IMPROVING THE OKLAHOMA DEPARTMENT OF TRANSPORTATION'S EQUIPMENT MANAGEMENT PRACTICES USING FLEET MANAGEMENT DATA

By

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Abstract: The departments of transportation in the U.S. typically possess a big fleet of vehicles and equipment. The equipment management face pressure to reduce cost and improve efficiency of utilization. Oklahoma Department of Transportation (ODOT) has approximately 4,300 pieces of equipment, with equipment purchase year ranging from 1964 to the present. A lot of the equipment has already exceeded its useful life and many others are running under suboptimal conditions with an increase in operating costs due to equipment aging and deterioration. Equipment replacement decisions could play very important role in controlling the cost, however, there is a lack of decision support tool and decisions are purely dependent on fleet managers' experience. Other than replacement with purchasing, state DOTs may use rent or lease to augment its existing fleet. The two major sources of costs of ownership cost (mainly as depreciation) and operating costs traditionally are estimated by empirical methods with many assumptions and a lot of errors could be involved. This research directly addresses the need of ODOT. The overarching goal of this study is to help ODOT accurately estimate equipment costs and improve its equipment management practices using the data recorded in its equipment fleet management system. New entity-relational database was setup with SQL procedures to calculate the equipment rental rates for all equipment class codes. Advanced data analytics of life cycle cost analysis, exploratory data analysis, and dynamic programing models were applied in MySQL workbench and Python notebook platforms to inform equipment replacement policies and rent-leasing strategies for specific class codes. Class code 5355 (Front-End Loader) and 5385 (1/2 Ton Fleetside Pickup) were selected as example demonstration for hourly-charged and mile-charged types. There are very similar cost-age patterns between the two classes of 5355 and 5385 and cost rates are in decreasing trend (statistically significant) for both classes in the life cycle cost analysis. With the application of replacement strategies by the dynamic programing model, the cumulative total cost could be reduced by roughly \$ 7,000 and \$ 8, 500 on average within the period from 2011 to 2019 for the optimized equipment in the class code 5355 and 5385, respectively. In comparison to the rental prices from different online agencies, 10% (7/70) of current equipment in class code 5355 and less than 1% (12 out of 449) of current equipment in class code 5385 are suggested for renting rather than owning.

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CHAPTER I

INTRODUCTION

Strategies for highway maintenance and repair activities across the state include using contractors or in-house personnel combined with equipment sourced through either purchase, lease, or rent. State ODOTs tend to use their in-house personnel and own equipment. As a result, they typically possess a big fleet of vehicles and equipment. Equipment ownership cost and operating costs are the two major categories of costs used to determine the lifecycle cost of a piece of equipment. Douglas (1978) organized the most common methods for estimating ownership costs and operating costs, including Associated General Contractors of America (AGC) method (Popescu 1992), the Corps of Engineers method (Corps of Engineers, 2003), Peurifoy and Schexnayder method (Peurifoy et al. 2002), Federal Emergency Management Agency (FEMA), and Cost Recovery Rental Rate Blue Book. However, many assumptions are made in these methods and it could be impossible to provide accurate equipment costs. Using the data recorded by fleet management systems tends to yield more accurate results for equipment ownership and operating costs since real equipment data are used and fewer assumptions are needed. As more state DOTs adopt computerized equipment management systems, fleet managers should be able to estimate the ownership and operating costs based on accurate data so that better economic decisions can be made. The data record by the fleet management systems reflects how individual DOTs use and maintain their equipment fleet. The decision analysis performed on the more accurate data would afford agencies better solutions, such as optimal replacement schedules and own-lease-or-rent decisions. Moreover, the budget forecast can be better determined.

The Oklahoma Department of Transportation (ODOT) utilizes “rental rates” as the primary metric in its equipment budget. The rental rate is the sum of equipment depreciation costs and operating costs in per unit of usage in terms of hours or miles. An earlier study by the research team indicates that the rates have not been updated since Fiscal Year 2010. Furthermore, there is no established best management practice for analyzing and adjusting equipment rental rates for reporting and budget forecasting. This creates uncertainty and inaccuracies.

Moreover, ODOT has approximately 4,300 pieces of equipment, with equipment purchase year ranging from 1964 to the present. A lot of the equipment has already exceeded its useful life. Running equipment under suboptimal conditions increases operating costs due to equipment aging and deterioration. The default equipment useful life specified by ODOT is subjective and lacks scientific reasoning. Equipment replacement decisions are purely dependent on fleet managers’ experience. Furthermore, ODOT primarily buys equipment. When it comes to equipment sourcing, strategies include own, rent, and lease. ODOT may miss the opportunity of investigating other equipment sourcing alternatives.

This research directly addresses the need of ODOT. The overarching goal of this research effort is to help ODOT strategically improve its equipment management practices using the data recorded in its equipment fleet management system. The system has a common feature of tracking equipment inventory, equipment repair and maintenance records, work orders, fuel records, and equipment usage. However, built-in advanced data analytics for decision making is still lacking. The specific objectives of this project are to:

- Assist ODOT in calculating ownership and operating costs of the selected types of equipment.
- Develop models for equipment management decisions (including replacement and own-rent-or-lease decisions).

- Develop and demonstrate advanced data analytics using MySQL and Python notebook platforms.
- Develop a resource guide to introduce ODOT management to state-of-the-art data analytical techniques and practices for equipment management.

CHAPTER II

REVIEW OF LITERATURE

In the following sections literatures about the equipment life cycle cost analysis, equipment replacement decisions, and Own-Rent-Lease decisions will be discussed, respectively.

Life cycle cost analysis (LCCA) models have been traditionally used as the basis for equipment management decisions (Gransberg and O′Connor 2015). Previous studies (Barringer and Weber 1997; Bengtsson and Kurdve 2016; Gransberg and O′Connor 2015) defined equipment life cycle cost (LCC) as the sum of equipment ownership costs and operating costs. Ownership costs are often called fixed costs, which occur regardless of equipment operation while operating costs are variable costs that are incurred when the equipment is used (Gransberg et al. 2006). Life cycle analysis also need to know the indirect cost which could include facility and utility bills and even the managers and other personnel costs. All of these costs are necessary for direct comparison of owning-renting-leasing cost between public and private sectors for fleet manager (National Academies of Sciences, Engineering, and Medicine, 2020)

Managers of transportation fleet always face difficulties in their decisions on if some certain equipment should be replaced and, if yes, when the best time is to replace. Many factors could be considered in replacing certain type of equipment, such as ages, mileages, running hours, operating costs, and even indirect costs of labor and supportive services. Thus, in reality, managers tend to use their own experience make keeping/replacing decisions based on some simple rules (e.g. age > 10 or mileage > 150,000 for a half-ton truck). However, a better decision could be approached through considering life cycle costs of equipment and finding the minimum cost time of the cycle (e.g. the economic life). With comprehensive fleet inventory and usage records, life cycle cost analysis can serve as an important indicator for managers to decide the proper time of replacement. Equipment replacement decisions can be assisted with mathematical models that involves a series of optimal calculations in costs. Equipment replacement models have been primarily researched in the industrial engineering field. Different economic models, including opportunity cost models, operation and maintenance costs equilibrium models, profitability models, and replacement cost models (AhireSanjay and MillerDavid 1997; Chang 2005; Dohi et al. 2001; Eilon et al. 1966; Sarache Castro et al. 2009) have been developed. The goal of the replacement analysis is to optimize the cost or utility function. In terms of optimization, various operations research techniques, including integer programming (Hritonenko and Yatsenko 2007), dynamic programming (Flynn and Chung 2004), decision trees (Baldin et al. 1988), simulation techniques (Zbigniew et al. 1985), Markovian models (Ávila-Godoy et al. 1997; Hopp and Nair 1994), and partially observable models (Sinuany-Stern et al. 1997) have made significant contributions to this field. Dynamic programing is promising since it provides a systematic procedure to determine optimal replacement choices for a series of interrelated decisions. Both deterministic dynamic programing (DDP) and stochastic dynamic programing (SDP) have also been applied in equipment replacement optimization with consideration of vehicles' annual utilization and maintenance costs (Hartman and Rogers 2006, Fan et al. 2012a and b).

Other than purchasing, state DOTs may use rent or lease to augment its existing fleet. There are also different mathematical models developed in other fields to help with buy-rent-or-lease decisions. For example, Johnson and Lewellen (1972) developed a financial model for analyzing lease-or-buy decisions and illustrate the model with an equipment example. Hargreaves (2002) developed a financial model comparing the economics of owning versus renting houses. Both studies admitted that lease-or-buy decisions are not purely economic decisions. Other non-economic factors can influence the final decision. As evidenced by previous studies, various analysis models do exist. However, an effort is required to glean those various models, re-examine the models, and fit them into ODOT's current fleet management system and available equipment data, so that optimal equipment decisions can be achieved.

CHAPTER III

DATASETS AND METHODOLOGY

In this chapter, the dataset from Agile Asset database and data processing in MySQL are first described, then the methods applied on the dataset, including dynamic programing models and exploratory data analysis, are revealed in detail.

3.1 Database construction and data processing in MySQL

ODOT provided the entire dataset including records on equipment fleet inventory as well as operation, maintenance, and repair activities. The entire dataset was exported from Agile Assets into in Excel spreadsheets provide by the ODOT maintenance division. At the time of the study, the dataset covered data records from Oct. 2010 to Sept. 2020. Since the data obtained from ODOT was an export from a relational database, multiple data tables were used to capture different aspects of information related to the equipment fleet. An entities-relational diagram resembling the Agile Assets system was used to create a relational database in MySQL Workbench (Figure 1). The detailed description of these tables can be found below.

- Equipment_Class_Code – The table presents the basic information about the classification of equipment. The class code classifies all the equipment based on equipment type and equipment size. A group of similar equipment shares the same class code.

- Equipment_Inventory – Inventory data table provides the basic information about every individual piece of equipment in ODOT's current inventory. Each piece of equipment is assigned with a unique Equipment ID.
- Equipment_Fueling – This data table provides information about the fuel purchase activities associated with individual pieces of equipment. Fuel consumption and fuel cost are an important factor to estimate the operating cost of equipment. The equipment fueling data table associates all the fuel records with equipment IDs.
- COMDATA_Fueling – COMDATA Fueling Data contains the record of all the purchases charged to the COMDATA card, including both fuel and non-fuel purchases. The data records are associated with equipment IDs.
- Setup_Project – This data table consists of records on maintenance repair activities and costs performed on all the equipment. All of the activities are associated with equipment IDs.
- Work Orders_Equipment_DC – This table shows miles driven or hours operated during the operation of the equipment to perform regular and maintenance work.
- Work_Orders – This table shows all costs incurred and miles driven or hours operated during the operation of the equipment to perform maintenance work in the field. Different form Work Orders_Equipment_DC, this table also includes costs not involving equipment operations.

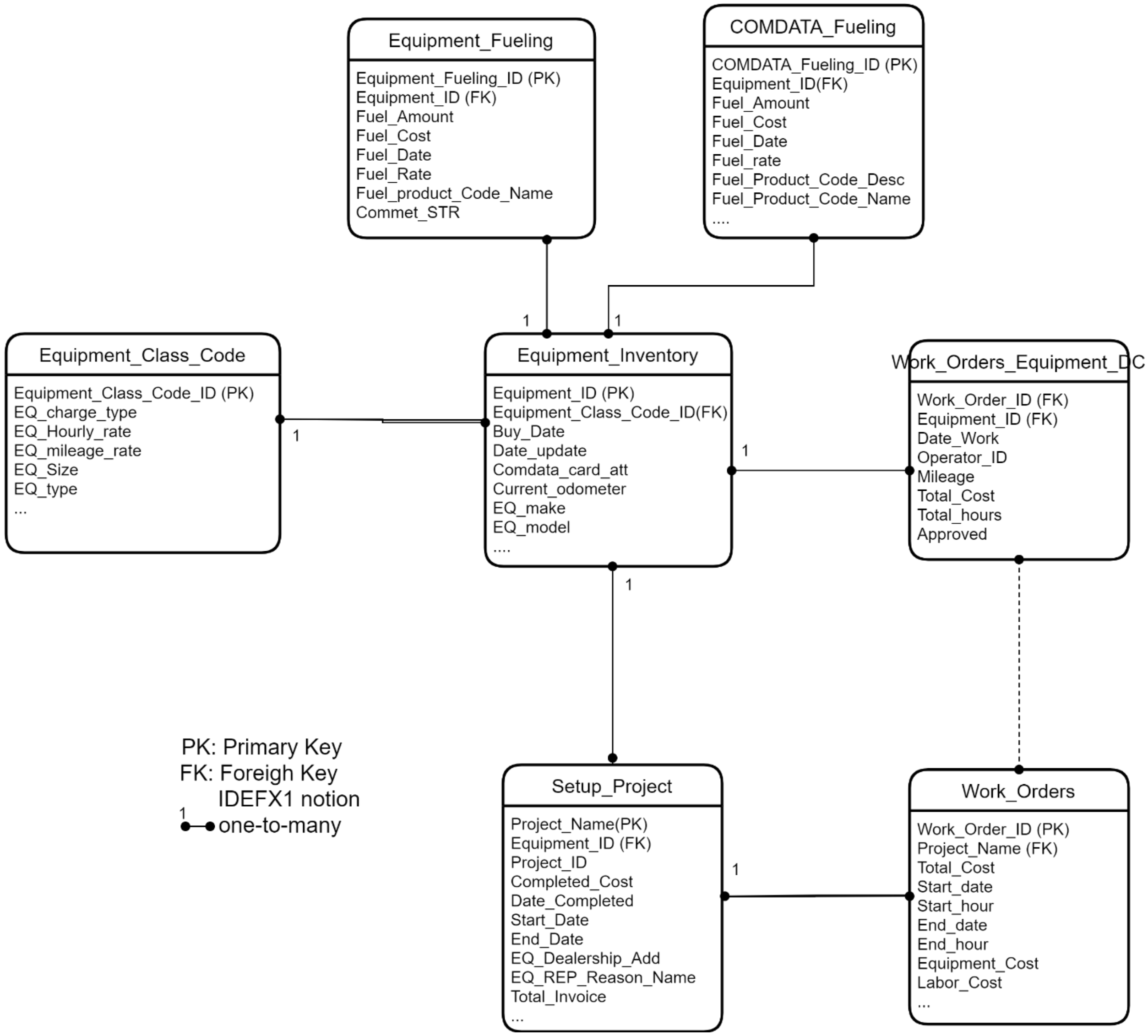


Figure 1. Entities-Relational Diagram (ERD) of ODOT equipment management database

