



**Figure 4-9: Distribution of high and low cost passenger vehicles by district.**

## 4.8. Analysis of Caltrans FAP

As part of the Federal-Aid Primary (FAP) system, Caltrans has designated a number of vehicles for replacement on a one-year and five-year plan. To select candidate vehicles for these plans, Caltrans prioritizes their fleet equipment using the Fleet Utilization Score discussed in Chapter 3-2. Equipment with higher scores are considered replacement candidates either in the one-year-plan or in the five-year-plan. A comparison of the replacement vehicles to the high cost vehicles is presented in Figure 4-10. All red lines represent equipment in the top 10% of cumulative cost and all green lines represent equipment in the bottom 10% of cumulative cost. All vehicles from the FAP list are plotted in blue. Where there is overlap with the top or bottom 10%, the FAP vehicles are represented by blue stars. The overlap between Caltrans' FAP list and the percentile plot may help determine whether the candidate on the FAP list are good candidates for replacement.

Figure 4-10 shows the overlap for the class PICKUP SUPER ½ TON EXTCAB AFV, which has the largest quantity of replacement candidates under one-year-plan. The meanings of the plot title are listed below:

"PICKUP SUPER ½ TON EXTCAB AFV (276)--1 Year Plan
q10=28/2 q90=28/14 R=220/66 (9)"

Where:

PICKUP SUPER ½ TON EXTCAB AFV: Name of the chosen maintenance class

276: Indicates the total number of equipment in the maintenance class

1 Year Plan: Equipment plotted in the figure is part of the one-year-plan

q10=28/2: Bottom 10% level has 28 pieces of equipment. Two pieces of equipment overlap with the FAP list

q90=28/14: Top 10% level with 28 pieces of equipment. Fourteen pieces of equipment overlap with the FAP list

R=220/66: There are 220 pieces of remaining equipment. Sixty-six of these pieces of equipment overlap with the FAP list

9: Indicates the reference year at which percentiles are calculated for each vehicle.

Figure 4-10 shows that there are two pieces of equipment on the FAP list, which have relatively low cumulative cost and may not be good candidates for replacement. Similarly, there are 14 pieces of equipment, which are in the top 10% of cumulative cost, but are not on the FAP replacement list. These pieces of equipment may require further analysis to determine whether they are good candidates for replacement.

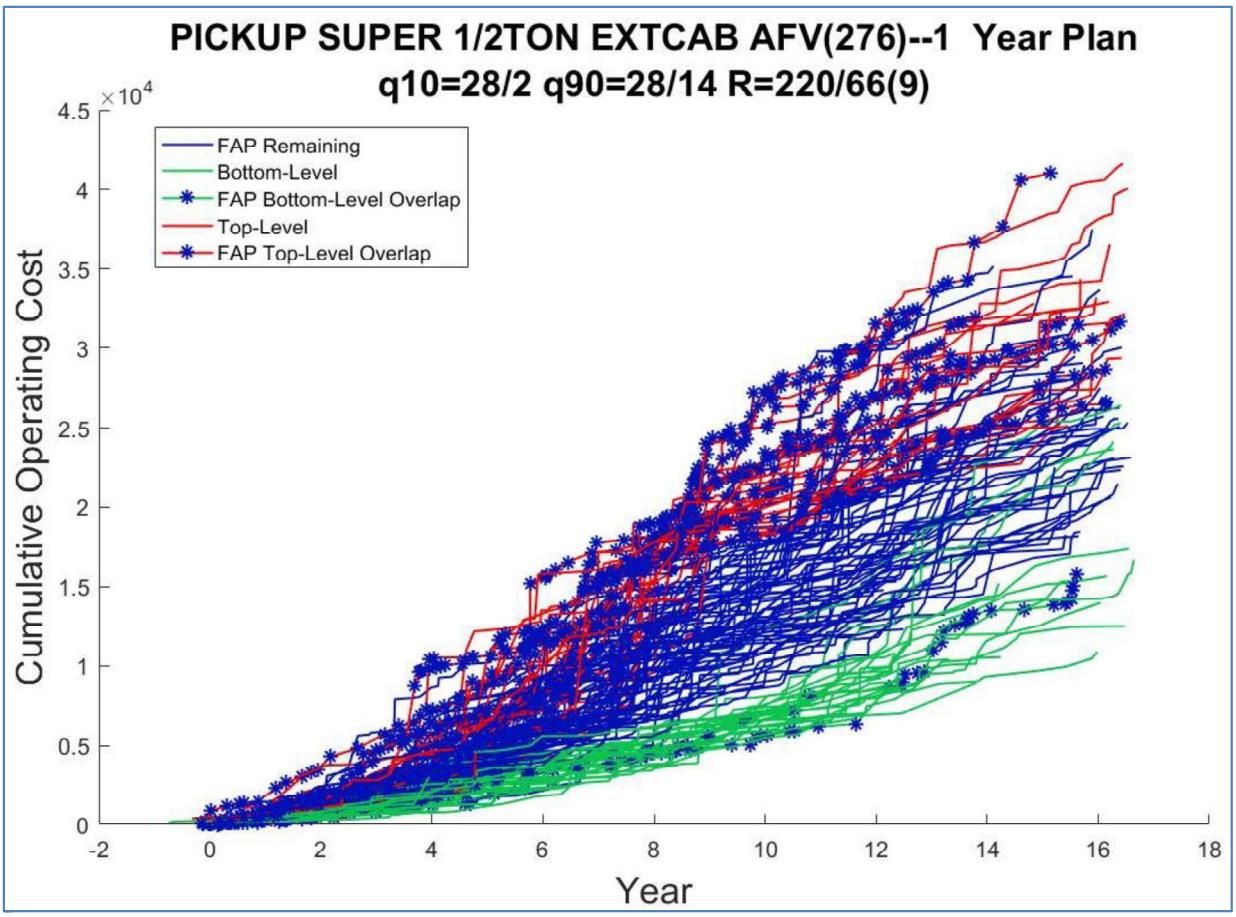



**Figure 4-10: Analysis of FAP candidates in Pickup Super ½ Ton EXTCAB AFV**

Figure 4-11 presents the analysis plot of FAP candidates and the top and bottom 10% of cumulative cost for the DUMP BODY W/PLOW & SPREADER maintenance class, which has a large quantity of replacement candidates under five-year-plan. Based on the figure, there are 243 pieces of equipment in this maintenance class and 21 pieces of equipment are in the bottom 10% of cumulative cost. Out of those 21 pieces of equipment, 16 are on the FAP 5-year-plan list. There are also 21 pieces of equipment in the top 10% of cumulative cost, five of which are on the FAP list. Further work should be conducted to determine why low cost vehicles are scheduled for replacement and some high-cost vehicles are not.

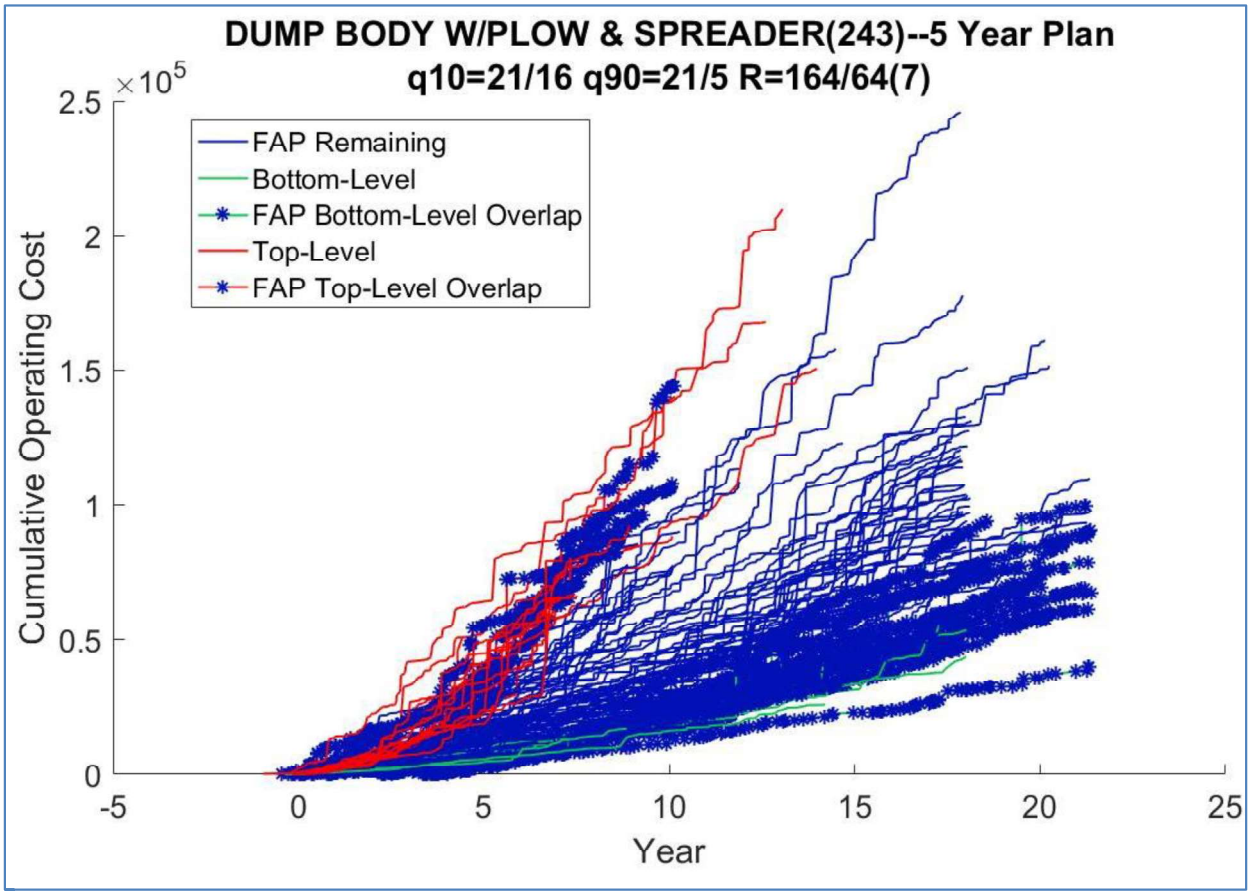



**Figure 4-11: Analysis of FAP candidates in Dump Body W/Plow & Spreader**

The trends for low and high cumulative cost vehicles show that most of the high cost equipment continues to have high costs for the life of the equipment. To try to quantify this observation, the research team built a matrix to show the probability that a piece of high cost equipment remains high cost for a certain number of years. The probabilities in the matrix are calculated using historical data from the Caltrans fleet data set. If, for example, there are 20 pieces of equipment are high cost at year 1, and after 4 years at year 5, only 10 of them remain high cost, then the probability at year 5 of a vehicle remaining high cost is 50%. This means that a high cost equipment in year 1 has 50% probability to be a high cost vehicle at year 5. The high cost probability matrix for the Pickup Super ½ Ton EXTCAB AFV class is presented in Figure 4-12. Reading the matrix horizontally, high cost equipment in year one has a 35.71% probability to stay high cost in year 10. High cost equipment at year 9 will have

a 78.57% probability to be high cost at year 10. It can be concluded that when the two years are close, the probability is usually higher.