This study focused on the equipment bought since 2010, since their operations and management including fueling, maintenance, and repairs are well recorded in the Agile Assets system. A query was created to select all the equipment bought since 2010 which is ranked based on quantity and shown in the table 1. The most bought equipment is ½ ton fleetside pickup with total quantity of 543, which is followed by gas-powered weed eater (527).

TABEL1. The numbers of equipment in each class bought since 2010

NO.	Equip. Class Code ID	Number of Equip.	Equipment Size/Description	Equipment Type
1	5385	543	1/2 TON FLEETSIDE	PICKUP
2	5115	527	GAS POWERED	WEED EATER
3	5363	368	ONE WAY	SNOW PLOW
4	5435	367	41000 GVW-DIESEL	TRUCK
5	5136	261	SINGLE SPINNER	SPREADER-HEAVY DUTY
6	5442	255	3/4 TON	CREW CAB PICKUP
7	5375	237	85 H.P. DIESEL	WHEEL TRACTOR
8	5261	218	15' ROTARY -	MOWING ATTACHMENT
9	5118	216	GASOLINE POWERED	BLOWER/VACUUM
10	5486	198	APPROX. 5 H.P.	CHAIN SAW
11	5488	180	APPROX. 4 H.P.	CHAIN SAW
12	5117	104	GASOLINE POWERED	HEDGE TRIMMER/PRUNER
13	5349	100	FOR TRACTOR/SKID STEER	ATTACHMENT - FRONT END LOADER
14	6499	86	GASOLINE ENGINE	CHEMICAL INDUCTION SYSTEM
15	5355	80	2 YD.	FRONT END LOADER
17	5102	68	5 HP - 10 HP	AIR COMPRESSOR
16	5189	68	SELF PROPELLED	POWER SWEEPER
18	5238	64	150 H.P.	MOTOR GRADER
19	5218	60	SOLAR POWER	TRAFFIC WARNING SYSTEM
20	5395	57	FULLSIZE	PICKUP
21	6497	57	1/2 TON	CREW CAB PICKUP
23	5443	54	1 TON	CREW CAB PICKUP
22	5444	54	2 WHEEL	TRAILER
24	5135	50	SINGLE SPINNER	SPREADER-HEAVY DUTY
25	5434	49	24000 GVW-DIESEL	TRUCK
26	5226	48	TRAILER MOUNTED	ATTENUATOR
27	5180	47	TRUCK MOUNTED	CHEMICAL APPLICATOR
28	5116	45	GAS POWERED	EDGE TRIMMER
29	5183	43	GASOLINE ENGINE	POWER WASHER
30	5185	39	SOLAR/BATTERY POWERED	RADAR/SPEED MONITOR
31	5319	37	9 WHEEL	ROLLER
32	5164	35	60 LB. - 26 INCH	PAVING BREAKER
33	5260	33	TRAILER MOUNTED	BRUSH CHIPPER

35	5123	31	92 NET H.P.	BACKHOE-LOADER-TRACTOR UNIT
34	5357	31	1/3 CU. YD. CAP.	SKID STEER LOADER
36	5113	29	GAS POWERED	EDGE TRIMMER
37	5098	28	185 CFM	AIR COMPRESSOR
38	5394	28	1 TON, DUAL REAR	PICKUP
40	5195	26	1750 WATTS - 4 HP AND	GENERATOR
39	5214	26	TRACTOR MOUNTED	EXCAVATOR
41	5251	26	50 INCH CUT	MOWER - ROTARY
43	5089	25	FOUR DOOR SEDAN-MID SIZE	AUTO - WHITE COLOR
42	5197	25	5000 WATTS-10 HP	GENERATOR
44	5248	24	60 INCH	MOWER - ROTARY
45	6292	23	BUILDING BACKUP	GENERATOR
46	5166	20	VIBRO-PLATE 3 HP	COMPACTOR
49	5176	20	HYD. DRAINAGE	POWER WASHER
48	5386	20	3/4 TON FLEETSIDE	PICKUP
47	6387	20	25-50 GALLON, ELECTRIC	HERBICIDE SPOT SPRAYER

There are various methods used for estimating ownership and operating costs. Each method may have its own formula and estimation principles. In general, the rates calculated by the AGC method are the highest while the equipment costs computed by the Corps of Engineers method are the lowest (Gransberg, 2006). In this project, the data recorded by fleet management systems were used to obtain more accurate results for equipment ownership and operating costs.

The following section describes the data processing flow charts and the SQL procedures involved. Depreciation could be the most important part of equipment cost. It is a fixed cost, however, depending on calculation methods, it could be very different for each year. Here we used two different methods, Straight-Line method (SL) and Double Declining-Balance method (DDB). SL method gives an equal amount of depreciation in each year of useful life while DDB generates very high initial depreciation in the first year of useful life, which then decrease in a factor toward the end of useful life of equipment. The specific equations for the two methods are shown below.

$$\text{Cost Rate } \left(\frac{\$}{\text{hour}} \text{ or } \frac{\$}{\text{mile}}\right) = \text{Depreciation Rate} + \text{Operating Cost} \quad \ldots \text{Eq.1}$$

$$\text{Depreciation rate (SL)} = \frac{\sum_{i=1}^{n}[(\text{Purchase price – Sold price or Salvage value}) * \text{SLDP}]}{\text{miles driven/hours used}} \quad \ldots \text{Eq.2}$$

$$\text{Depreciation rate (DDB)} = \frac{\sum_{i=1}^{n} 2 * \text{SLDP} * \text{BV}i}{\text{miles driven/hours used}} \quad \ldots \text{Eq.3}$$

SLDP: straight-line depreciation percent

BVi: book value at the beginning of the age i

n: ages (1, 2, …,10)

$$\text{Operating Cost} = \frac{\text{Maintenance and repair cost + Fueling cost}}{\text{miles driven/hours used}} \quad \ldots \text{Eq. 4}$$

Both methods require original price, useful life, and salvage value of the equipment, and the information can be found in the two tables of equipment_inventory and equipment_class_code. A procedure was developed (named as “load_dp”, see Query 1 in Appendices) to calculate annual depreciation for each equipment through a loop function in MySQL. Figure 2 shows the flow chart on the depreciation calculation process.

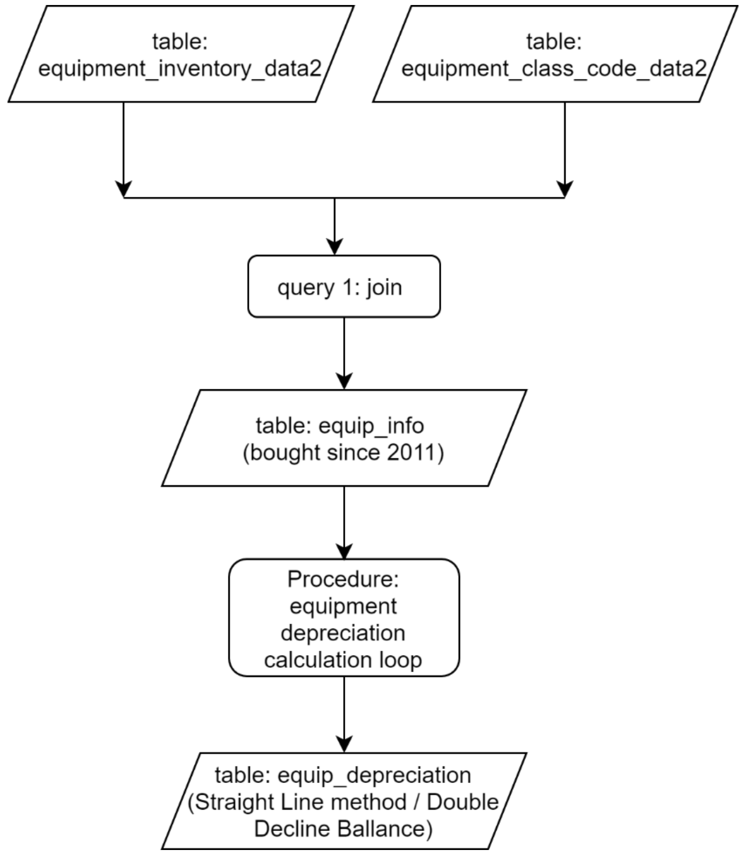


Figure 2. Flowchart for Calculating Depreciation Rate ($/year)

The other parts of annual cost of fueling cost and maintenance and repair cost were calculated in the time series in accordance with depreciation values that were created previously. The tables of Comdata_fueling, Equipment_fueling, and Setup_project were involved in this process. The table Comdate_fueling is primarily composed of fueling cost records but some maintenance costs (such as spare parts change, oil change, ties related cost) were also included. According to fueling rate (if greater than $4/gallon), this part of cost was separated and classified into maintenance cost category. The table Equipment_fueling only contains fueling activity records, such as fueling amount and cost. The table of setup_project provides the maintenance/repair cost that are further divided into sub classes of equipment cost, parts cost, and labor cost, etc. A procedure was developed (named as “dp_to_all_costs”, see Query 2 in Appendices) to calculate annual total cost for each equipment in MySQL. Figure 3 shows the flow chart on the total cost calculation process.

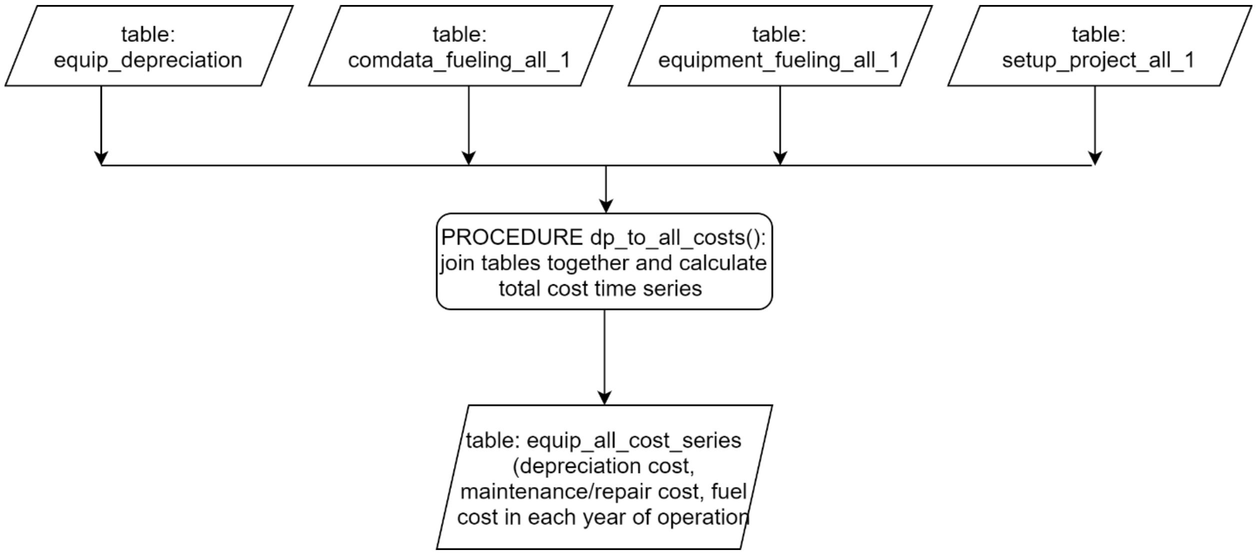


Figure 3. Flowchart for generation of annual total cost time series ($/year)

Equipment cost charged on miles was calculated as dollar per mile (dpm), which relies on the table, equip_all_cost_series, containing all types of cost obtained in the previous step and the table containing basic information of equipment (such as odometer). Mile per gallon (mpg) was calculated for each equipment based on its odometer and total fueling amount, which can be used to obtain annual running miles in turns based on annual fueling amount. Therefore, dpm at each year or cumulatively for whole life can be calculated once the annual total cost and miles were calculated. Figure 4 is the flow process on obtaining the mpg and dpm at both annual and whole-life scales for the equipment charged on miles. A procedure called “dollar_per_mile” (Query 3 in Appendices) was developed to facilitate this process.

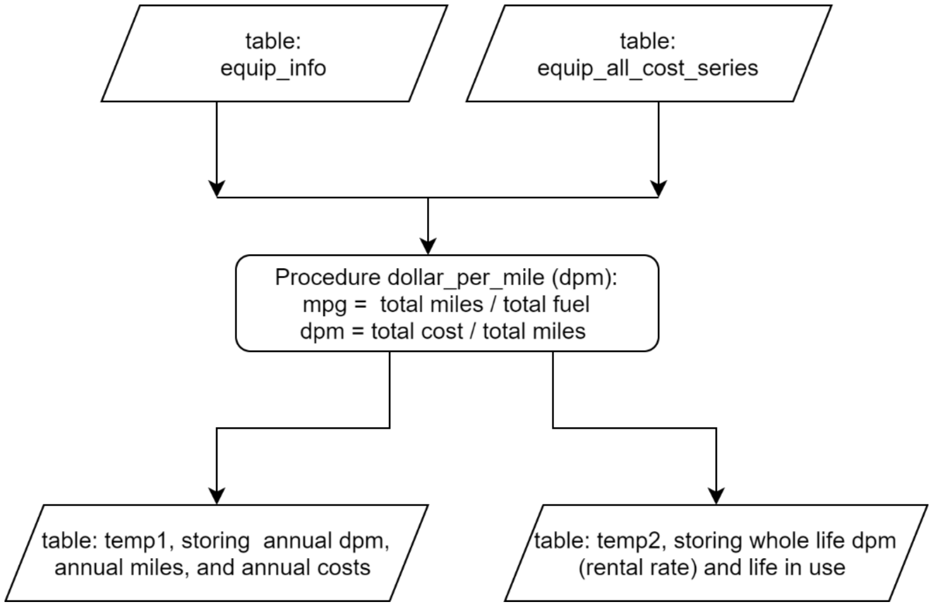


Figure 4. Flowchart for the cost of dollar per mile at both annual and whole-life scales for equipment charged on miles

Similarly, equipment cost charged on hours was calculated as dollar per hour (dph). The table, equip_all_cost_series, containing all types of cost obtained in the previous step was needed; however, an additional table, work_orders_equipment_dc, was also needed for the total work hours of equipment. Hour per gallon (hpg) was calculated for each equipment based on its total work hours and fueling amount, which was used in turns to obtain annual work hour based on annual fueling amount. Therefore, dph at each year or cumulatively for whole life can be found once the annual cost and miles were calculated. Figure 5 is the flow process on obtaining the hpg and dph at both annual and whole-life scales for the equipment charged on hours. A procedure called “dollar_per_hour” (Query 4 in Appendices) was developed to facilitate this process.

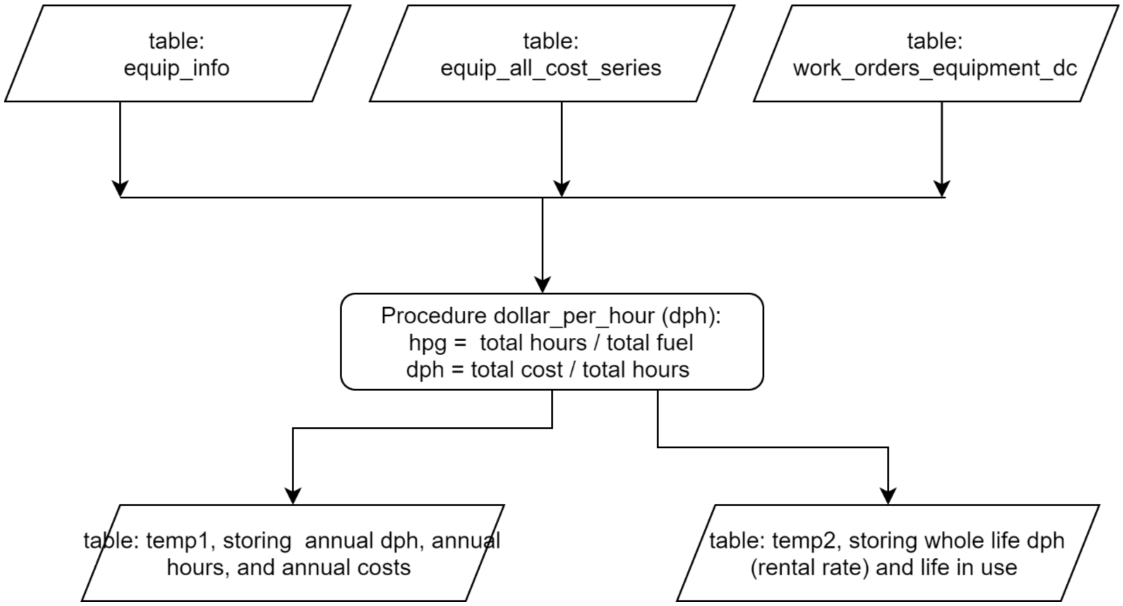


Figure 5. Flowchart for the cost of dollar per hour at both annual and whole-life scales for equipment charged on hours

Above mentioned that equipment charged by dpm and dph can be processed by the procedures “dollar_per_mile” and “dollar_per_hour” respectively. One more procedure (named as “class_code_cost”, Query 5 in Appendices) was created to process all the equipment (the ones bought since 2010) in a loop way in which charge types as the control to divert the process either to procedure “dollar_per_mile” or “dollar_per_hour” and eventually all the equipment was processed. Four tables in two sets are finally generated of which two for mile-based equipment and another two for hour-based equipment. One set of tables is for time series of annual cost and rental rates (dpm and dph) and the other set is for the whole life averages of rental rates and other information such as current ages and average work miles or hours each year. The detailed process is shown in the flow chart of Figure 6.

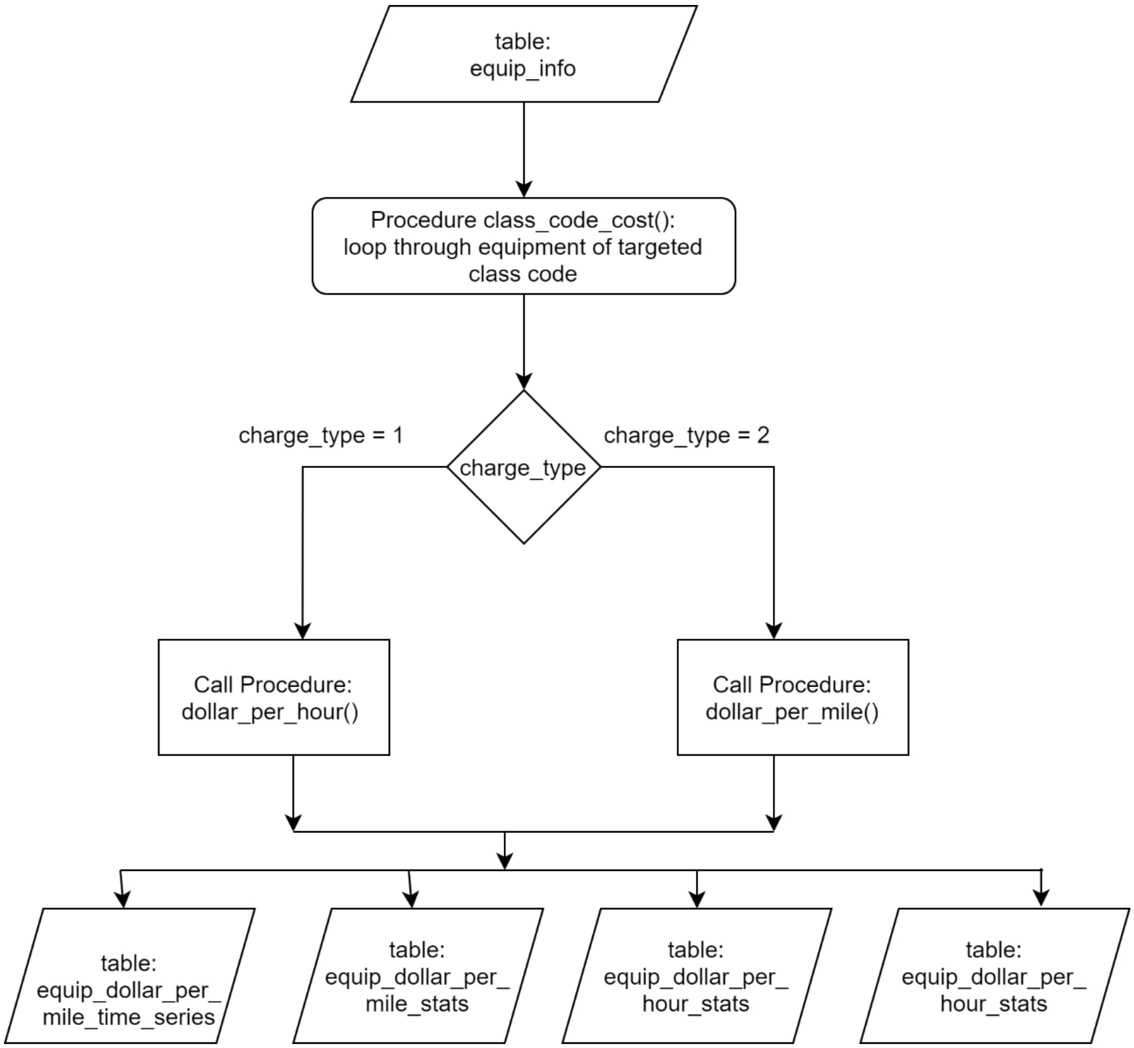


Figure 6. Flowchart for rental rates (dpm and dph) and time series for all the equipment in each class code

3.2 Dynamic Programing Models

Dynamic Programing models are used for equipment replacement decisions due to its high efficiency in optimization of equipment total cost over a time horizon. The computing savings can be huge especially for large version of problems such as this study with thousands of equipment pieces. The basic features describing the dynamic programing in this application can be described as: 1. Equipment life span was divided into stages that are the historical years the equipment experienced. At each stage a policy decision is required to made, and here it is either “keep” or “replace” the equipment. 2. There were different numbers of states associated with each stage. Here, the states are the ages of equipment that can vary from 1 to 10 if a 10-year old equipment is available (e.g. the ones bought in 2011 and kept until 2020). 3. Then a backward iterative solution (beginning first from the optimal policy for the last stage) was defined to find the optimal decision policy that would be made for the equipment historical period to reduce total cost in consideration of depreciation cost, maintenance/repair cost, and fueling cost. 4. A recursive function (see section 3.2.1 for details) was developed for stage n given the optimal policy for stage n+1. The dynamic programing used here was a deterministic model meaning the state at next stage are completely determined by the state and decision at the current stage. The model also faced uncertainty in depreciation rate and maintenance cost when a “replace” decision made for equipment. Depreciation was calculated based on historical purchasing price changes with a linear regression model (see section 3.2.2) and maintenance/repair cost followed the historical cost pattern in terms of equipment ages. The fueling cost was assumed to follow the historical annual cost of equipment life span. This means the tasks are performed by equipment is kept the same no matter if there is replacement or not for the equipment. By doing so, cost rate can be also minimized when minimizing total costs.

3.2.1 Dynamic Programing - Minimize the recursive function

$$f_n(S_n) = cost_n(S_n) + f_{n+1}(\{S_n + 1, if\ Q_n = \text{"Keep"}; 1, if\ Q_n = \text{"Replace"}\}) \qquad \text{…Eq. 5}$$

S_n: $states\ of\ equipment\ at\ stage\ n; corresponding\ to\ the\ ages\ of\ equipment$

$$S_1 = 1; S_2 = \{1,2\}; S_3 = \{1,2,3\}; \dots; S_{10} = \{1,2,3, \dots, 10\}$$

Q_n: $decisions\ made\ at\ stage\ n\ (\text{"}Keep\text{"}\ or\ \text{"}Replace\text{"}\ equipment)$

$cost_n$: $total\ cost\ at\ stage\ n\ (including\ depreciation, fueling\ cost, and$

$maintenance\ cost)$

n: stage, corresponding to years of the equipment life span, from 2011 to 2020

$$cost_n(S_n) = depreciation\ (S_n, n) + maintenance\_cost(S_n) + \ \ fueling\_cost(n) \qquad \text{…Eq. 6}$$

depreciation: depreciation cost at the stage n, depending on equipment ages and bought years. Straight-line depreciation method is used first.

maintenance_cost: maintenance and repair cost at stage n, depending only on the ages of equipment

fueling_cost: fueling cost at stage n, depending only on the stages which are the years of the equipment life spans

3.2.2 Input data and parameter estimates

The challenges of input data obtainment include depreciation rate which varies with both the equipment bought year and ages. In general, equipment original price increased in the past 10 years with linear or non-linear trends depending on equipment class codes. Here we fit a linear line into the original prices in the past and then extract a yearly price series which later were fed into the model as a depreciation rate calculation at different time points. Figures 7 and 8 below are original price changes and their estimation (fitting lines) for the class code 5355 (Front-end Loader) and 5385 (½ ton Fleetside Pickup). The original price for the class code 5355 increased from $78,000 in 2011 to $130,000 in 2017. The original price for the class code 5385 increased from $19,000 in 2011 to $41,000 in 2018. The price increases were mostly caused by the upgrade for the new models of the equipment.