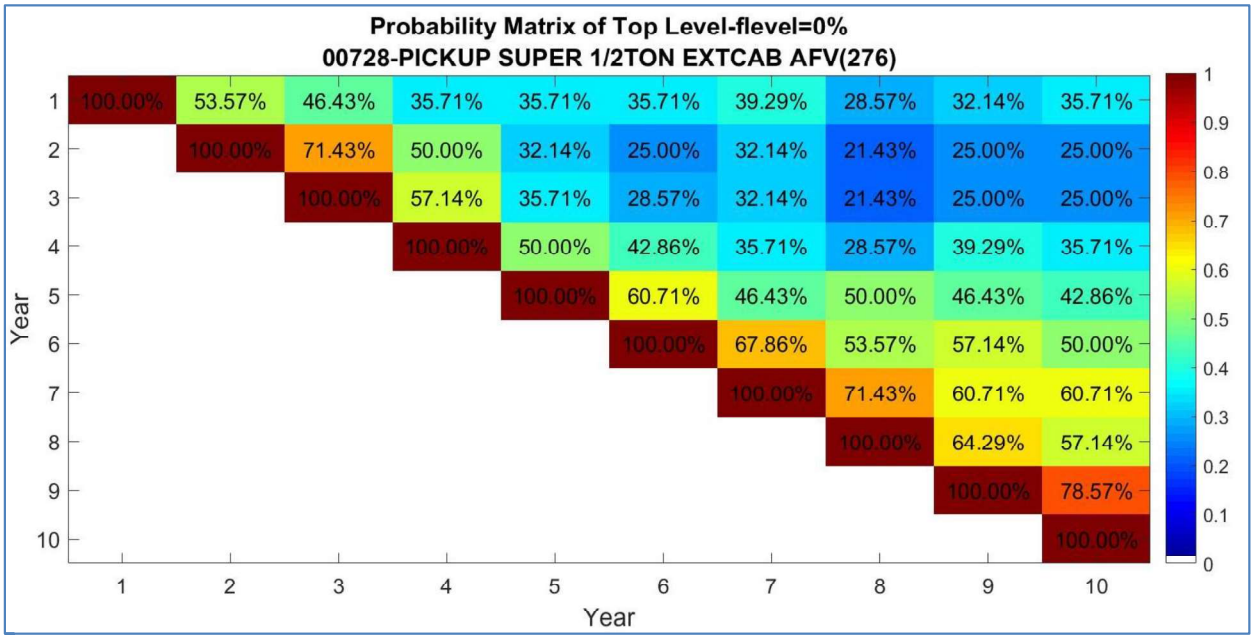



**Figure 4-12: Probability Matrix of Top Level with flevel=0%--MC 00728**

The probabilities presented in Figure 4-12 show some unexpected fluctuations. For example, at year 4, equipment in the top level has 35.71% chance to stay in top level at year 7, 28.57% chance at year 8, and 39.29% chance at year 9. Such fluctuations occur due to some high cost vehicles are near the threshold of high cost, dipping above and below that threshold throughout the years. This phenomenon is depicted in Figure 4-13, where the two green lines are the cumulative costs for two different vehicles and the black line is the 10% high cumulative cost threshold. To classify these vehicles that hover around the high-cost line as high cost, the research team added a parameter call "flevel". This parameter creates a window to allow for such fluctuation. To be specific, setting the "flevel" equal to 5%, decreases the threshold value by 5%.

With the "flevel" set at 15%, the top threshold value is decreased by 15% and the fluctuation is minimized as in Figure 4-14. The probability that a high cost vehicle in year one, remains high cost in year 10 is no longer 35.71% but 46.43% and the probability that a high cost vehicle in year 9 remains high cost in year 10 becomes 100%. The improvement is significant and more intuitive, especially for the later years. Increasing the "flevel" increases the range for high cost vehicles and increases the probability that a vehicle will be considered high cost.

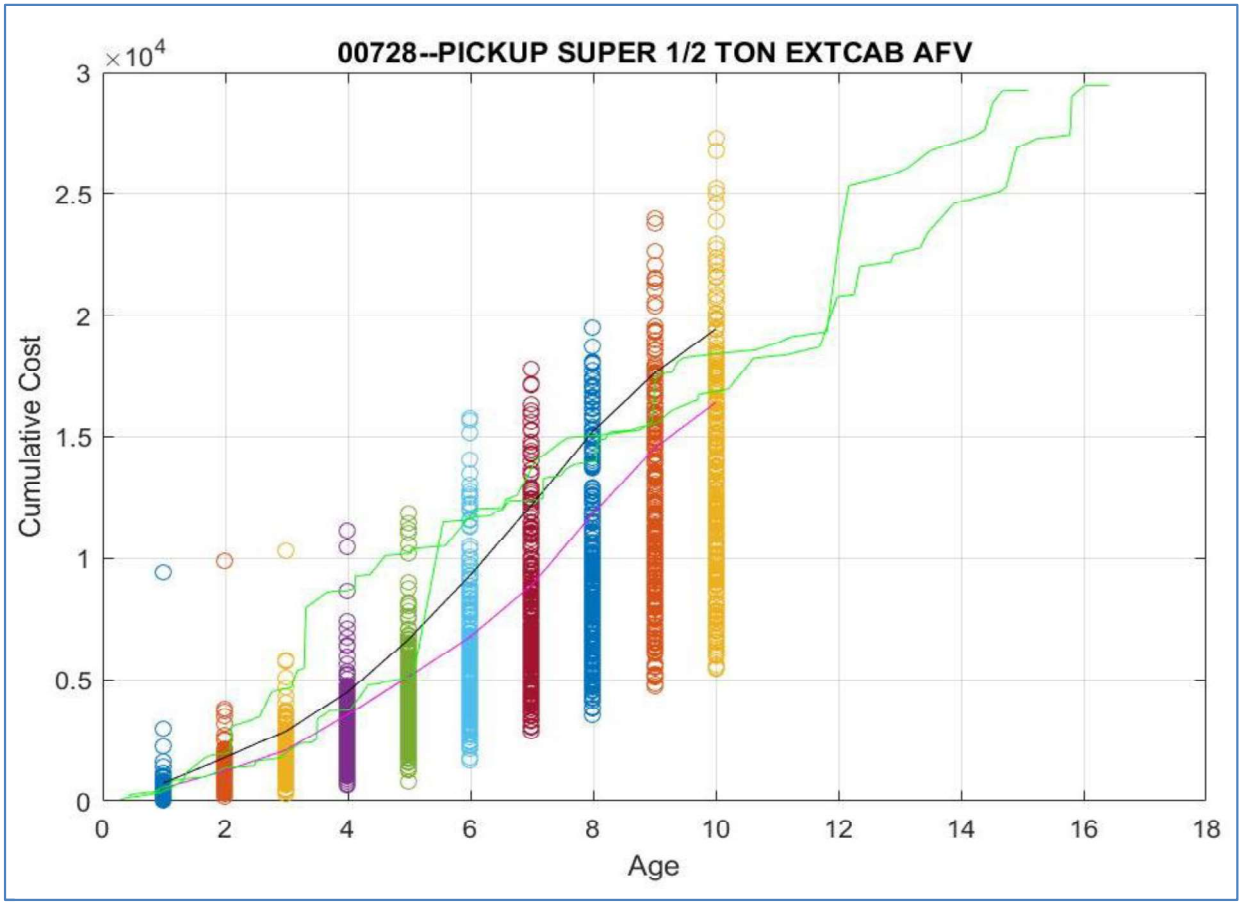



**Figure 4-13: Explanation of Probability Fluctuation**

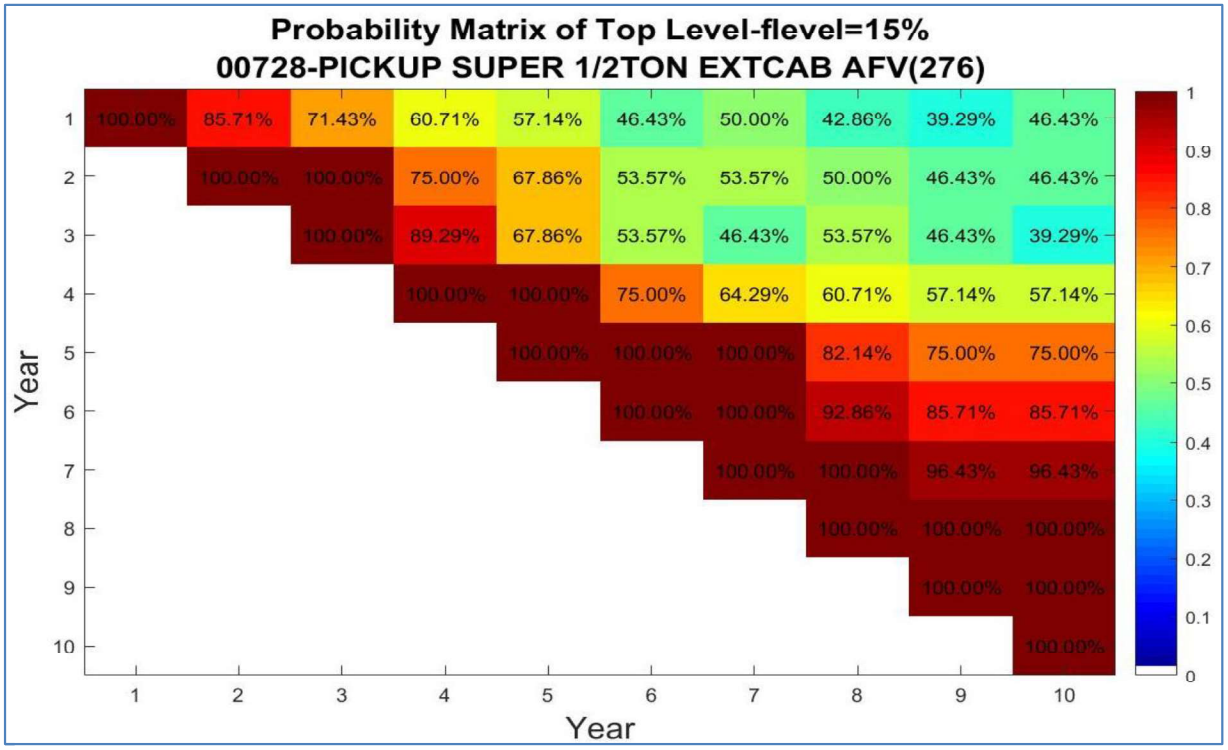



**Figure 4-14: Probability Matrix of Top Level with flevel=15%--MC 00728**

## 4.9. Usage Management

Analysis was conducted by the research team to determine if vehicle retention could potentially be extended by leveling vehicle usage across Caltrans districts. Utilizing this method, high usage units from one district would be switched with low usage units from another, similar to rotating tires on a vehicle. To research this idea, the mileage distribution for a sample category was examined for the vehicle class "Pickup W/A/C ¾ Ton". Since usage here is indicated by total vehicle mileage, it is necessary to compare equipment with the same model year or actual in service year. The histogram of equipment quantity by service year for the "Pickup W/A/C ¾ Ton "vehicle class shows that the largest quantity of vehicles have a service year of 2014.

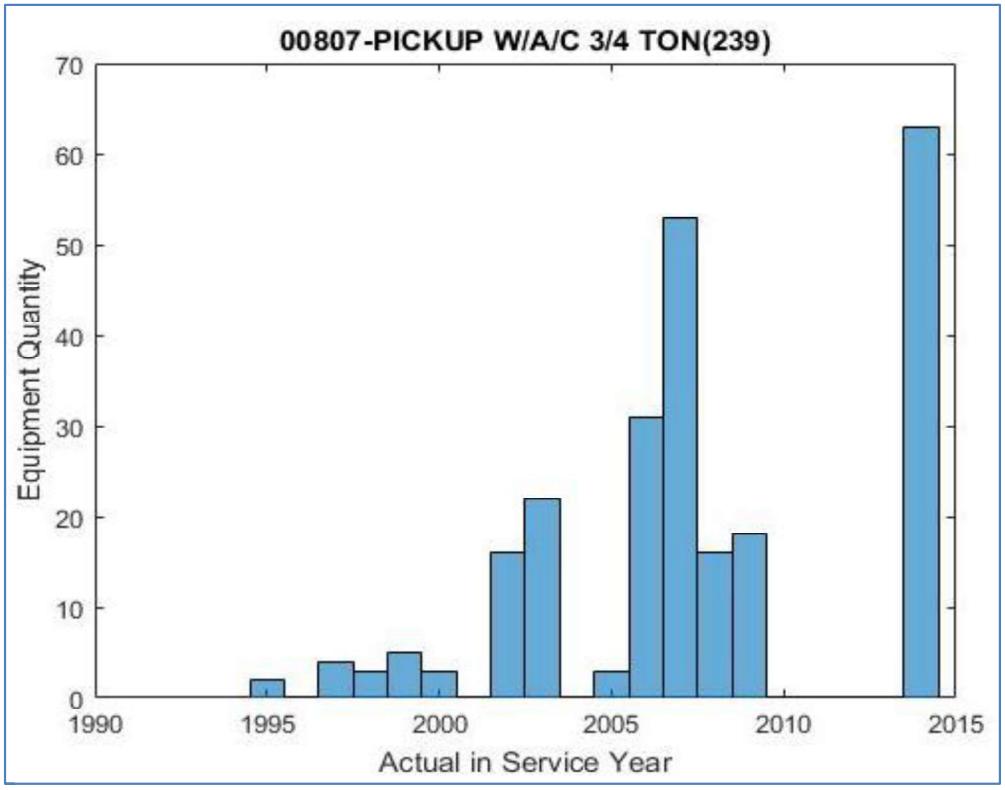



**Figure 4-15: Pickup W/A/C ¾ ton actual in service year distribution.**

The scatter plot in Figure 4-16, shows life-to-date usage in miles by district for various pieces of equipment. Each blue dot represents the life-to-date usage in miles of one piece of equipment in a certain district. There are 63 "Pickup w/a/c ¾ ton" with service dates starting in 2014. The number on the top border of the figure shows the number of equipment in each district. The data in Figure 4-16 shows that in most districts that have "Pickup w/a/c ¾ ton", there is a wide range in usage. This would seem to indicate that, at least for this category, equipment could be rotated within a district and that rotating equipment between districts would not be required.