As mentioned above, this study assumes that maintenance and repair cost depend only on the ages of equipment. Fueling costs depend only on the stages which are the years of the equipment life span. These assumptions can maximally mimic equipment maintenance costs and operation hours (or running miles) associated cost if the equipment is replaced for cost savings.

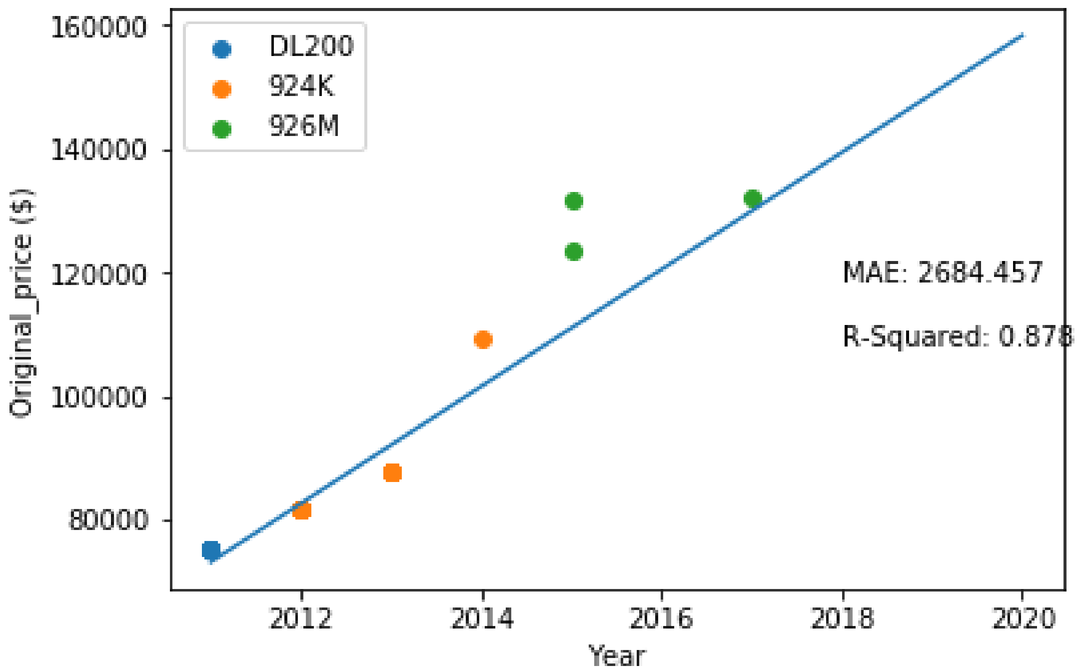


Figure 7. Original price variability with years and models for the equipment class code 5355 (Front-end Loader)

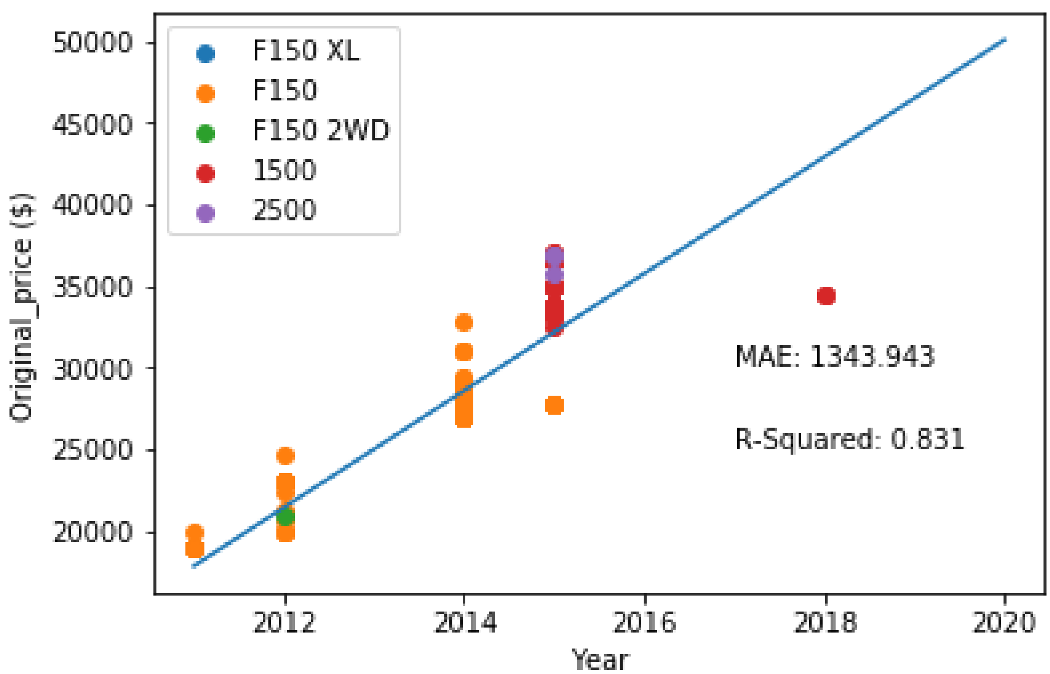


Figure 8. Original price variability with years and models for the equipment class code 5385

3.3 Important Features Associated with Equipment Cost Rates

Exploratory data analysis has been widely used by data science field to analyze and investigate data sets and summarize their main characteristics for pattern recognition, anomalies identification, and hypothesis tests. Target variables and predictive variables are correlated or examined for their relationships. In this study, cost rates of dollar per hour/mile are target variables and predictive variables are total cost, utilization and other features that need to be explored.

A framework (Figure 9) was developed to find the useful features to determine the top costly equipment and associated cost rates. A series of factors were considered, which include equipment ages, usages of hours/miles in terms of cumulative amount and average annual terms, total cost, fuel efficiency. The correlation coefficient and statistical significance tests were used as metrics in the analysis.

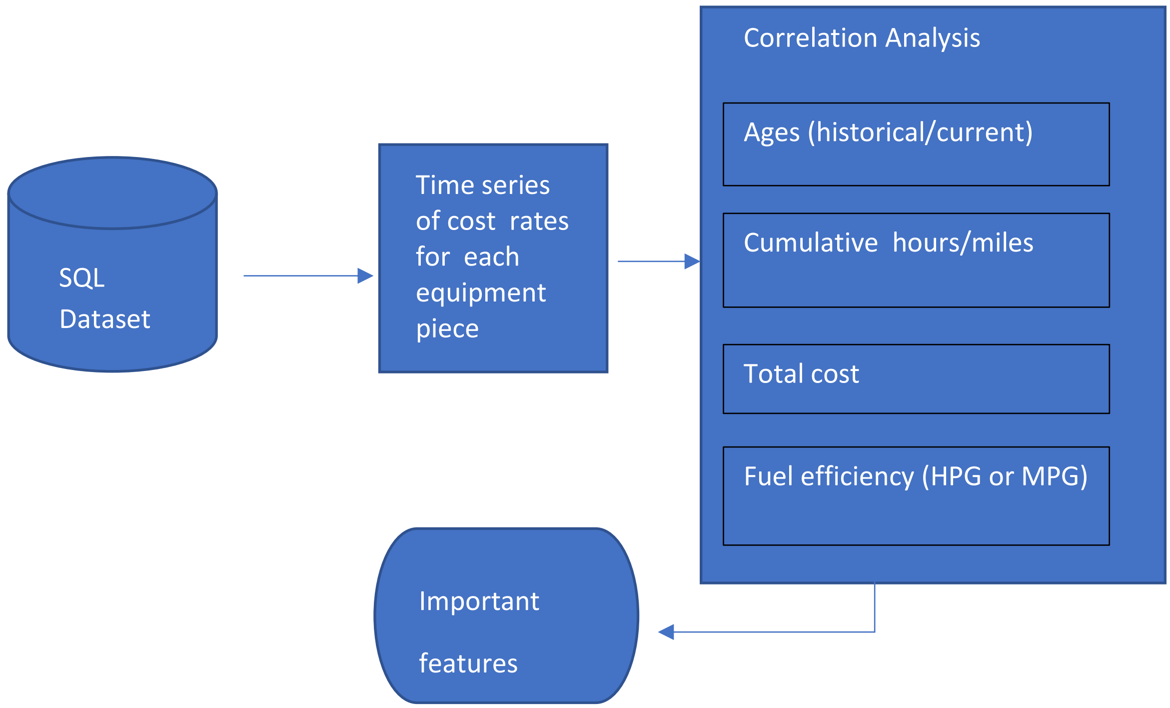


Figure 9. A framework used to determine important features for prediction of equipment cost rates

CHAPTER IV

FINDINGS

In this chapter, equipment replacement decisions are discussed with respect to the two methods, economic life cycle analysis and dynamic programing models, for the two frequently used equipment in equipment class code 5355 and 5385. Class code 5355 (charged on hours) is for the 2 YD Front-End Loader and class code 5385 (charged on miles) is for the ½ ton Fleetside Pickup trucks.

4.1 Life Cycle Cost Analysis

4.1.1 Equipment class code 5355

4.1.1.1 The relationship between equipment costs and ages

There are 70 pieces of equipment in the class code 5355 with ages varying from 4 to 10 as of year 2020, which allow a continuous life cycle analysis from age 1 to age 10 with consideration of cost variability from the different equipment pieces. Figure 10 shows the histograms of costs for this class using the two different depreciation methods of Straight Line and Double Decline Balance (DDB). The DDB method tends to yield larger costs because it distributes largest depreciation in the earliest life of the equipment, while the overal distribution shapes are very similar between the two methods.

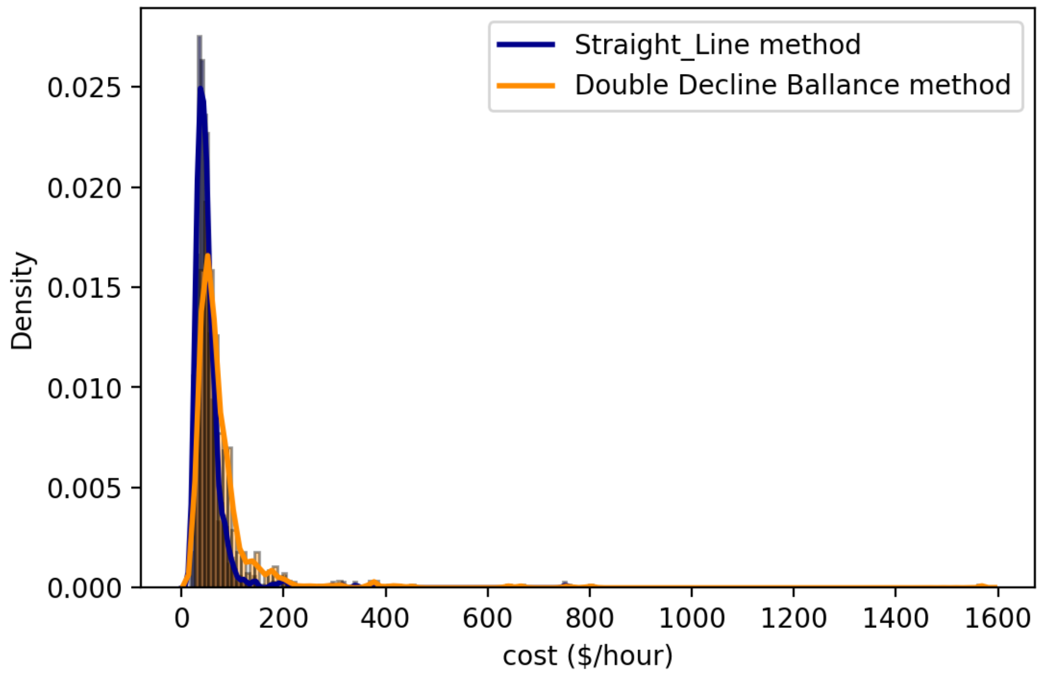


Figure 10. Histograms of cost rate of equipment class 5355 using two different depreciation methods

Equipment cost rate ($/hour) in the first year is with huge variability which could be more than $700/hour to less than $20/hour irrespective of the deprecation methods (Figure 11). The variability reduces very quickly starting from the second year and it becomes very stable from the fifth year in the Straight-Line method so that there is no clear decreasing trend ($p = 0.29$ for ages 5 -10). However, the Double Declining Balance method permits a clear decreasing trend in the cost rate for the whole life span of the equipment ($p < 0.05$). This phenomenon happens because large portion of deprecation occur at the early life of equipment while minimal depreciation is ascribed to later years in the DDB method. The means of the cost rate in each age group change in different patterns for these two methods too (Figure 12). Again, a clear decreasing trend shows for DDB method but not in Straight-Line method. But both methods produce an equal mean in the cost rate at the age of 10 for this equipment class.

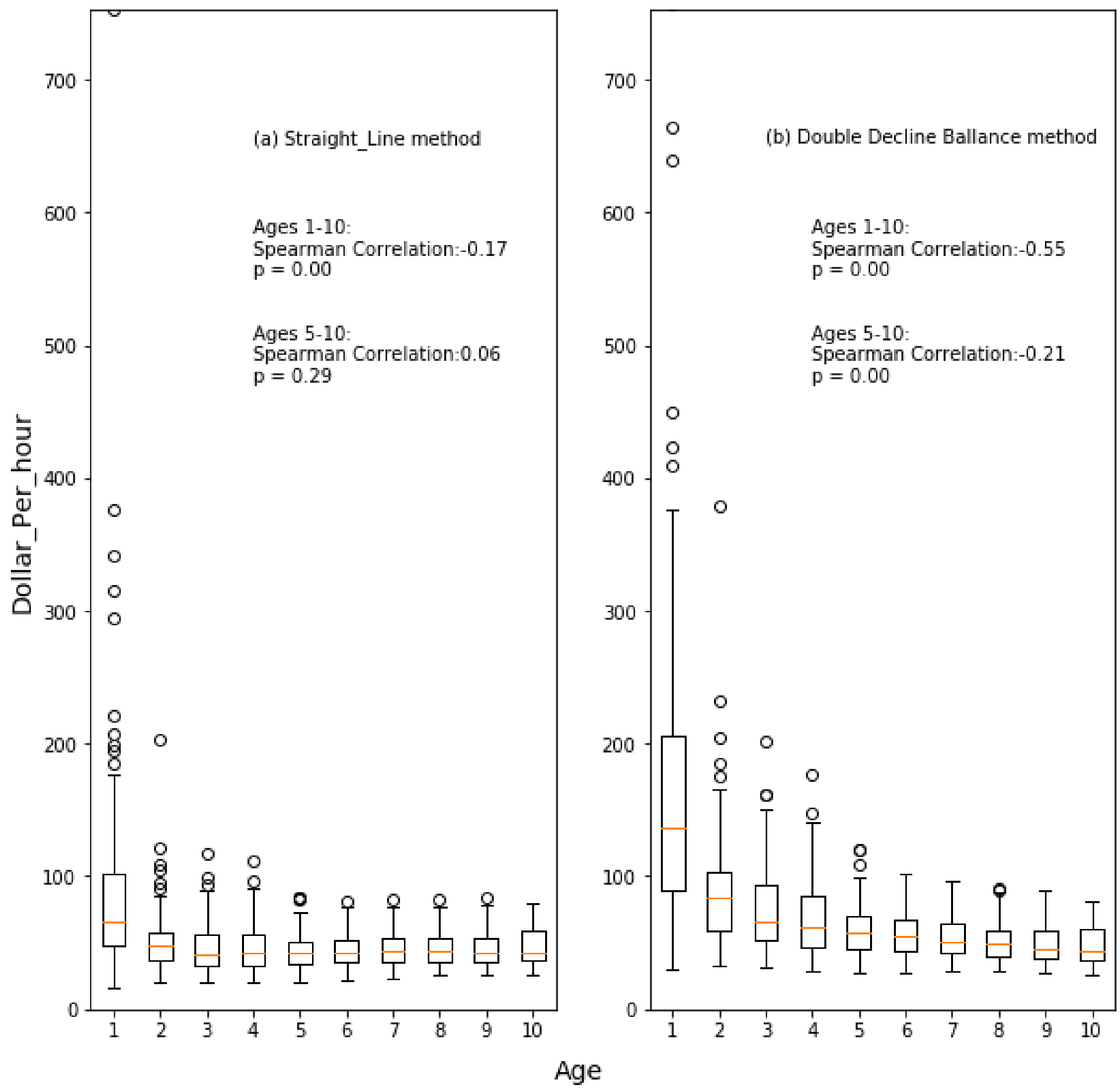


Figure 11. Cost rate variability in each age group for equipment class 5355

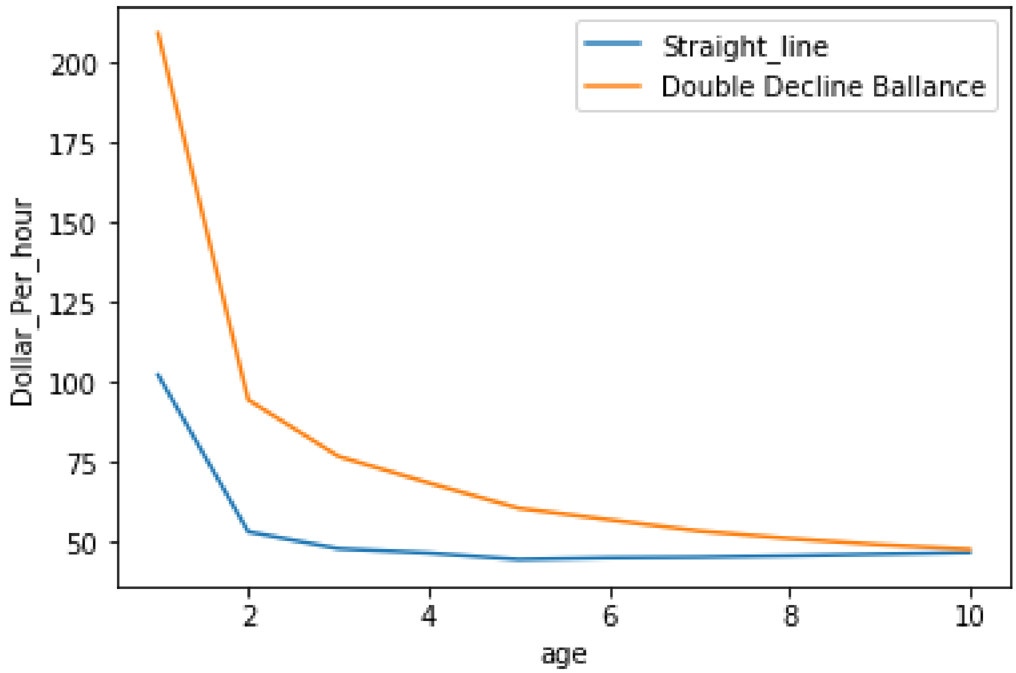


Figure 12. The cost rate mean in each age group for equipment class 5355

4.1.1.2 The relationship between equipment cost rate and usage (cumulative annual hours)

Equipment cost rate ($/hour) decreases with the increase of cumulative hours of equipment usage (Figure 13a). A power function was used to fit the data and statistical significance was tested for both parameters ($p < 0.05$) as shown in the Figure 13a. Similarly, the cost rate ($/hour) also decreases with the increase of cumulative total costs of equipment (Figure 13b), which was also statistically significant for both parameters in a power function. The equipment cost of dollar per hour increases with the decline of gas efficiency but statistically not as significant as the relationship with cumulative hours and cumulative total costs (Figure 13c).

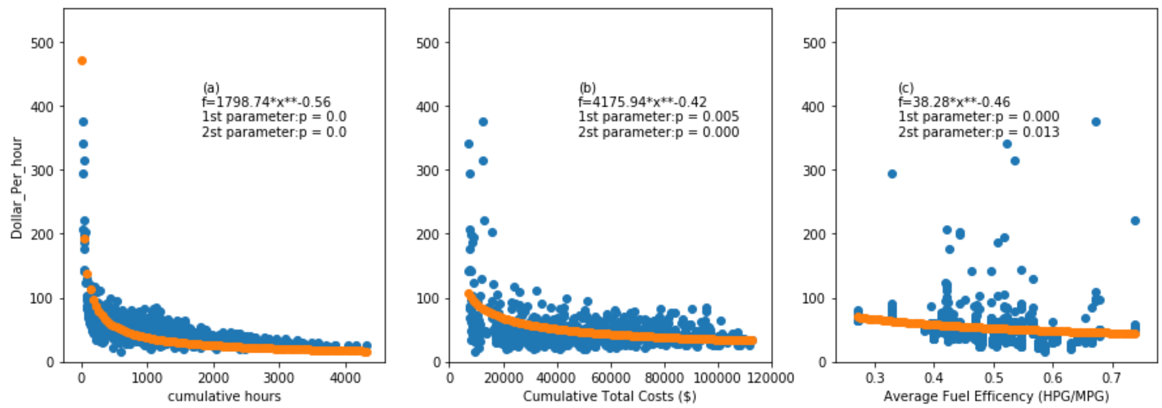


Figure 13. The relationships between cost rate ($/hour) and cumulative hours (a), cumulative total costs (b), and fuel efficiency (c) for all ages of the equipment in class 5355

The relationship between the cost rate ($/hour) and the cumulative hours of usage become even stronger when only considering the stage of the current ages for each piece of equipment. This is a subset of all stages of equipment with the excluding of the previous stages of the historical ages. As can be seen, total operation hours are equal or greater than 1000 (Figure 14a) and ages are equal and greater than 4 (Figure 14d). The cost rate is more negatively correlated with usage of cumulative hours (Figure 14a). The cost rate is also more negatively correlated with the cumulative total costs for the equipment (Figure 14b). Interestingly, the cost rate becomes also negatively correlated with fuel efficiency of equipment (Figure 14c). Age becomes a less important factor in affecting the cost rate (Figure 14d) and this is consistent with the statistical test in Figure 11a that after age 5 the cost rate trending is not significant anymore.

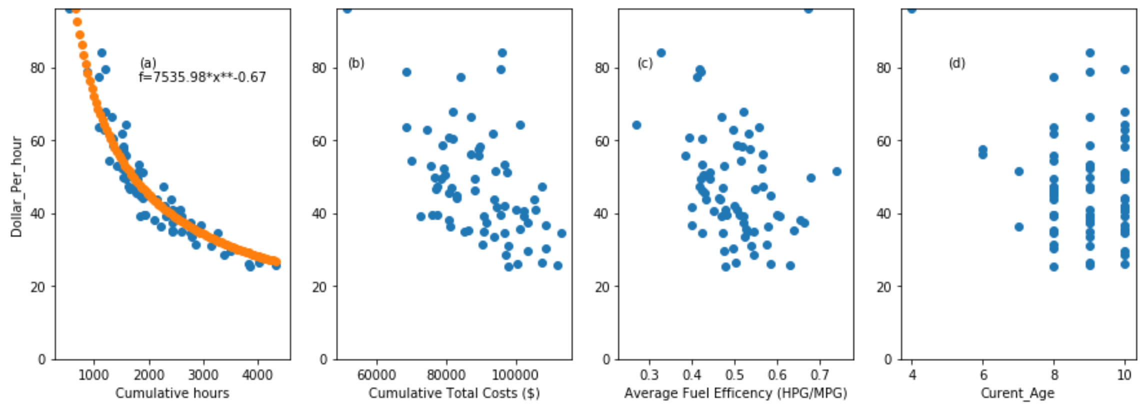


Figure 14. The relationships between the cost rate ($/hour) and cumulative hours (a), cumulative total costs (b), fuel efficiency (c), and ages (d) for the current ages of the equipment in class 5355

Life cycle cost analysis suggests that cost rate of equipment class 5355 decreases very fast in the first five years of life span with both Straight_Line and DDB depreciation methods. It keeps decrease from age 5 to age 10 in the DDB while mostly keeps constant in the Straight-Line method. No matter which depreciation method is considered, it is better to keep the equipment until the end of useful life for an economic purpose. Cost rate decreases with increases of both cumulative hours and cumulative total costs, which suggests that equipment in this class tend to be used more frequently in their later ages. This would not be a wise strategy considering that equipment usually functions better in younger age, however, it could be natural cause that there were more job duties in most recently years compared to further past years. The usage of cumulative hours is more correlated with cost rate than cumulative total cost and should be considered as the more important factor in equipment management. In addition, fuel efficiency also plays some positive role in cost rate and managers should consider improve equipment utilization when equipment is young and function well.

4.1.2 Equipment Class Code 5385

4.1.2.1 The relationship between equipment costs and ages

There are 543 (449 with valid data) pieces of equipment in this class code with ages varying from 2 to 10 as of year 2020, which allow a continuous life cycle analysis from age 1 to age 10 with consideration of cost variability from the different equipment pieces. Figure 15 shows the histograms of costs for this class using the two different depreciation methods of Straight Line and Double Decline Balance. Similarly, the DDB method tends to yield larger costs because it distributes the largest depreciation in the early life of the equipment.