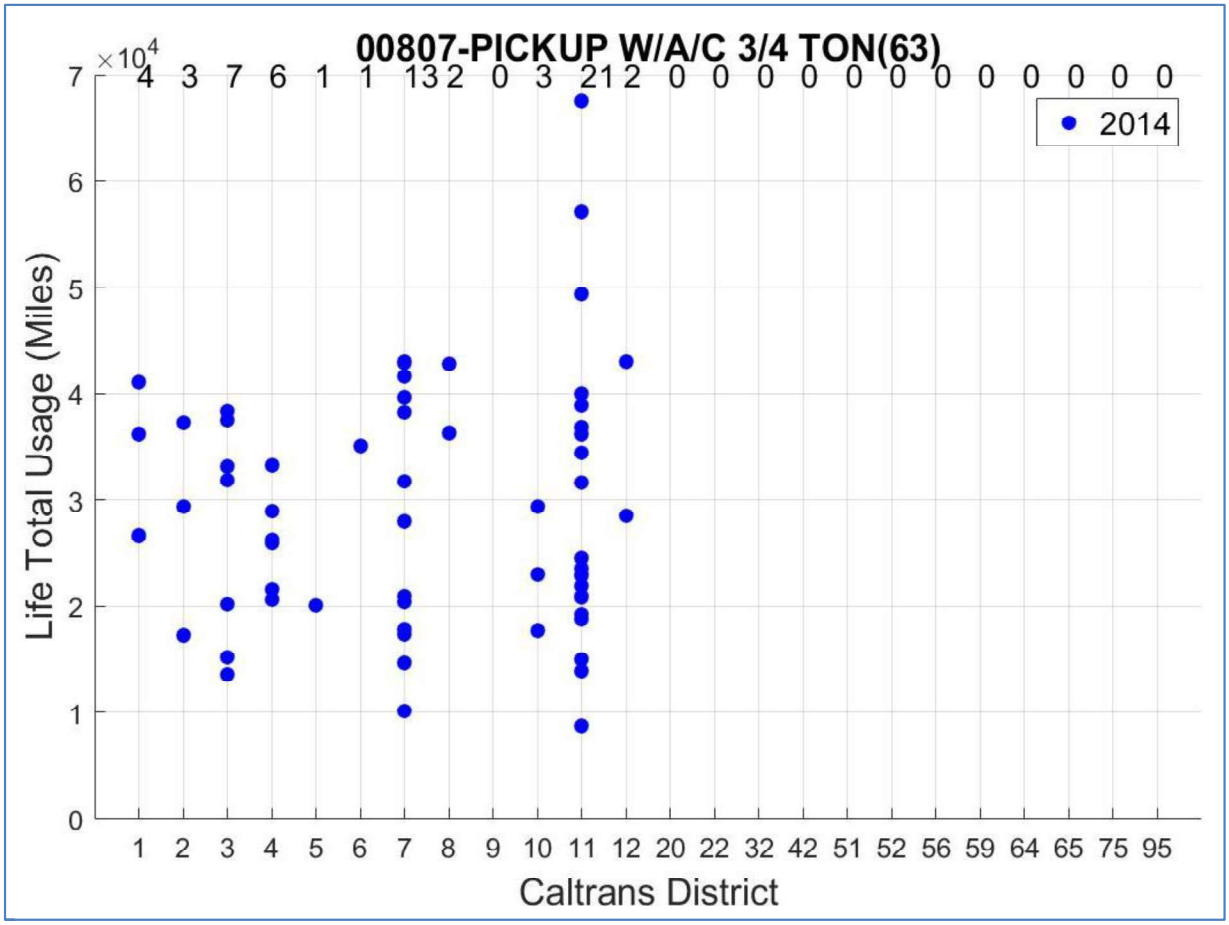



**Figure 4-16: Pickup W/A/C ¾ Ton Life Total Usage Distribution (Model Year 2014)**

## 4.10. Comparison of Brine Using Counties

Additional analysis was performed to investigate the possible effect of brine usage on vehicle costs. Two regions in near proximity to each other were selected: Truckee and Kingvale. The city of Kingvale is known to use brine on roadways for anti-icing or pre-wetting measures. The city of Truckee does not have a brine usage program. Cumulative cost data for trucks in both Truckee and Kingvale are presented in Figure 4-17. Although, Kingvale does have some lower cumulative cost vehicles, most of the high cost vehicles belong to Kingvale, which may be a result of brine usage

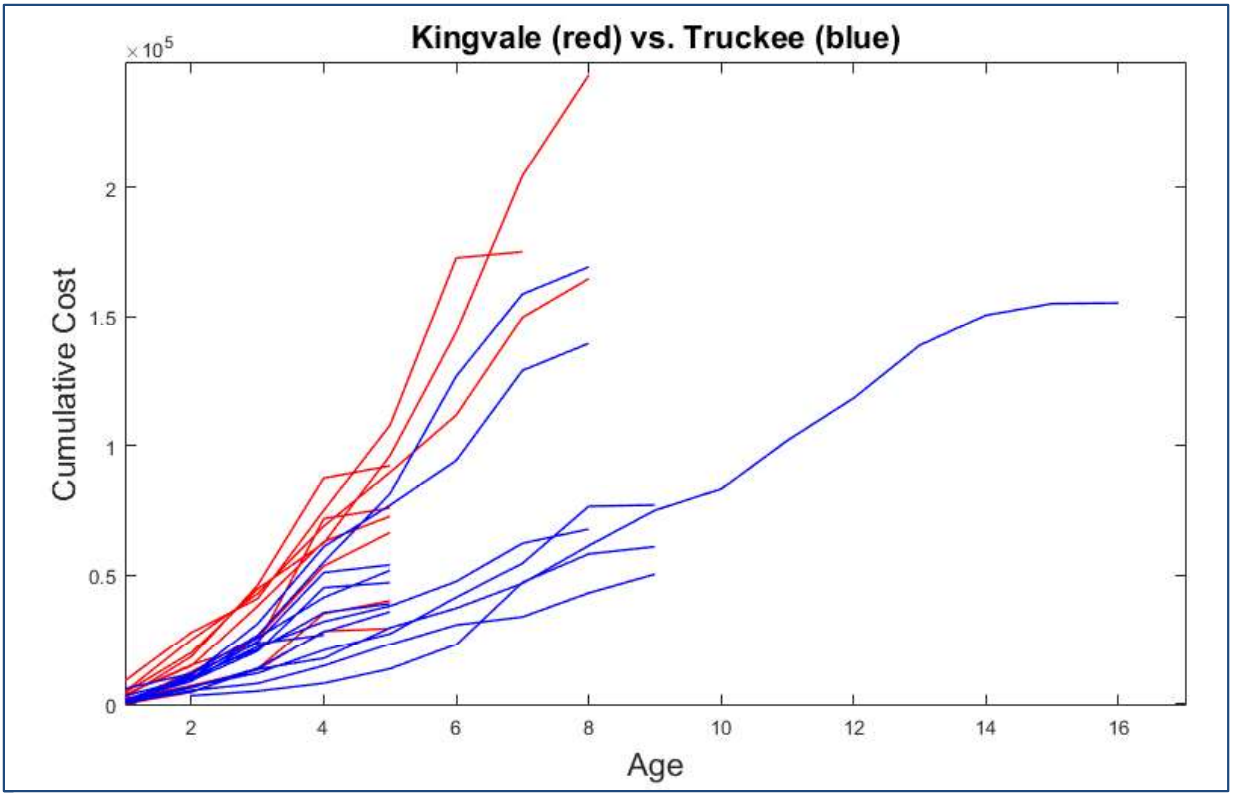



**Figure 4-17: Comparison of cumulative cost truck data relative to brine usage.**

## 4.11. Vehicle Sold Age and Remaining Value

Data from a Caltrans disposal report was evaluated and the quantity of vehicles sold by vehicle age were examined. Figure 4-18 and Figure 4-19 show the ages of sold Caltrans vehicles for a ½-ton pickup class and a dump body class. These examples show that the majority of vehicles for these two classes are sold within an 8 to 9 year range of vehicle ages, but that most ½-ton trucks are sold at 11 years of age and most dump bodies are sold at 19 years of age. These examples show that the typical age at which vehicles are replaced can vary greatly by vehicle type.

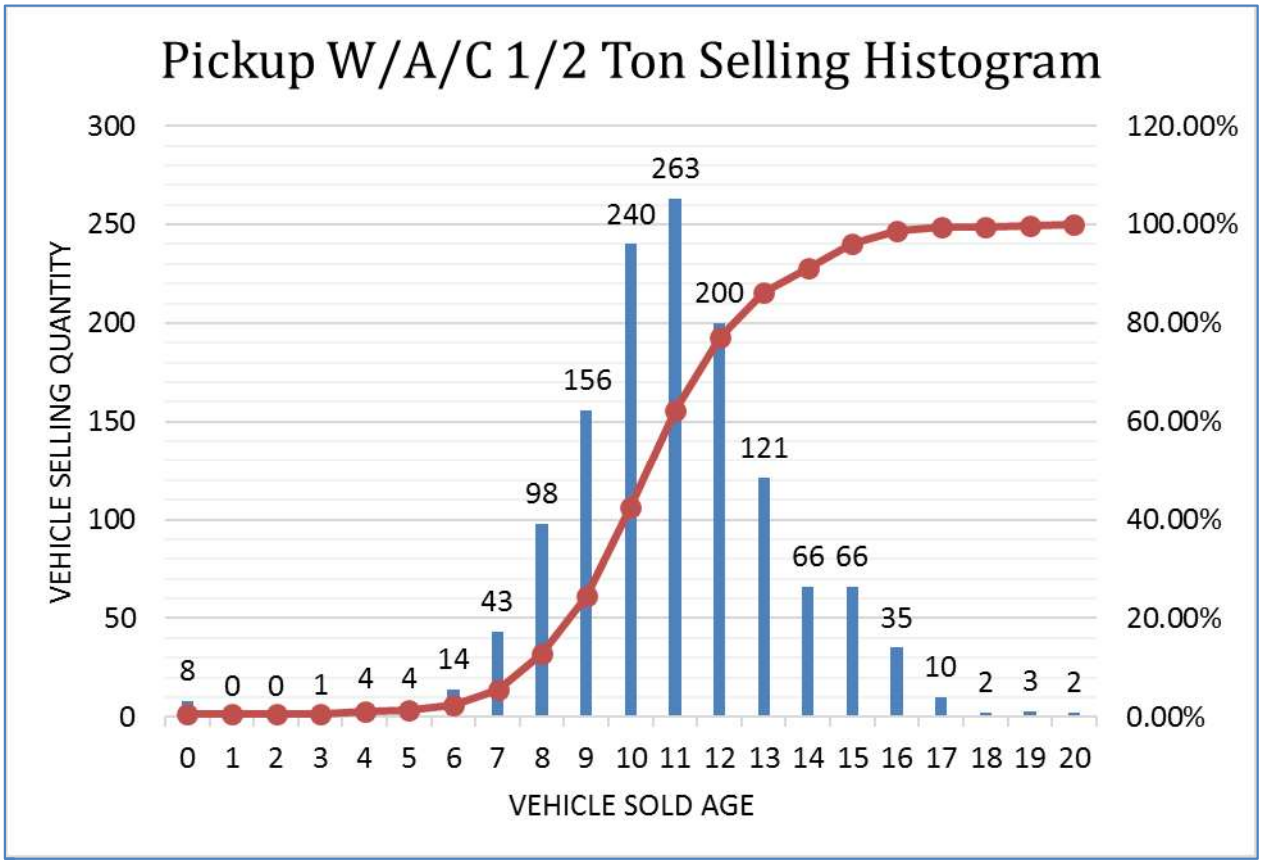



**Figure 4-18: Distribution of vehicles sold by vehicle age for ½-ton pickup class.**

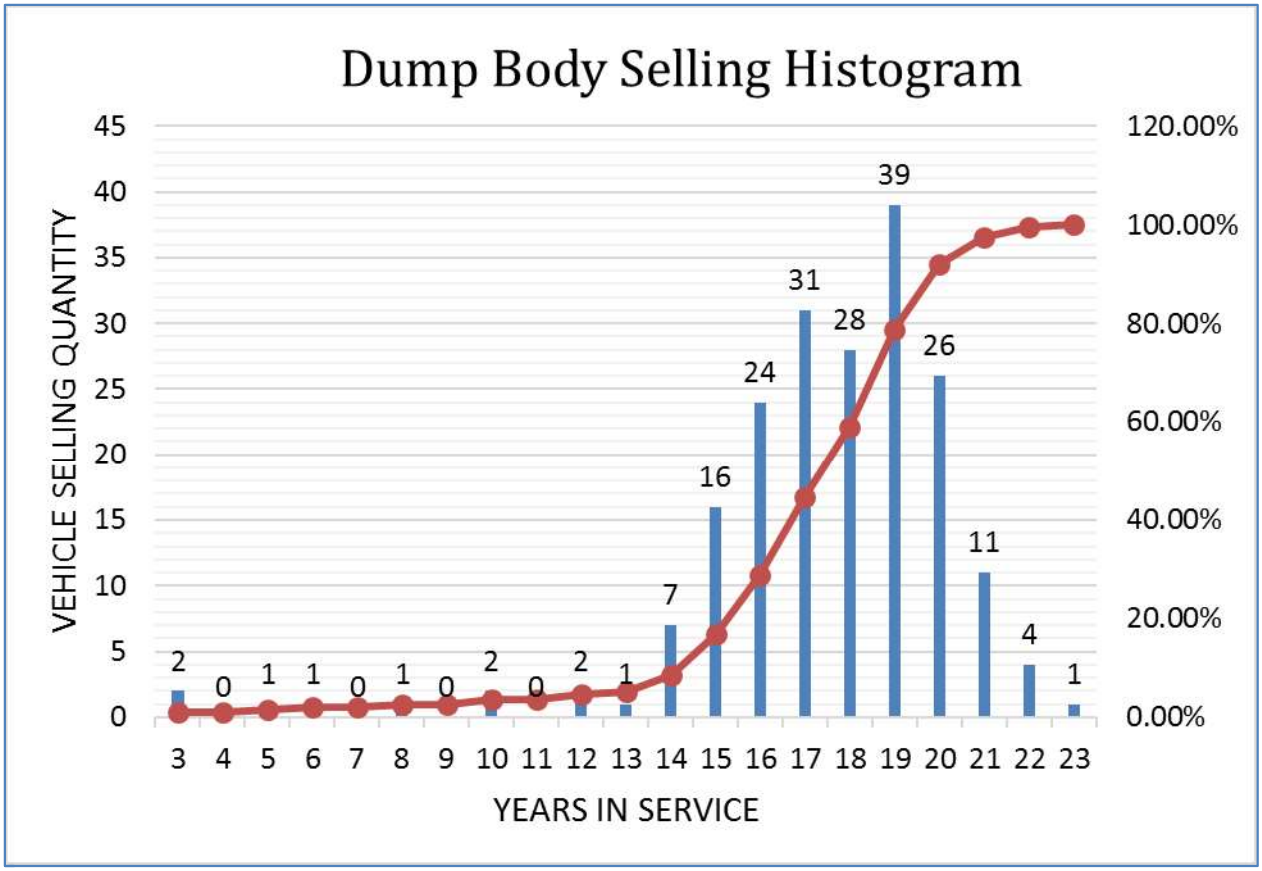



**Figure 4-19: Distribution of vehicles sold by vehicle age for dump body class.**

In addition to vehicle age, the percentage of remaining value at the time of sale was examined. The percentage of remaining value or resale value based on Caltrans sales data was calculated from the capitalized value and the sale price. Figure 4-20 and Figure 4-21 show the percentage of remaining value by vehicle age for ½-ton pickups and dump bodies. Although the resale value will depend greatly on the condition of the individual vehicle, the plot for the ½-ton pickups does show a well-behaved decreasing trend in resale value with vehicle age. Figure 4-20 also shows that the resale value at the peak sale age for pickups (11 years) is around 12%. Figure 4-21 shows that the resale value for the dump body class does not seem to correlate strongly with age, and may be governed by other factors.

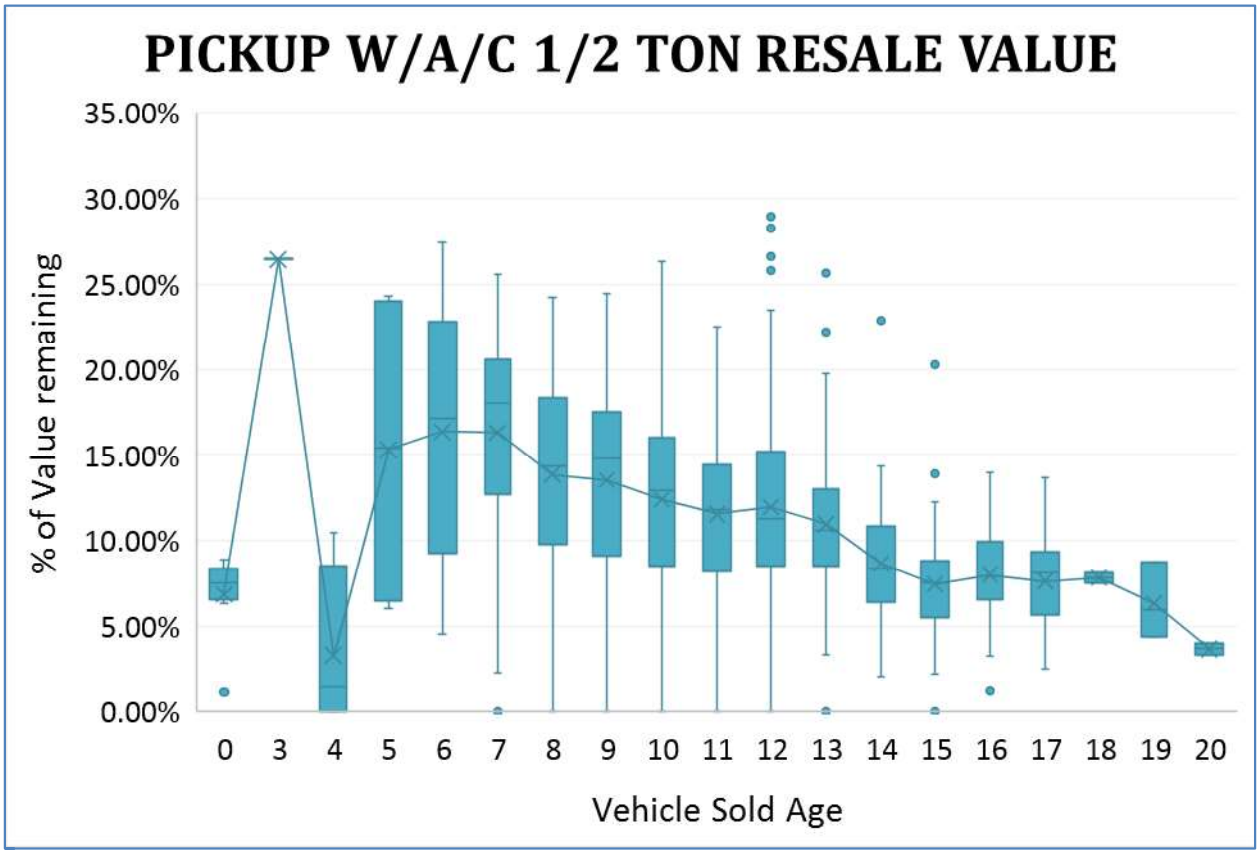



**Figure 4-20: Remaining value by age sold for ½-ton pickup class.**

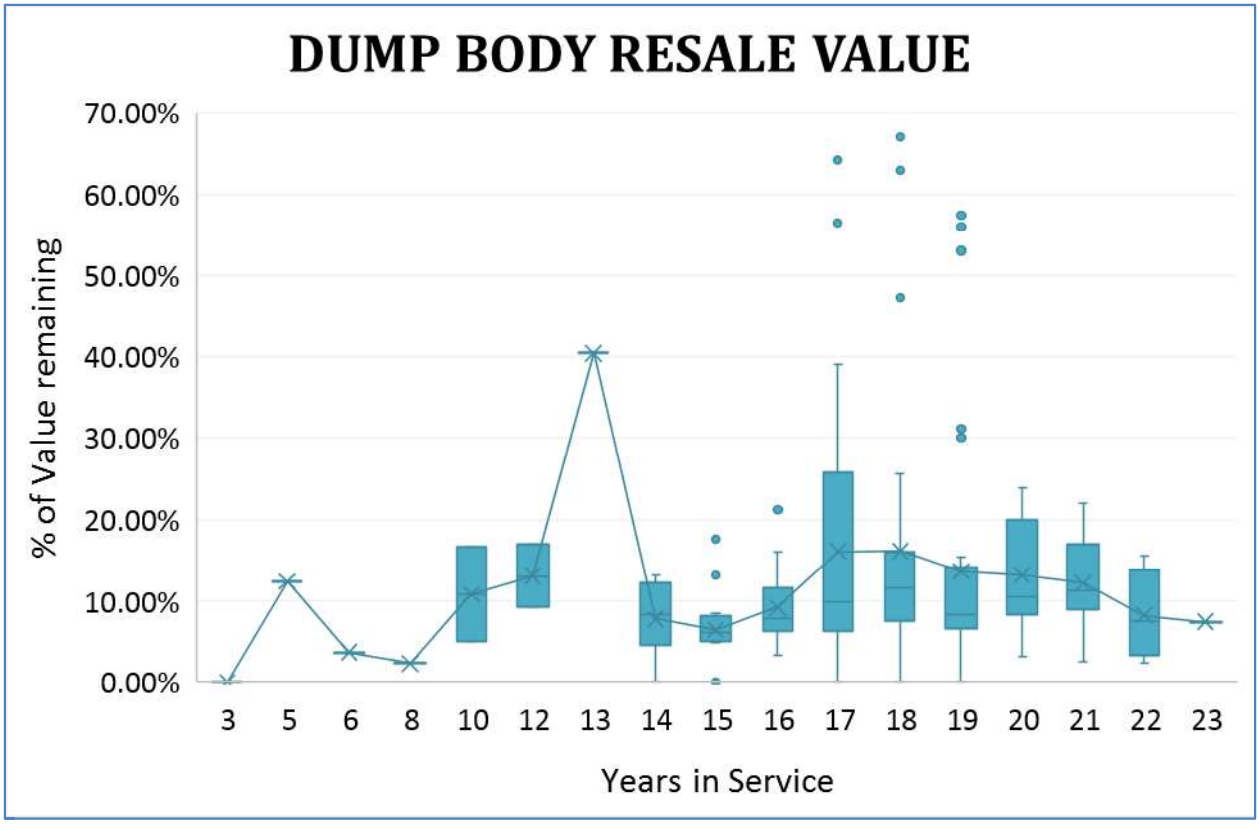



**Figure 4-21: Remaining value by age sold for dump body class.**

Resale value by vehicle mileage was also examined. In this analysis, the resale value for the ½ -ton pickup category shows a decreasing trend with increasing mileage as expected. The resale value of the dump body

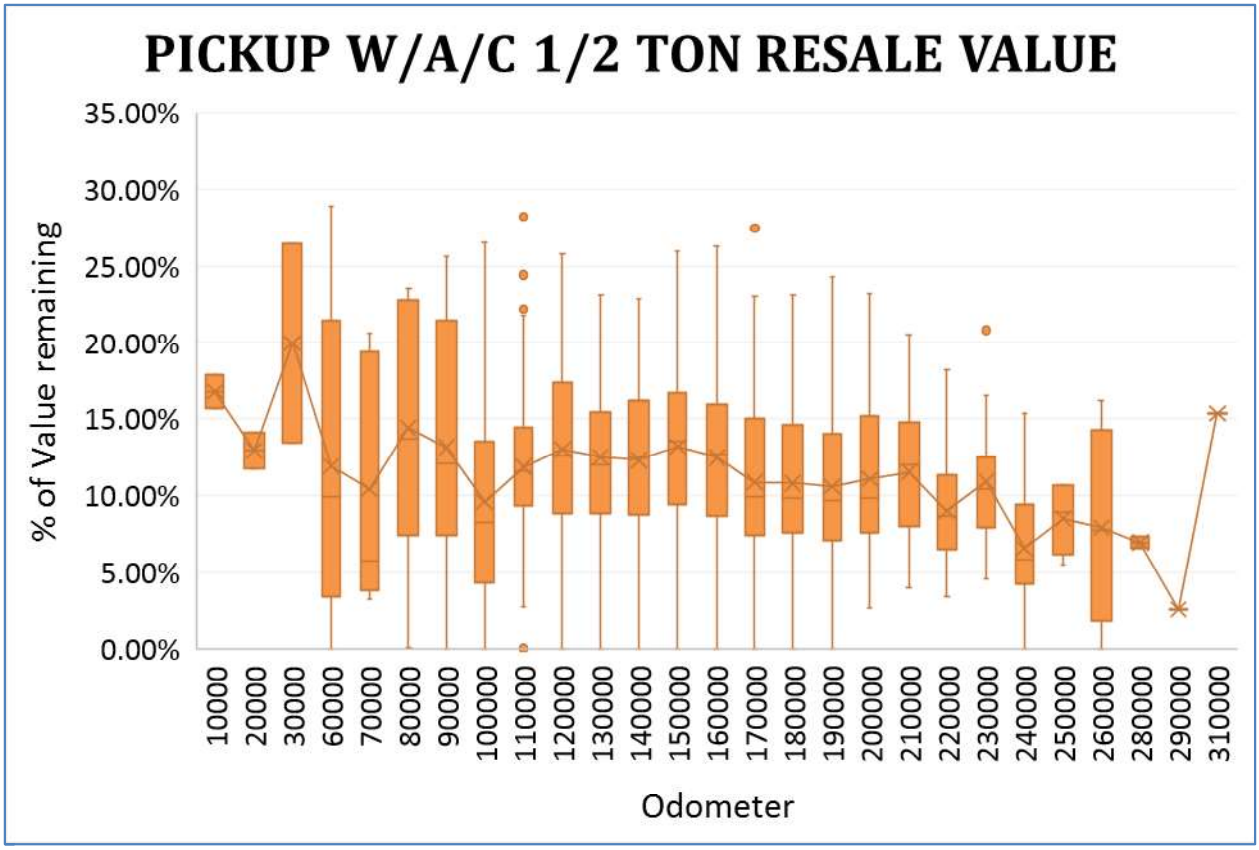

PICKUP W/A/C 1/2 TON RESALE VALUE
% of Value remaining
35.00%
30.00%
25.00%
20.00%
15.00%
10.00%
5.00%
0.00%
10000
20000
30000
60000
70000
80000
90000
100000
110000
120000
130000
140000
150000
160000
170000
180000
190000
200000
210000
220000
230000
240000
250000
260000
280000
290000
310000
Odometer