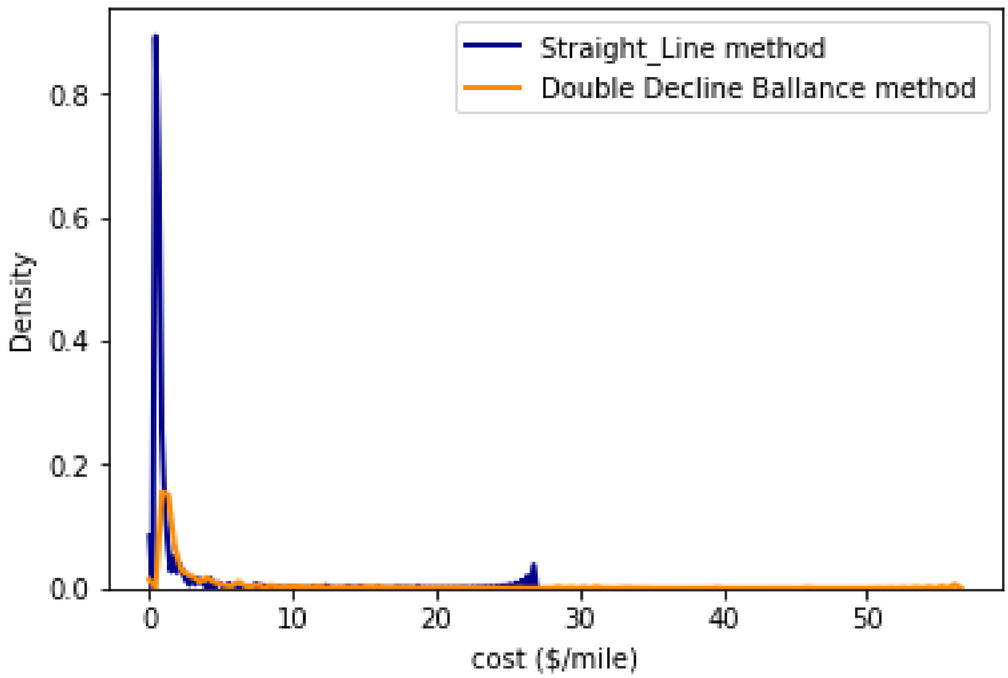


Figure 15. Histograms of costs for equipment class 5385 using two different depreciation methods

The cost rate of dollar per mile ($/mile) is usually the largest in the first year with huge variability (Figure 16), which ranges more than $25/mile to less than $1/mile irrespective of the deprecation methods of Straight-Line or Double Declining Balance (DBB). The variability reduces very quickly starting from the second year and it becomes very stable from the eighth year in both the Straight-Line and DBB methods. Both depreciation methods permit a clear decreasing trend in the cost for the whole life span of the equipment ($p < 0.01$). The means of the cost rate in each age group are different but change in a similar pattern with a clear decreasing trend for the two methods (Figure 16). The two methods produce an equal mean in the cost rate at the age of 10 for this equipment class, which is close to $0.5/mile (Figure 17).

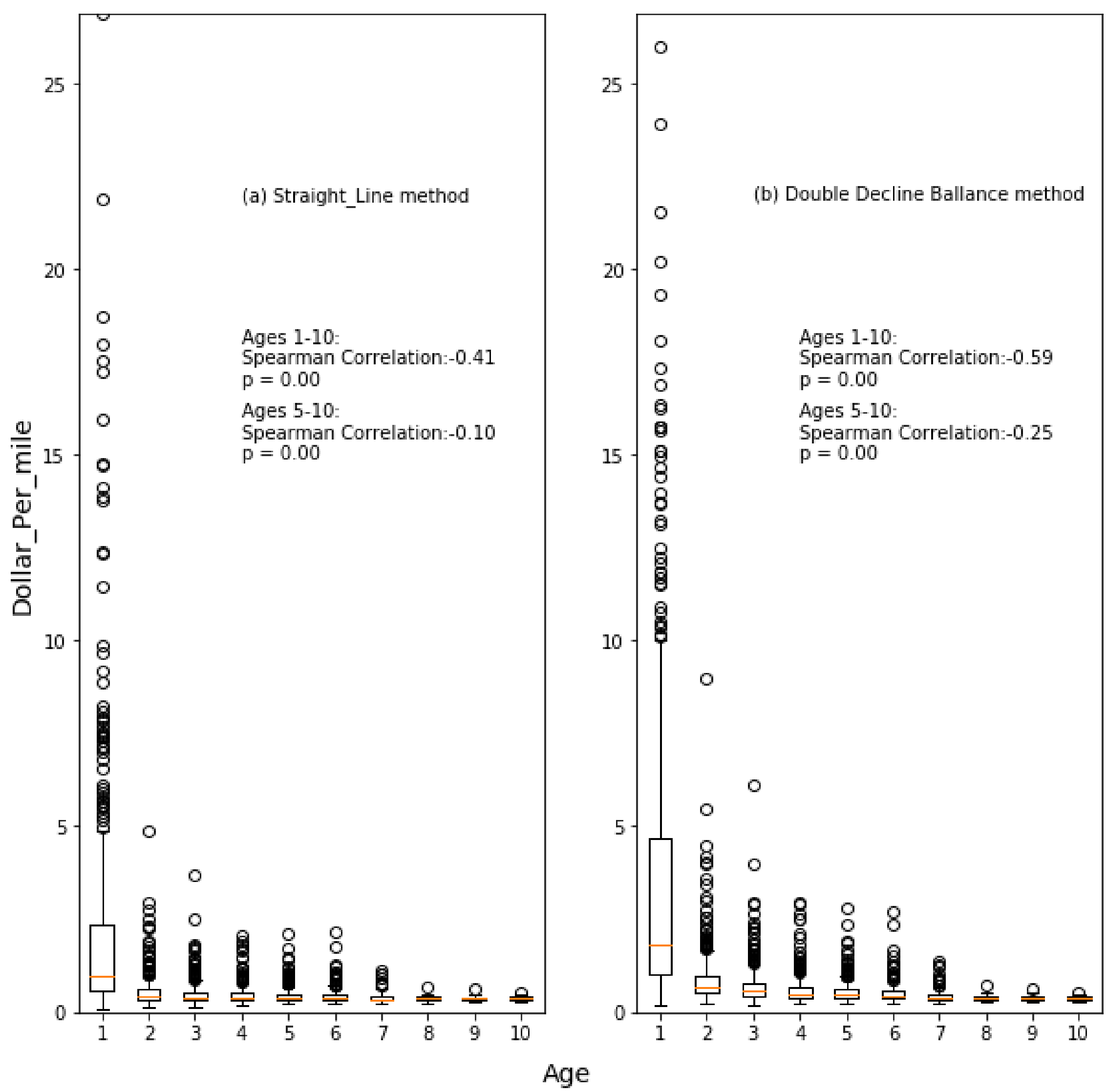


Figure 16. The cost of dollar per mile in each age group for equipment class 5385

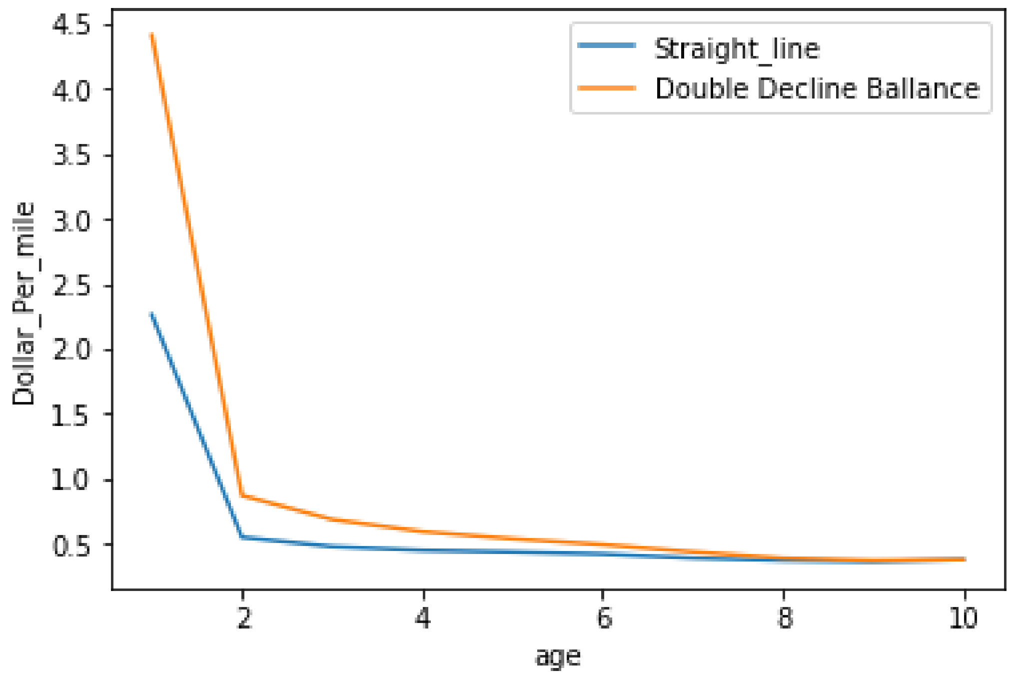


Figure 17. The means of cost of dollar per mile in each age group for equipment class 5385

4.1.2.2 The relationship between equipment cost and usage (cumulative miles)

Equipment cost rate of dollar per mile ($/mile) decreases with the increase of cumulative miles of equipment usage (Figure 18a). A power function was used to fit the data and both parameters were tested statistically significant ($p < 0.01$) as shown in the figure. Similarly, the cost rate also decreases with the increase of cumulative total costs of equipment (Figure 18b), which was also statistically significant for both parameters in a power function but at a relative lower confidence level ($p < 0.05$). The equipment cost rate also decreases with increase of gas efficiency of equipment but not statistically significant (Figure 18c).

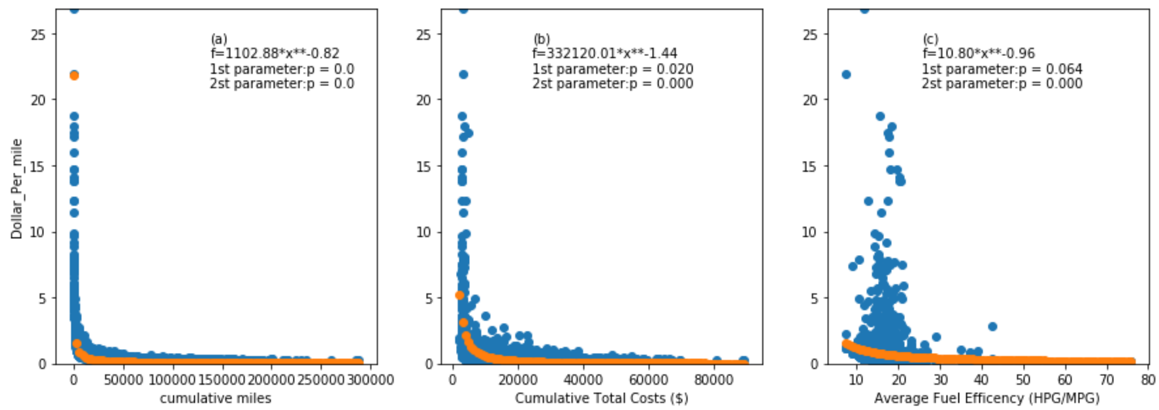


Figure 18. The relationships between cost of dollar per mile and cumulative miles (a), cumulative total costs (b), and fuel efficiency (c) for all ages of the equipment in class 5385

The negative correlation between cost rate of dollar per mile and the usage of cumulative miles becomes even stronger when only considering the stage of the current ages for each piece of equipment (Figure 19a). The cost rate is less negatively correlated with the total costs compared to cumulative miles (Figure 19b). Interestingly, the cost rate becomes also negatively correlated with fuel efficiency of equipment (Figure 19c). Age becomes a least important factor in affecting the cost rate in this subset of data only for current age stage of equipment (Figure 19d).

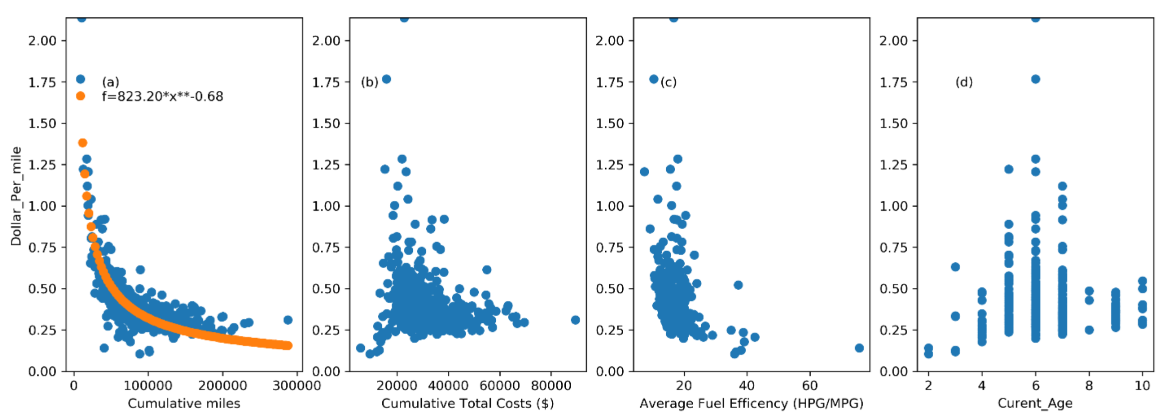


Figure 19. The relationships between cost of dollar per mile and cumulative miles (a), cumulative total costs (b), fuel efficiency (c) and ages (d) for the current ages of the equipment in class 5385

Life cycle cost analysis for class code 5385 suggests that cost rate of this class keep decreasing with increase of ages no matter which depreciation methods were used. There are very similar cost-age patterns between the two classes of 5355 and 5385 except that cost rate keeps constant after age 5 in class 5355 while it keeps decreasing in class 5385 with the Straight-Line depreciation method. Therefore, a similar suggestion would apply to class 5385 that it is better to keep all the equipment until the end of useful life for economic purpose. Fuel efficiency also shows some importance in controlling the cost rate so it is beneficial to use the equipment more at their young ages when equipment function well.

4.2 Dynamic Programing Modeling Results

The dynamic modeling approach resulted in replacement strategies for 12 out of 70 pieces of equipment in the class code 5355. The other 58 pieces of equipment would not need any replacement strategies since they are cost-optimal under current management activities. The equipment bought in more recent years (e.g. 2014, 2015, and 2017) would be more likely to be replaced to reduce the total costs. The equipment bought in earlier years (e.g., 2011, 2012, and 2013) would tend to have no replacement strategies (Figure 20).

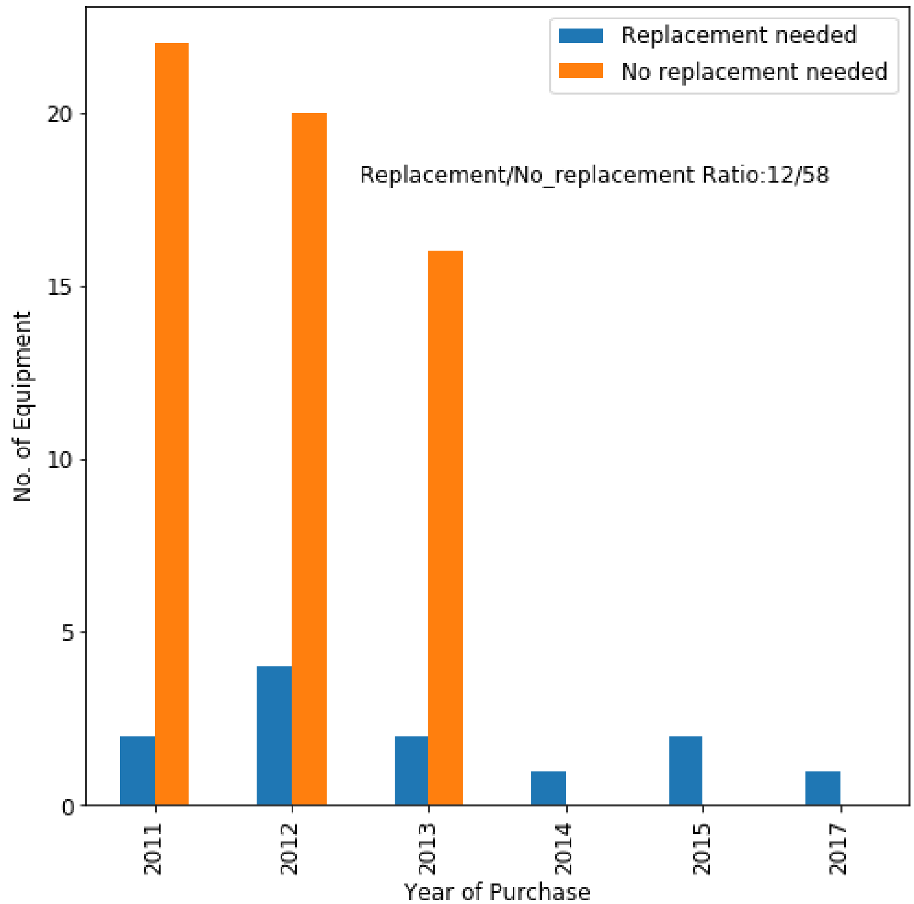


Figure 20. Numbers of equipment with replacement suggestions vs. no replacement suggestions with the years of purchase for the class code 5355

With the application of replacement strategies by the dynamic modeling approach, the cumulative total cost could be reduced by roughly $ 7,000 on average within the period from 2011 to 2019 for the class code 5355 (Figure 21a). However, the lowest cumulative total cost is still associated with the equipment without replacement needs throughout their life spans. For the equipment with replacement suggestions, the best replacing time is at the end of age 1 (50% chance), followed by the ends of age 6 or 7 (30-40%) (Figure 21b).

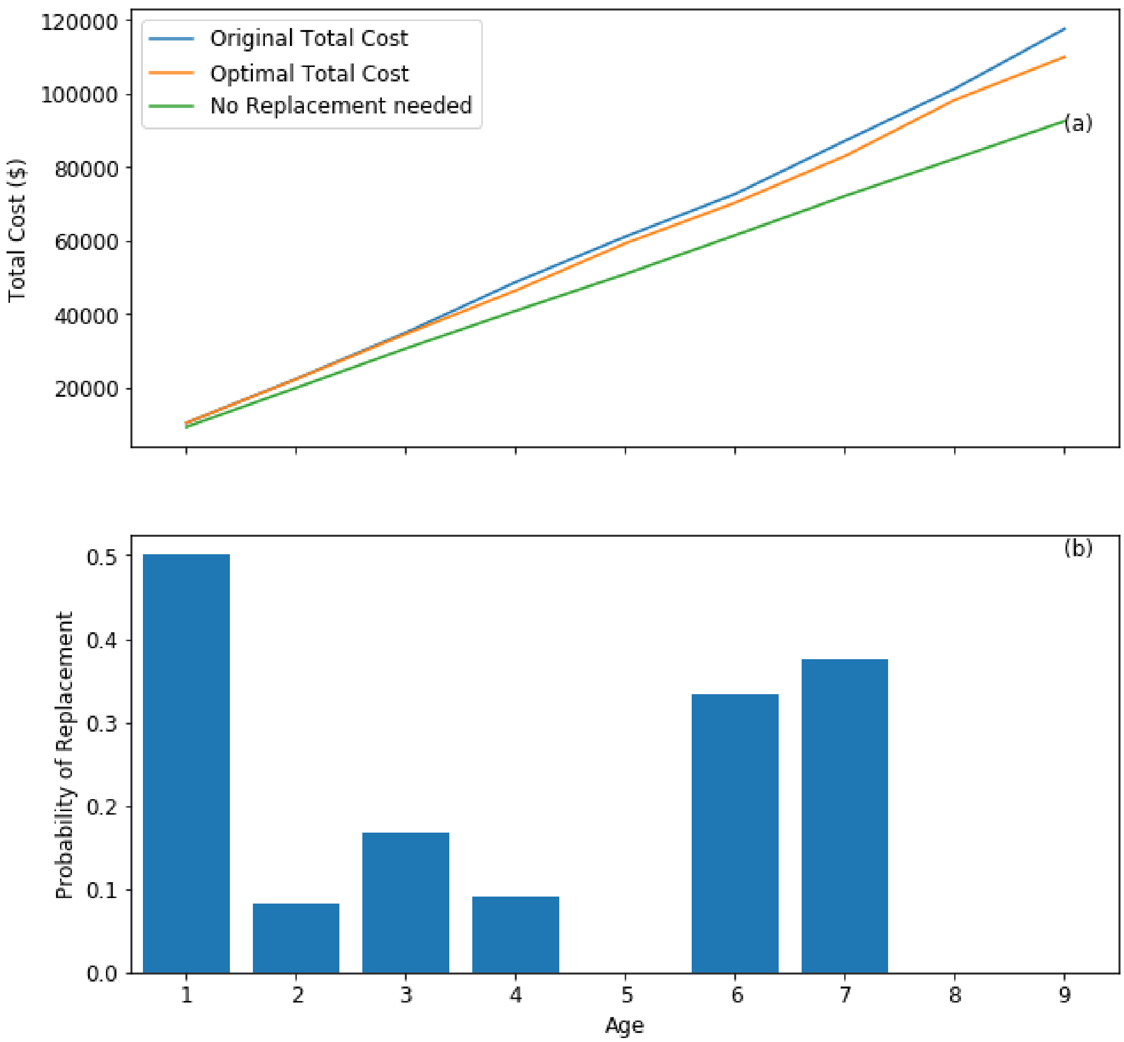


Figure 21. Comparison of the means of original cumulative total cost and optimal cumulative total cost by the dynamic modeling approach (a) and the probability of being replaced under different ages (b) for the equipment class code 5355

The dynamic modeling approach resulted in replacement strategies for 123 (out of 449) pieces of equipment to reduce the total cost for the class code 5355. The rest 326 pieces of equipment would not need any replacement strategies since their costs are optimal under current management activities. Different from class code 5385, the equipment bought in more recent years (e.g. 2014, 2015, and 2016) would not have higher tendency to be applied with replacement strategies than those bought in the earlier years (2011 and 2012). The equipment bought in 2018 would tend to be applied with no replacement strategies (Figure 22).

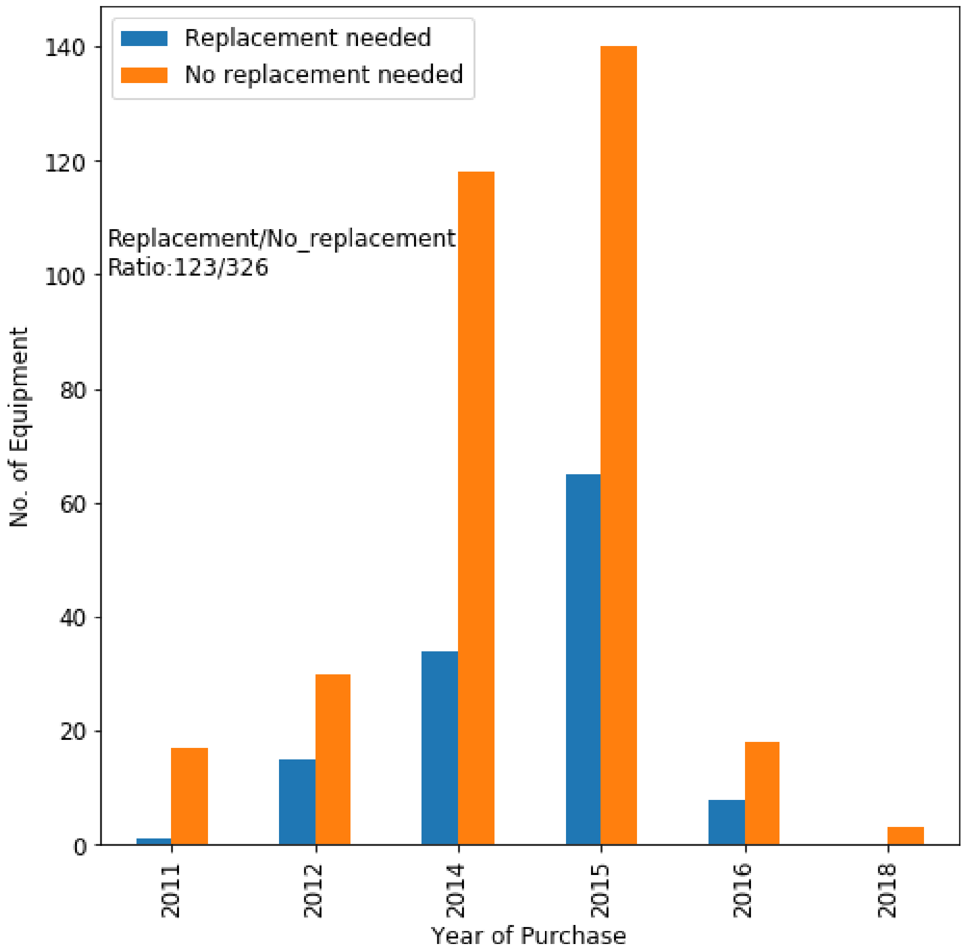


Figure 22 Numbers of equipment with replacement suggestions vs. no replacement suggestions with the years of purchase for the class code 5385

With the application of replacement strategies by the dynamic modeling approach, the cumulative total cost could be reduced by roughly $ 8,500 on average within the period from 2011 to 2019 for the class code 5385 (Figure 23a). However, the lowest cumulative total cost is still associated with the equipment without replacement needs throughout their life spans. For the equipment with replacement suggestions, the best replacing time is still at the end of age 1 (60% chance), and the chance is in a decreasing trend with the increase of ages (Figure 23b).