**Figure 4-22: Remaining value by vehicle mileage for ½-ton pickup class.**

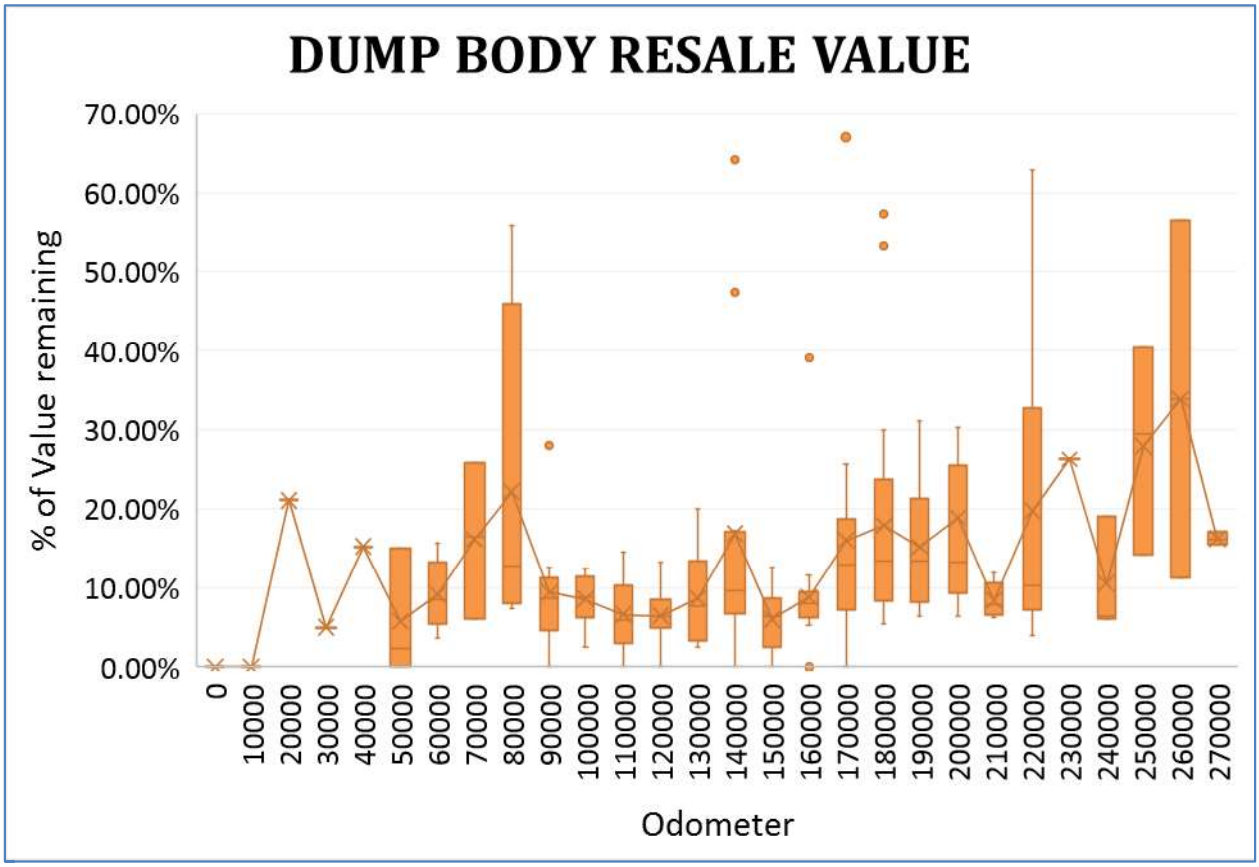



**Figure 4-23: Remaining value by mileage for dump body class.**

# 5. Application of LCCA FRM

In comparison to the other methodologies reviewed, LCCA is more data-driven, less subjective, and considers the three parameters that Caltrans finds most important namely: repair cost, age and usage. An LCCA was applied to Caltrans fleet data and the results are presented in this chapter.

## 5.1. Application of LCCA

According to the life cycle cost theory, different equipment operating intervals will generate different equivalent uniform annual cost (EUAC) (6). The most economic operating interval appears when the EUAC reaches the minimum. Since EUAC is the total of equivalent annual operating cost and equivalent annual owning cost, to get the minimum, the owning and operating cost should be first calculated.

For the LCCA, the Double-Declining Balance (DDB) depreciation method was used. This method "applies a constant depreciation rate to the property's declining book value" to form

the owning cost (7). In contrast to the straight-line depreciation method, which uses a constant depreciation charge annually, the DDB depreciation reflects a decreasing loss in market value through equipment's life, which is considered to be more realistic. For each maintenance class, the depreciable life is standardized at 7 years, and the final salvage value was initially estimated to be 10% of the equipment's capitalized value. Although the 7 years and 10% salvage value are the generalized values commonly used by many organizations, they can vary by type of fleet equipment, especially since they do have a large impact on the LCCA. For example, if the operating costs and the salvage value remain the same, longer depreciable life may cause shorter optimal life cycle. In addition to the loss in market value, the annual owning cost also includes the annual interest charge, which is known as the opportunity loss in the interest return if investing the equipment resale value. The formula of the annual owning cost is shown below.

$$\boldsymbol{Annual\ Owning\ Cost = Annual\ DDB\ depreciation + Annual\ interest\ charge}$$

$$\boldsymbol{Annual\ DDB\ depreciation} = \frac{\boldsymbol{2}}{\boldsymbol{N}} \times \boldsymbol{MV_{t-1}} = \frac{\boldsymbol{2}}{\boldsymbol{N}}\left(\boldsymbol{C} - \sum_{\boldsymbol{j=1}}^{\boldsymbol{t-1}} \boldsymbol{d_j}\right)$$

$$\boldsymbol{Annual\ interest\ charge} = \boldsymbol{i} \times \boldsymbol{MV_t} = \boldsymbol{i} \times \left(\boldsymbol{C} - \sum_{\boldsymbol{j=1}}^{\boldsymbol{t}} \boldsymbol{d_j}\right)$$

Where:

$MV_{t-1}$ = Equipment's market value in year t-1
t = Year
N=Depreciable life
C=Capitalized Value
$d_t$ = Depreciation charge in year t
i = interest rate

More complicated than owning cost, the determination of operating cost consists of numerous factors. In the Caltrans fleet database, there are four types of costs: preventative maintenance (PM) cost, repair cost, commercial PM cost, and commercial repair cost, and each type includes both labor and parts. Adding these cost components together provides the total operating cost.

$$\boldsymbol{Operating\ Cost = PMLC + PMPC + RLC + RPC + CPMLC + CPMPC + CRLC + CRPC}$$

Where:

PMLC = preventative maintenance labor cost
PMPC = preventative maintenance parts cost
RLC = repair labor cost
RPC = repair parts cost
CPMLC = commercial preventative maintenance labor cost
CPMPC = commercial preventative maintenance parts cost
CRLC = commercial repair labor cost
CRPC = commercial repair parts cost

There are several issues involved in applying LCCA to real world operating data such as which regression method should be used to fit operating data in order to predict future data more accurately; should operating costs be based on cumulative cost, annual cost, or cost per usage (hours or miles); and what trend best describes usage. Although cumulative operating cost is the easiest to fit using a second order polynomial trend, the regression will be highly influenced by the accumulation of occasional cost spikes, especially ones occurring in earlier years.

An important issue that was observed from data analysis is that the annual operating data is not always increasing during an equipment's lifetime, which may result in a downtrend in the annual cost regression and will prevent reaching the minimum total EUAC. This issue is understandable since aging equipment may be utilized less and subsequently the cost spent on repairs may decrease. Normalizing cost by usage helps alleviate this problem and provides a more reasonable method for characterizing the cost components. As the equipment ages, the operating cost per usage shows a linear uptrend. Relative to vehicle usage, Caltrans' fleet data shows a common power regression with the order less than one, which well represents the gradually decreasing usage with vehicle age. The annual operating cost is calculated as the product of the annual cost per usage and the annual usage.

The final step in the LCCA is to convert the annual owning and operating cost to EUAC, which is accomplished by multiplying the total present value of owning and operating cost through years by capital recovery factor (7).

$$TPV_{ownt} = \sum_{j=1}^{t} PV_{ownj} = \sum_{j=1}^{t} AC_{ownj} \times (1+i)^{-j}$$

$$TPV_{opet} = \sum_{j=1}^{t} PV_{opej} = \sum_{j=1}^{t} AC_{opej} \times (1+i)^{-j}$$

$$EUAC_{ownt} = TPV_{ownt} \times capital\ recovery\ factor = TPV_{ownt} \times \frac{i(1+i)^t}{(1+i)^t-1}$$

$$EUAC_{opet} = TPV_{opet} \times capital\ recovery\ factor = TPV_{opet} \times \frac{i(1+i)^t}{(1+i)^t-1}$$

$$EUAC_t = EUAC_{ownt} + EUAC_{opet}$$

Where:

$TPV_{ownt}$ = Total present value of owning cost within t years
$TPV_{opet}$ = Total present value of operating cost within t years
$PV_{ownt}$ = Present value of owning cost in year t
$PV_{opet}$ = Present value of operating cost in year t
$AC_{ownt}$ = Annual owning cost in year t
$AC_{opet}$ = Annual operating cost in year t
$EUAC_{ownt}$ = Equivalent uniform annual owning cost through year t
$EUAC_{opet}$ = Equivalent uniform annual operating cost through year t
$EUAC_t$ = Equivalent uniform annual cost through year t
i = interest rate

Figure 5-1 shows the graphical result of LCCA at the maintenance class level. In this example, we ran the LCCA for Sedan Compacts, which is one of the maintenance classes in passenger vehicle category. To eliminate the problems caused by younger equipment, vehicles included in the LCCA are all purchased before 2010, which includes vehicles at least 6 years old. For the sedan compact, there are 7 vehicles that are included in LCCA. In this figure, the blue line represents the annual owning cost, which keeps decreasing as the equipment life is spread over years until the determined depreciable year 7. The red line represents the general annual operating cost for Sedan Compacts, which keeps increasing as the equipment is used. The yellow line is the equivalent uniform annual cost, and the black dot shows the optimal point year, where the EUAC reaches the minimum. This figure tells us the best replacement cycle for Sedan Compacts is 16 years.

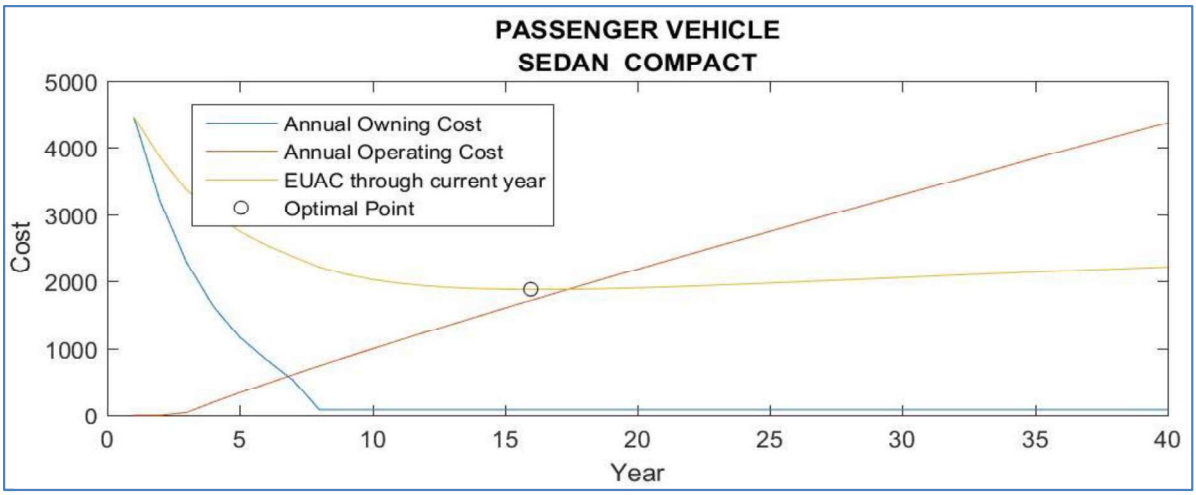



**Figure 5-1: Graphical result of LCCA for compact sedan.**

Utilizing the same calculation process, the LCCA was implemented for two pieces of individual equipment. In Figure 5-2 and Figure 5-3, two individual dump body vehicles were evaluated. Both vehicles are Dump Bodies with Plow and Spreader, and in the same category "Medium Duty Truck". The LCCA results for these two trucks of the same type are extremely different. Figure 5-2 shows that the optimal life cycle for equipment 0337150 is 27 years, and figure 5-3 shows that the optimal life cycle for equipment 0337204 is 14 years. The difference between the optimal lives for these two vehicles is 13 years, and from the figures, it is evident that the cause for this difference is the difference in annual operating costs. This comparison indicates that even the same type of equipment will have significantly different life cycle, since their conditions, usage and operating conditions are not all the same. This indicates that the operating cost is one of the leading factors that will significantly affect LCCA result. This analysis determines that setting one optimal life cycle standard for every equipment unit in one maintenance class or category is not appropriate. In the next section, some improvements will be introduced regarding the theoretical LCCA model to mitigate these types of disparities.

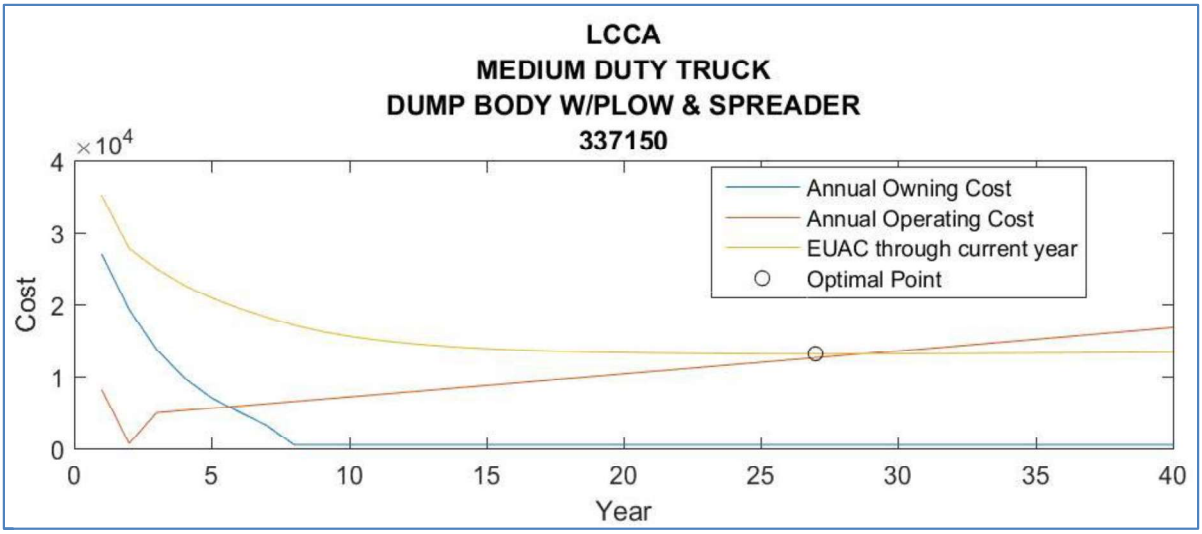



**Figure 5-2: Graphical Result of LCCA (Equipment ID: 0337150)**

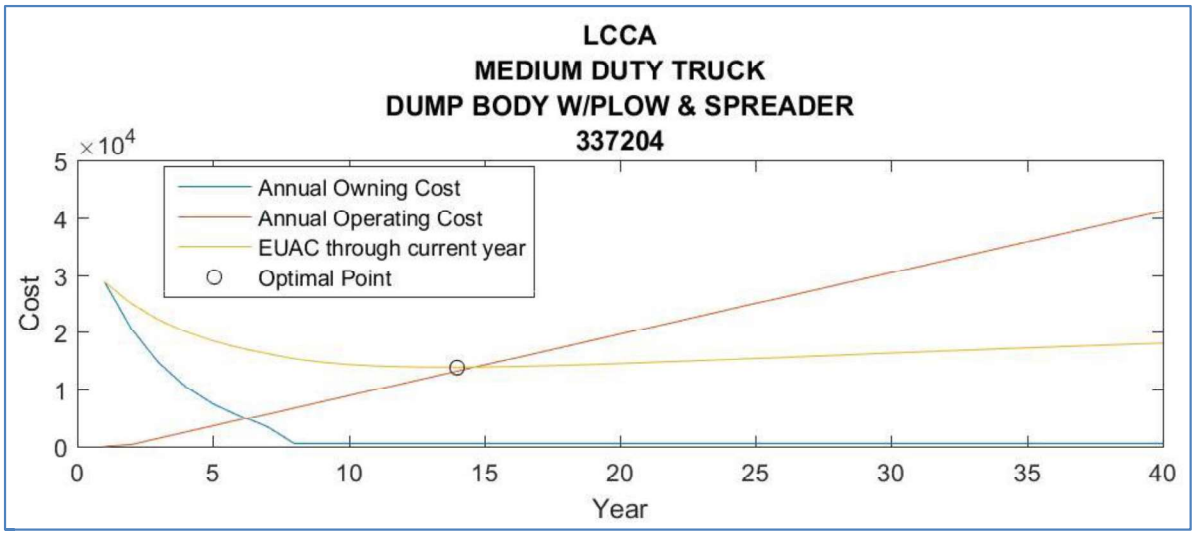



**Figure 5-3: Graphical result of LCCA for equipment ID 0337204.**

## 5.2. Enhanced LCCA

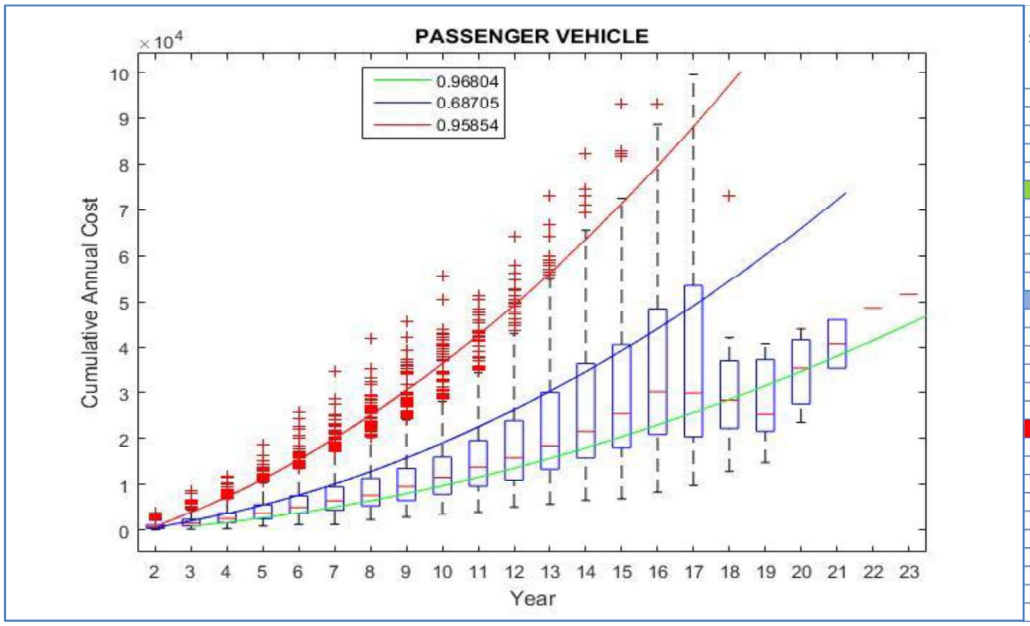
The LCCA model has some disadvantages when dealing with real world data. Some of the preconditions and assumptions are too ideal to be applied to real-world fleet data. Thus, based on the basic LCCA, making enhancements is necessary, especially for the modeling of operating cost, which has significant impacts on the result. To improve the LCCA, an Enhanced LCCA method was developed and a new method to predict the operating cost more accurately was implemented.

LCCA is very sensitive to operating cost and therefore, the accuracy of the regression model for the cost trend plays an important role in the LCCA. To generate a LCCA result for each equipment category, the most essential step is to predict an operating cost curve that is applicable for all equipment within a category. Caltrans historical fleet data shows that it is

very common that vehicles in the same category have operating conditions that vary dramatically with time. This makes it very challenging to fit all data pairs with a single curve, especially when outliers may drag the curve down or pull the curve up. Regardless of the type of regression model being used, such distortion always exists and will dramatically affect the optimal life cycle.

To solve this problem, an enhanced LCCA Model has been developed. Instead of fitting data pairs with one regression curve, this model separates the cumulative operating cost data into three regions. Taking the Passenger Vehicle Category as an example, from the boxplot in Figure 5-4, it is evident that there are multiple outliers, labeled with red crosses, which describe the high operating costs for different vehicles at different years. This Model presumes that these outliers can be grouped as the worst-case scenario, which represents equipment operated with abnormally high costs, and major repairs occurring more frequently. This scenario provides an upper level for this category based on the analyzed dataset. Similarly, the lower level reflects the lower operating cost of well-operated equipment, without costly accidents or other major repairs during their lifetime. The middle level includes equipment that is operated normally, with average accidents and repairs. In Figure 5-4, these three levels are depicted in three colors: green, blue and red, each represents the second order polynomial regression of median, over median and over 95% quantile cumulative annual cost. For each situation, the LCCA reaches an optimal life cycle, which is 8 years for the upper level, 10 years for the middle level, and 14 years for the lower level.

As stated previously, the LCCA result is very sensitive to increases in operating cost, which can be interpreted as the corresponding relationship between the operating cost regression coefficient and the most economic life cycle. A change in the second order coefficient will change the optimal life cycle as well. In Figure 5-4, the area between the green and blue color shows the correlation between coefficient and optimal life cycle between the lower and middle levels; the area between blue and red color shows the correlation between coefficient and the optimal life cycle between the middle level and upper level. In other words, if the second order coefficient is in the range from 70 to 130, the optimal life cycle will fall between 10 and 14 years, or if the slope is in the range from 130 to 200, the optimal life cycle will fall between 8 to 10 years. Since the owning cost and operating cost vary between equipment types, the optimal life cycle value will also change between equipment types.




| Second Order Coefficient | Optimal Life Cycle |
|---|---|
| | Sedan Compact |
| 20 | 30 |
| 30 | 24 |
| 40 | 20 |
| 50 | 17 |
| 60 | 16 |
| 70 | 14 |
| 80 | 13 |
| 90 | 12 |
| 100 | 12 |
| 110 | 11 |
| 120 | 11 |
| 130 | 10 |
| 140 | 10 |
| 150 | 9 |
| 160 | 9 |
| 170 | 9 |
| 180 | 8 |
| 190 | 8 |
| 200 | 8 |
| 210 | 8 |
| 220 | 8 |
| 230 | 6 |
| 240 | 6 |
| 250 | 6 |
| 260 | 6 |
| 270 | 5 |
| 280 | 5 |
| 290 | 5 |
| 300 | 5 |

**Figure 5-4: Enhanced LCCA model**

The enhanced model sets three triggers based on three regression lines of the relationship between operating cost and vehicle age. One to two years before each trigger year, equipment at or above the trigger in this category should be assessed. The assessment is mainly focused on the increasing cumulative operating cost trend, i.e. which region the increasing pattern belongs to and whether this equipment should be replaced. For example, if a piece of equipment has cost values that have a regression between the lower and middle level, this indicates that this piece of equipment can be kept until the next trigger. However, if the coefficient is between the middle and upper level, this indicates that the piece of equipment should be considered as a replacement candidate and replaced at no later than 10 years.

## 5.3. Composite Operating Cost

As indicated in the Enhanced LCCA Model, each equipment may be operated differently, so it is inappropriate to fit data pairs with one regression curve or just apply the average value. After visualizing the historical cost data from the Caltrans' fleet, it was observed that equipment's cumulative operating cost has more frequent and increased variability as the vehicle ages. Splitting the operating cost into the three components: PM cost, Repair cost and CML cost, shows that the cumulative PM cost is fairly linear, which means the annual PM cost is approximately a constant value. However, looking at the Repair cost and Commercial cost, their cost patterns are characterized by larger periodic cost events producing a step pattern in the cumulative cost line. (Figure 5-5)

Based on the observed characteristics of the operating costs, the idea of Composite Operating Cost (COC) was developed, which defines the operating costs as a combination of costly tasks and the baseline costs. The baseline cost comes from periodic preventative maintenance, fuel, safety inspection, and some other regular routine maintenance or small repairs. The

costly tasks are defined as non-routine tasks, which occur infrequently, such as major repairs, accidents, or damage caused by severe vehicle equipment operation. As the equipment ages, the probability and frequency of such costly tasks increases, as well as the magnitude of expenditures. In each year, the COC should include the baseline cost and costs from the potential costly tasks, which equals the expected value calculated as the sum of all possible costs each multiplied by the probability of their occurrence.

$$E_t = \beta_{1t}C_{1t} + \beta_{2t}C_{2t} + \cdots + \beta_{nt}C_{nt}$$
$$B_t = (1 - \sum_{i=1}^{n}\beta_{it}) * RC_t$$
$$COC_t = E_t + B_t$$

Where:

t = year

i = different tasks, $i \in [1, n]$

$\beta_{it}$ = the probability of occurrence for $i^{th}$ costly task in year t, $i \in [1, n]$

$C_{it}$ = the average cost for $i^{th}$ costly task in year t, $i \in [1, n]$

$E_t$ = expected value of costly tasks in year t

$B_t$ = baseline cost in year t

$RC_t$ = routine costs in year t

$COC_t$ = composite operating cost in year t

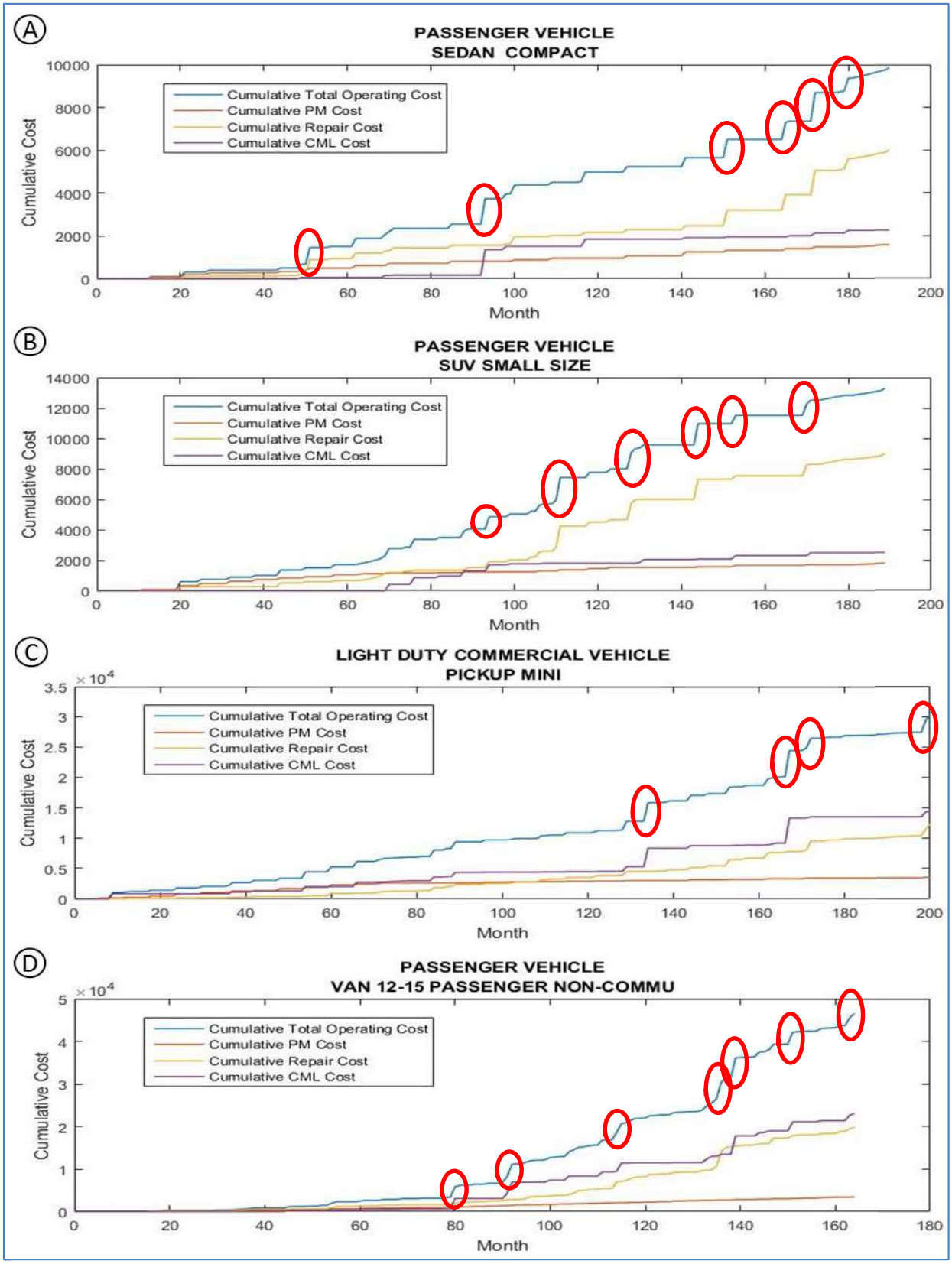



**Figure 5-5: Composite operating cost visualization**

The three-region LCCA analysis methodology was applied to the Caltrans vehicle fleet with the inclusion of Composite Operating Cost analysis to address individual vehicle variability. The recommended vehicle replacement life was compared with prior VMC methods. The integrated approach identifies vehicles with early-elevated costs while retaining vehicles with lower operating and owning costs. This enhanced and integrated LCCA method provides vehicle specific recommendations relative to trends specific within vehicle categories.

# 6. Conclusions

## 6.1. Concluding Remarks

The objectives of this research were to investigate the vehicle equipment replacement decision-making methodologies available to the California Department of Transportation (Caltrans) and other agencies with similar vehicle fleet operations. The goal of these methodologies is to optimize the replacement timing of aging vehicle equipment in a way that minimizes total costs while maintaining important fleet characteristics. An overview and discussion of key factors for the vehicle equipment replacement decision-making process and various Fleet Replacement Methods (FRM) utilized by Caltrans and other states' Department of Transportation (DOTs) is included. Also, three FRM categories--Pre-Defined Threshold, Life Cycle Cost Analysis (LCCA), and Mathematical Ranking Method--are compared and summarized in this report; and several FRMs previously or currently being used by state DOTs were described in detail. Following the evaluation of each replacement method, the LCCA method was chosen as the most applicable alternative to Caltrans' current FRM. The development of the LCCA model presented challenges and opportunities. Considering the characteristics of the life cycle cost and the thorough analysis of Caltrans data, an enhanced LCCA method and a new terminology, Composite Operating Cost (COC), were introduced. These two components help to enhance the basic LCCA, addressing some of the limitations that are characteristic of the LCCA, and providing a more realistic result for the fleet replacement decision-making process.

## 6.2. Recommendations for Future Research

In the future, additional criteria could be quantified and included in the LCCA model, such as downtime, effectiveness, emission mandate, future technology trend, risk of parts unavailability, equipment reliability, etc. These criteria may account for hidden costs that can influence the decision of choosing a replacement candidate. For example, the downtime refers to all costs associated with equipment out of service for repairs or maintenance. Usually, downtime results in losing revenue or incurring excessive costs. However, since DOTs are a non-profit government agency, the downtime cost indirectly effects employee cost, overtime for emergency repairs, disruption and recovery costs, etc. Since these costs vary by specific situation, it is difficult to develop one single formula to calculate such costs. Additional hidden costs may be caused by equipment effectiveness, which is a measure of relative desirability received, including availability, reliability, maintainability, and capability. As equipment ages, the effectiveness will keep decreasing, and some associated

costs should be considered. Continuing discussions and interactions are encouraged to aid the refinement of Caltrans fleet replacement practice.

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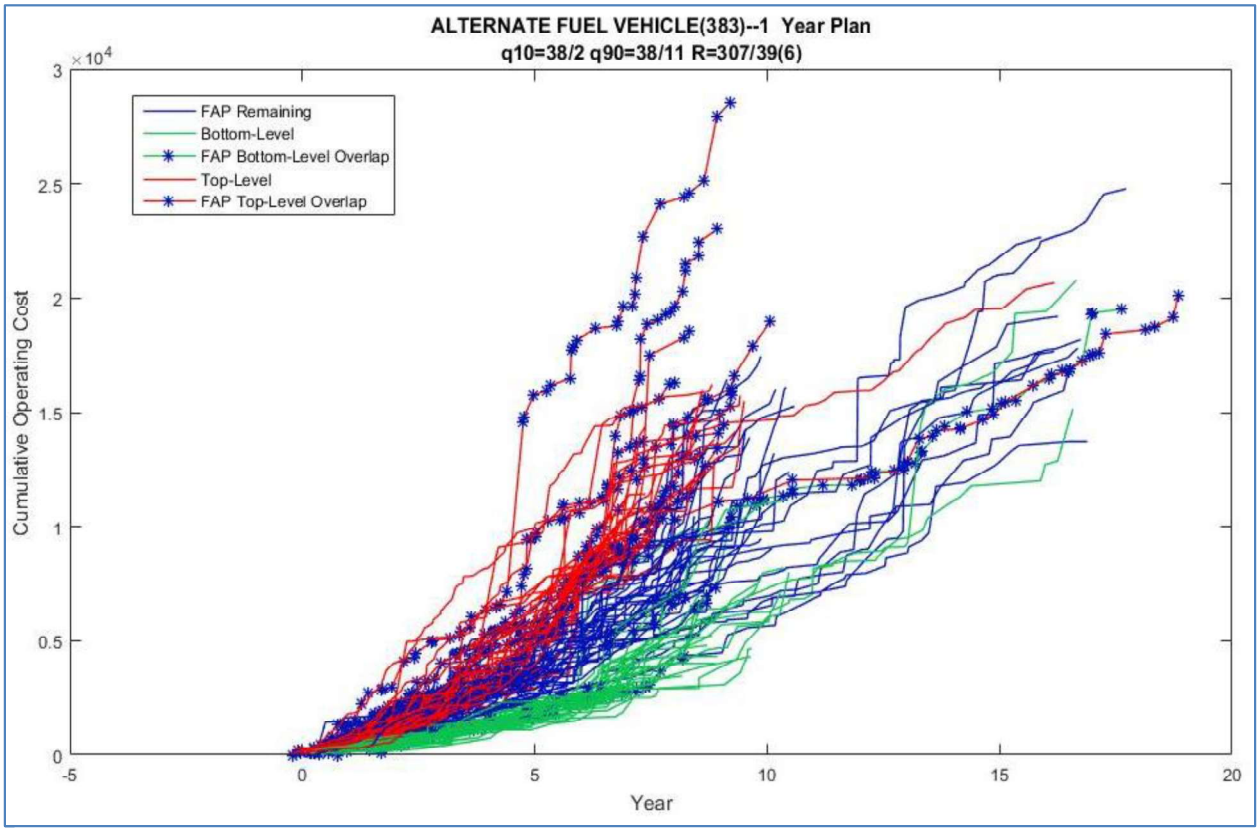
# Appendix A: Developed Matlab Functions

During the course of this project, several Matlab functions were developed for data analysis specific to this project. These functions are presented briefly here.

## *Fapoverlap*

The fapoverlap function was developed to compare a candidate replacement list with the top and bottom level vehicles based on cumulative operating cost. The intput to the function is the vehicle category, percentile, and reference point in years. The output generated is a graph with FAP vehicles in blue, the top input percentile of vehicles in red and the bottom input percentile of vehicles in green. The blue "*" represent points were the FAP vehicle overlaps with either the top or bottom of the input percentile. This indicates if the chosen vehicle is a high or low cost vehicle based on the input percentile.

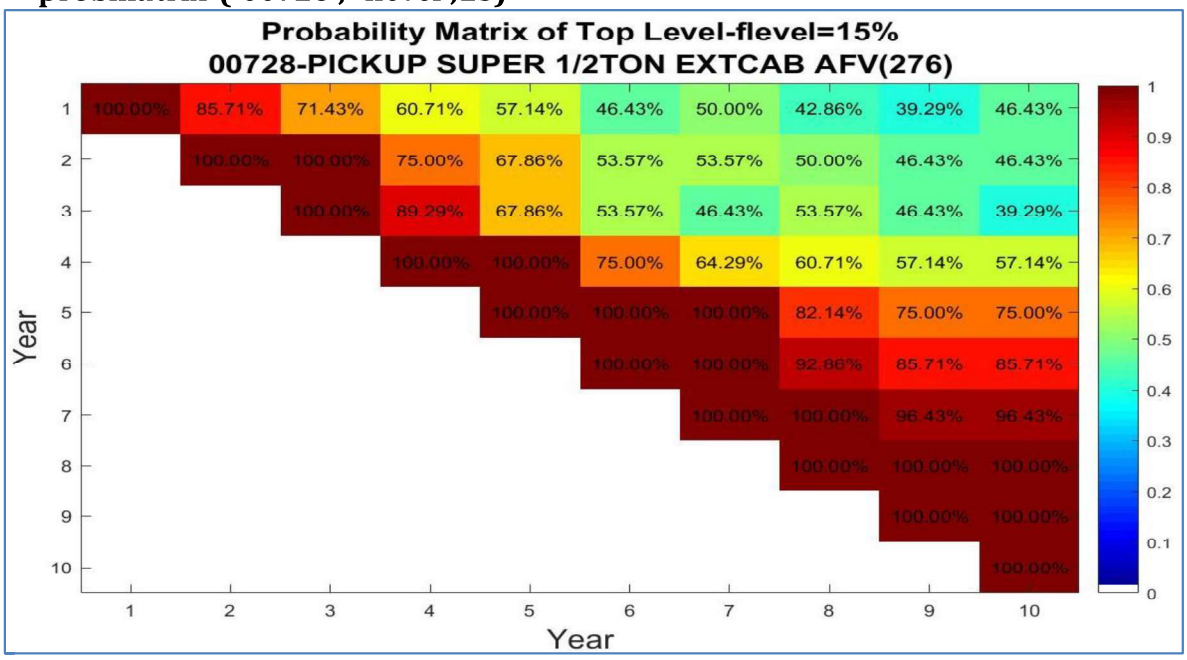
**>>[eq_top_overlap eq_bottom_overlap eq_fap_remains]=fapoverlap(10,'00108',6,1);**



## *Probmatrix*

The probmatrix function outputs a matrix of percentages for a given vehicle category that indicates the probability that a high cost vehicle in a given year will remain a high cost vehicle after 10 years.

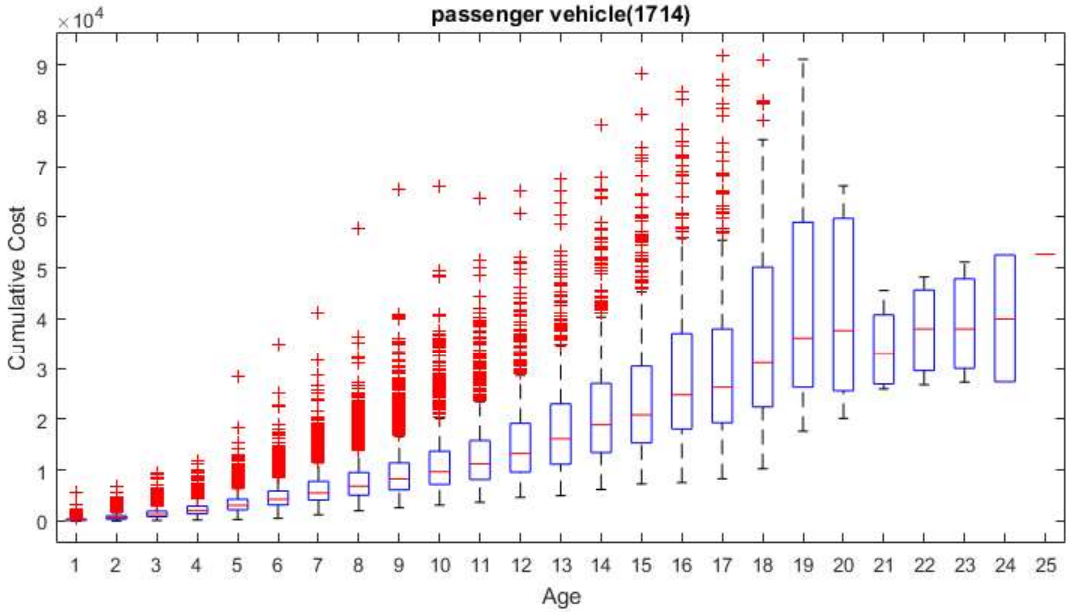
**>>probmatrix ('00728', 'flevel',15)**



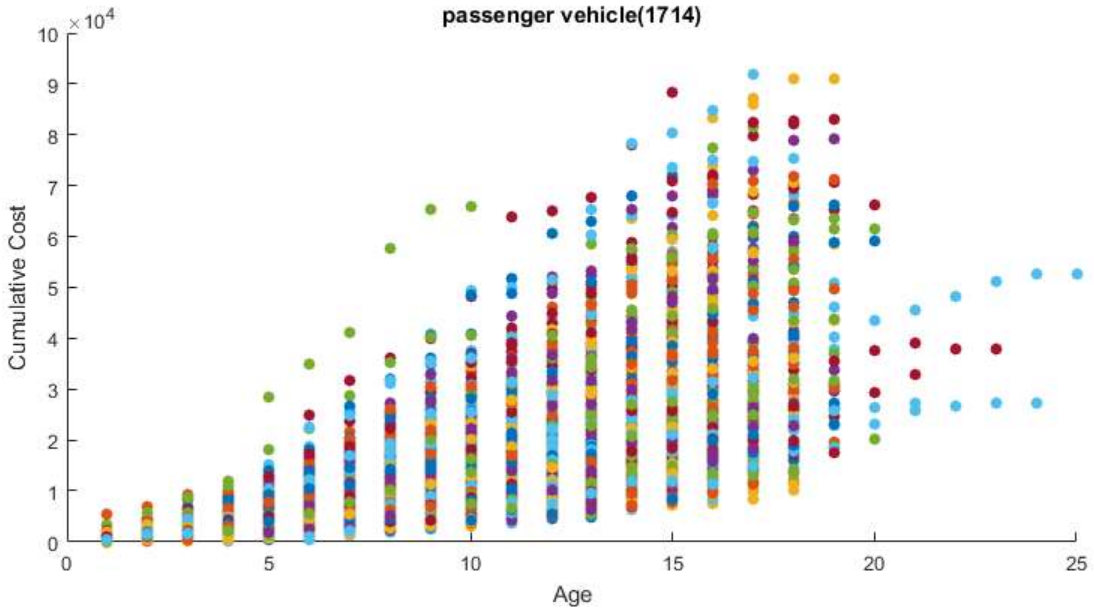
## *Fleetplot*

The fleetplot function is a specialized plotting function that recognizes various inputs based on the Caltrans fleet data and creates a number of plots based on user inputs. Using this function, the user can choose a vehicle category, maintenance class, vehicle id, list of vehicle ids and plot individual or summary data for various x and y values specified in the input arguments. Several examples of the plotting function are presented below.

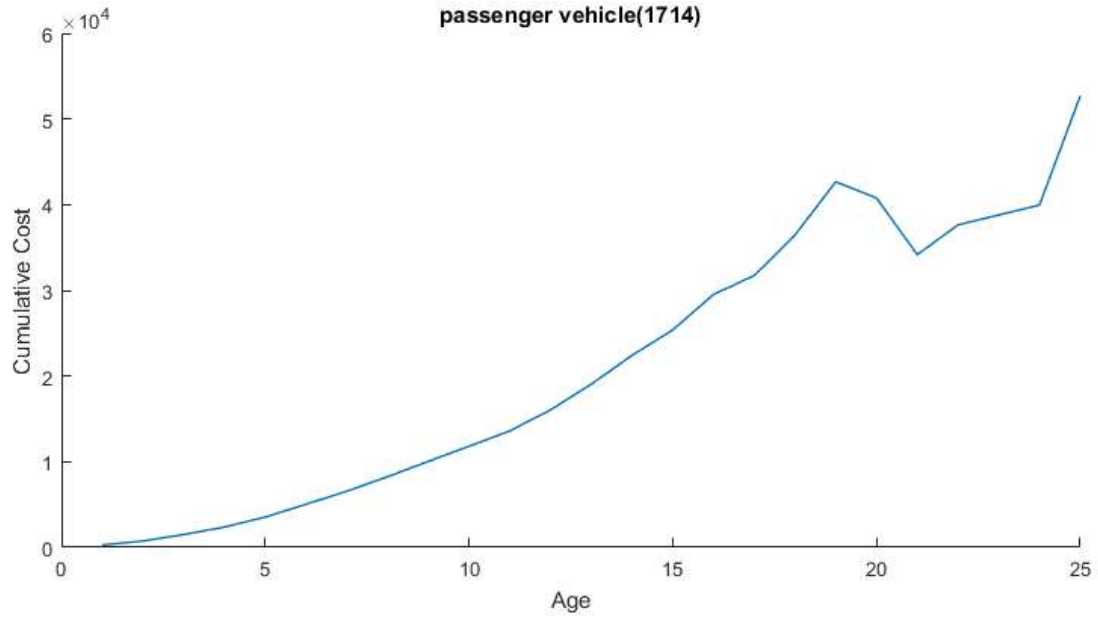
**>>fleetplot( 'category','passenger vehicle','plottype','boxplot')**



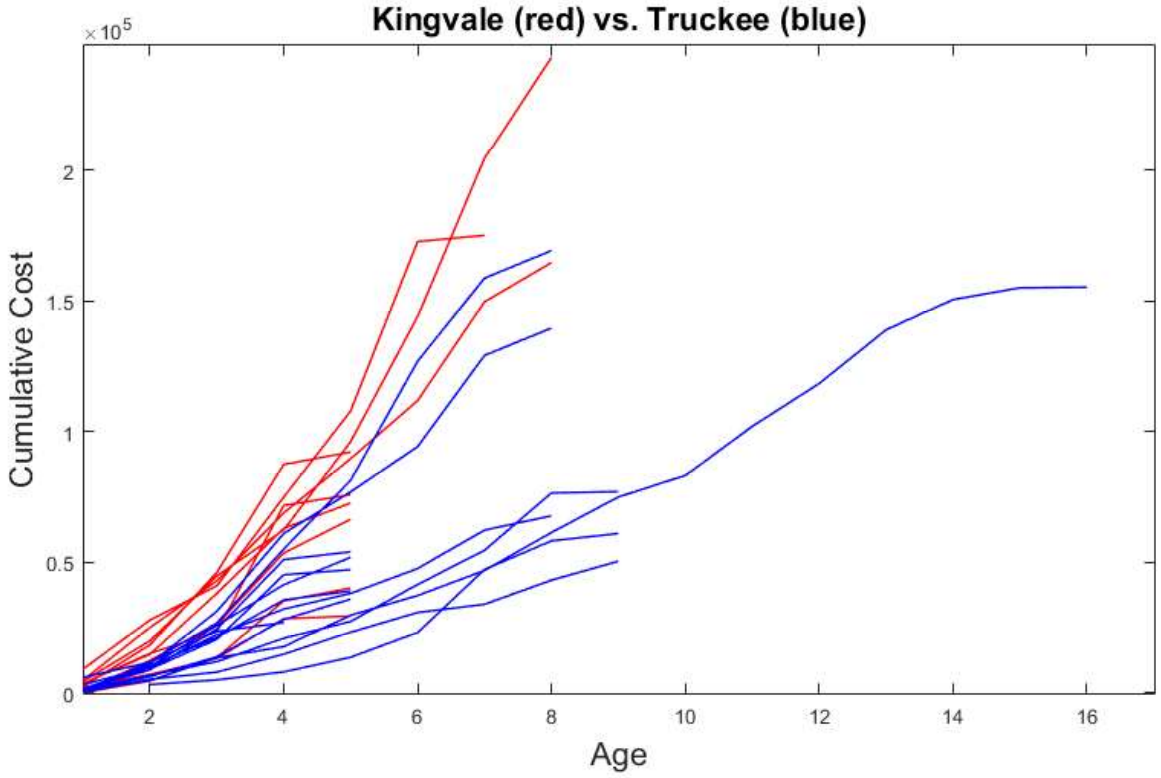
**>>fleetplot( 'category','passenger vehicle','plottype','scatter')**




**>>fleetplot( 'category','passenger vehicle','plottype','average')**



**>>fleetplot(**
**'vehid',{'7008130';'7008131';'7004446';'7008210';'7008211';'0530506';'7008216';'**
**7008220';'7000024';'7005037';'7005036'},'plotcolor','r')**
**>>fleetplot(**
**'vehid',{'7006007';'0338703';'7005025';'7006011';'0330128';'7006402';'7002281';'**
**7011279';'7002282';'7008215';'7008217';'7008219';'7008221';'0536506';'7008232'**
**;'7008231';'7005035';'7004452';'7010218'},'figurehandle',1,'plotcolor','b')**
**>> title('Kingvale (red) vs. Truckee (blue)')**



### *Usagemgmt*

The usagemgmt function plots equipment quantity by service year and total usage by district for specified model years. This function was developed to investigate the idea of equipment usage management between districts as well as within districts.

**>>usagemgmt( '00807','modelyr',{2007,2014});**