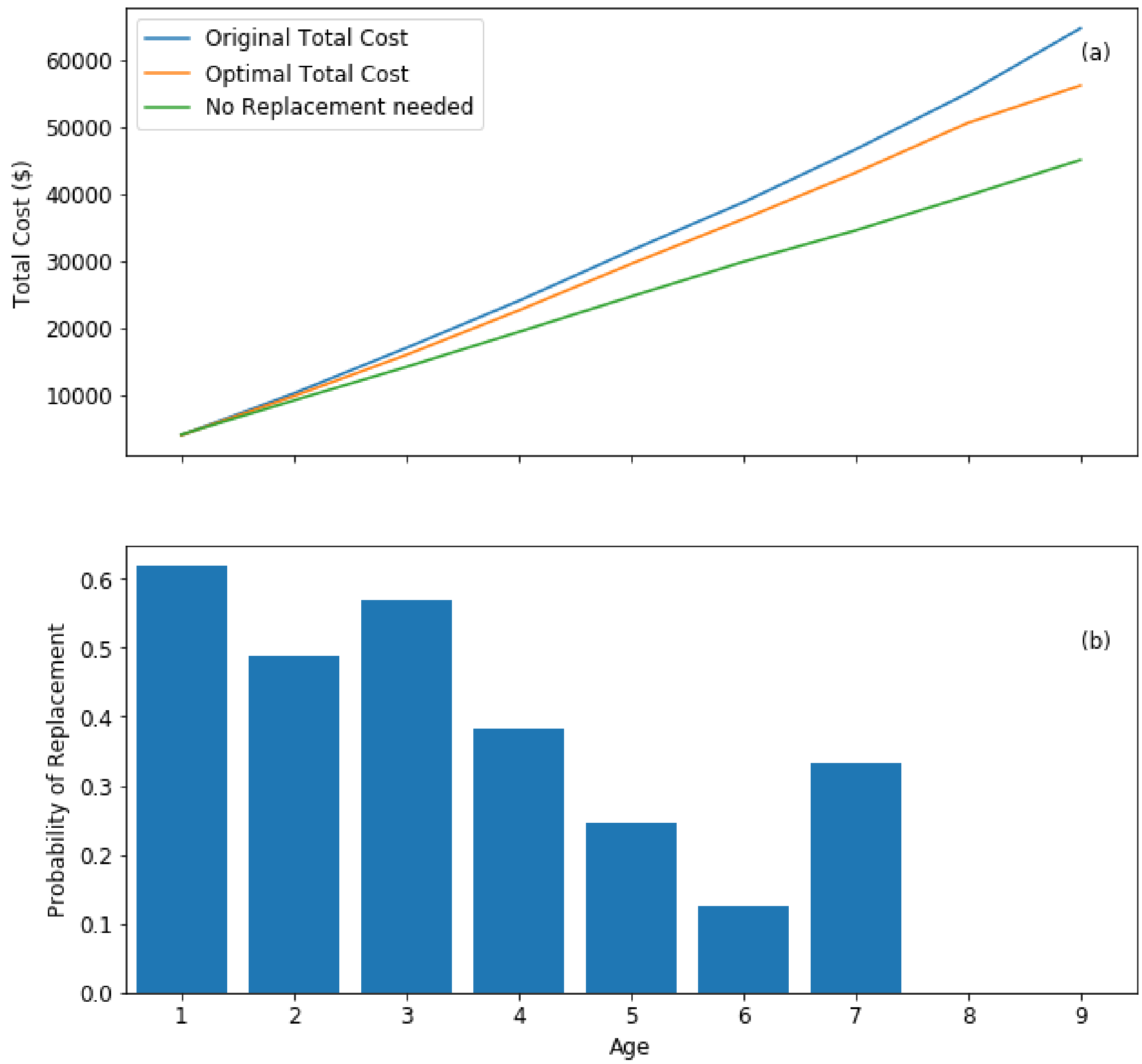


Figure 23. Comparison of original total cost and optimal total cost with the dynamic modeling approach (a) and the probability of being replaced under different ages (b) for the equipment class code 5385

Lifer cycle cost analysis considers the whole equipment class for their cost rate change with age. Equipment members in both class codes 5355 and 5385 are suggested to be kept until the end of useful life with the life cycle cost analysis. However, dynamic programing approach suggests that there should be different policies for different equipment pieces and 17% (12/70) and 27% (123/449) of equipment in class 5355 and 5385 are suggested to be replaced respectively. These results from the two different methods are consistent considering that life cycle analysis process equipment for the whole class code statistically while dynamic programing approach processes each specific equipment piece in the classes. Dynamic programing approach also indicates that replacement occurs when significant amount of maintenance/repair cost incurred for some specific equipment pieces in their mid-life that management should pay attention in replacement decisions. Tables A1 and A2 in Appendices show an example equipment with changes over years in maintenance cost, depreciation, and total costs between before and after replacement.

The dynamic programing modeling above is with Straight-Line depreciation. Figures A1 to A3 in Appendices also show the dynamic programing results with Double Declining Balance. Basically, with this depreciation method, replacement is not needed any more for any equipment in the class code 5355 (Front-End Loader) and only 8 pieces of class code 5385 (Fleetside Pickup trucks) can be optimized in cost with replacement. Again. the replacement occurs at the end of first year to avoid the huge increase in maintenance cost in the mid-life of equipment. Table A3 shows the cost change for the same example equipment with Double Declining Balance depreciation, which is not suggested for replacing anymore with this deprecation method.

4.3 Rental Rates for Both Hours- and Miles- Based Equipment

5 Tables 2 and 3 include the rental rates updated for hours- and miles- based equipment, respectively. These rates are based on the full life span records of equipment’s fixed and variable costs since purchased date. However, some equipment with key records (such as original price, working hours, etc.) missing and only the ones with complete records are used

in the rental rate computation. Therefore, the rental rates for the class code with more equipment members with available data (e.g. the class code 5385 with 450 pieces) would have higher accuracy than those class codes with only a few equipment (usually less than 10 pieces). Most of the rates are slightly different from the previous reported values and they are comparable if there are enough number of equipment in the class code. For the class code 5355, rental rate is $47. 3/hour ($44.6/hour in previous report); for class code 5385, the rate is $0.41/mile which is estimated as $0.35/mile in the previous report.

Table 2. Rental Rate for Hourly Based Equipment Using Straight Line Depreciation Method

EQUIPMENT CLASS CODE_ID	SPEC NUMBER	DESCRITION	DEPREC. RATE	OPERATION COST	RENTAL RATE	NUM_OF_EQUIP. USED
5095	EQ 03-07	WELDER	$10.03	$18.19	$28.22	3
5096	EQ 04-02	AIR COMPRESSOR	$26.25	$12.65	$38.90	3
5098	EQ 04-04	AIR COMPRESSOR	$31.90	$57.02	$88.92	13
5101	EQ 04-08	AIR COMPRESSOR	$53.70	$1.69	$55.40	3
5102	EQ 04-09	AIR COMPRESSOR	$21.15	$10.46	$31.61	14
5104	EQ 06-02	ASPHALT DISTRIBUTOR	$181.87	$18.88	$200.74	6
5105	EQ 06-03	ASPHALT DISTRIBUTOR	$294.83	$34.55	$329.38	3
5121	EQ 11-03	BACKHOE-LOADER-TRACTOR UNIT	$45.86	$7.87	$53.74	3
5123	EQ 11-05	BACKHOE-LOADER-TRACTOR UNIT	$41.63	$10.25	$51.88	21
5135	EQ 15-06	SPREADER-HEAVY DUTY	$16.88	$6.45	$23.33	14
5136	EQ 15-07	SPREADER-HEAVY DUTY	$30.82	$15.40	$46.22	123
5189	EQ 30-13	POWER SWEEPER	$50.99	$20.02	$71.01	26
5237	EQ 42-13	MOTOR GRADER	$69.81	$32.54	$102.34	18
5238	EQ 42-14	MOTOR GRADER	$57.76	$21.22	$78.98	60
5259	EQ 46-01	BRUSH CHIPPER	$66.51	$9.17	$75.68	3
5260	EQ 46-02	BRUSH CHIPPER	$0.73	$5.84	$6.57	3
5261	EQ 47-06	MOWING ATTACHMENT	$7.79	$6.57	$14.36	53
5266	EQ 47-11	MOWING ATTACHMENT	$13.05	$10.29	$23.34	11
5293	EQ 58-03	DERRICK UNIT	$113.91	$0.46	$114.37	4
5319	EQ 60-16	ROLLER	$149.75	$13.07	$162.82	8
5355	EQ 77-02	FRONT END LOADER	$34.05	$13.26	$47.31	70
5357	EQ 77-04	SKID STEER LOADER	$35.54	$19.34	$54.88	24
5363	EQ 78-01	SNOW PLOW	$31.66	$9.34	$41.00	144
5375	EQ 82-10	WHEEL TRACTOR	$15.60	$17.65	$33.25	84
5378	EQ 82-13	ALL TERRAIN VEHICLE	$2.94	$5.13	$8.07	3
5481	EQ 96-05	CENTERLINE STRIPING MACHINE	$193.63	$42.67	$236.31	3

Table 3. Rental Rate for Miles Based Equipment Using Straight Line Depreciation Method

EQUIPMENT _CLASS_ CODE_ID	DESCRIPTION	SPEC NUMBER	SIZE	DEPREC. RATE	OPERATION COST	RENTAL RATE	NUM_OF _EQUIP. USED
5086	AUTO - FACTORY COLOR	EQ 01-02	FOUR DOOR SEDAN-MID SIZE	$0.17	$0.16	$0.33	8
5089	AUTO - WHITE COLOR	EQ 02-02	FOUR DOOR SEDAN-MID SIZE	$0.36	$0.14	$0.51	25
5090	AUTO - WHITE COLOR	EQ 02-03	FOUR DOOR SEDAN-COMPACT	$0.57	$0.19	$0.77	8
5385	PICKUP	EQ 84-01	1/2 TON FLEETSIDE	$0.23	$0.18	$0.41	450
5386	PICKUP	EQ 84-02	3/4 TON FLEETSIDE	$0.17	$0.27	$0.44	15
5394	PICKUP	EQ 84-16	1 TON, DUAL REAR	$0.42	$0.40	$0.82	26
5395	PICKUP	EQ 84-17	FULLSIZE	$0.18	$0.22	$0.40	53
5399	PICKUP	EQ 84-22	15,000 GVW	$0.45	$0.52	$0.97	3
5401	VAN-MINI	EQ 85-04	4900 G.V.W	$0.28	$0.24	$0.52	4
5407	VAN	EQ 85-13	8500 GVW	$0.11	$0.39	$0.49	9
5419	TRUCK - MAINTENANCE	EQ 86-23	2 TON W/STEEL FLAT BED(86-B-6)	$0.37	$0.56	$0.93	3
5420	TRUCK	EQ 86-25	24000 GVW - DIESEL	$0.25	$0.43	$0.67	3
5428	TRUCK - TRACTOR	EQ 86-40	3 TON - DIESEL - HAUL	$0.74	$0.98	$1.72	10
5429	TRUCK - DIESEL-HAUL	EQ 86-41	3 TON DIESEL	$0.80	$0.95	$1.75	3
5430	TRUCK	EQ 86-42	41000 GVW - DIESEL	$1.38	$2.38	$3.76	3
5433	TRUCK	EQ 86-46	27,500 GVW-MID RANGE	$0.29	$0.95	$1.24	4
5434	TRUCK	EQ 86-47	24000 GVW-DIESEL	$0.64	$0.86	$1.50	39
5435	TRUCK	EQ 86-48	41000 GVW-DIESEL	$0.66	$0.83	$1.49	235
5442	CREW CAB PICKUP	EQ 88-01	3/4 TON	$0.20	$0.29	$0.49	196
5443	CREW CAB PICKUP	EQ 88-02	1 TON	$0.27	$0.40	$0.67	49
6497	CREW CAB PICKUP	EQ 88-03	1/2 TON	$0.23	$0.20	$0.43	36

5.1 Own-Rent-Lease Decisions

A framework was developed to target effective measures to determine costly equipment. These equipment turns out to be least frequently used ones based on cumulative hours/miles over life span as shown in the previous figures (Figures 14 and 19). Although cumulative hours/miles could be good metrics to indicate high-cost equipment, annual average hours/miles are even better because they are more correlated with cost rates as shown in Figures 23 and 26 below.

Figure 24a shows the cumulative density function of cost rate from equipment in class code 5355 and the strong correlation between average annual hours and cost rates is shown in Figure 24b. This correlation is much stronger than the correlation between cumulative annual hours and cost rates (Figure 14a). In order to compare the cost with rental agencies' price quote, the fueling cost was removed from total costs of the equipment in the class.

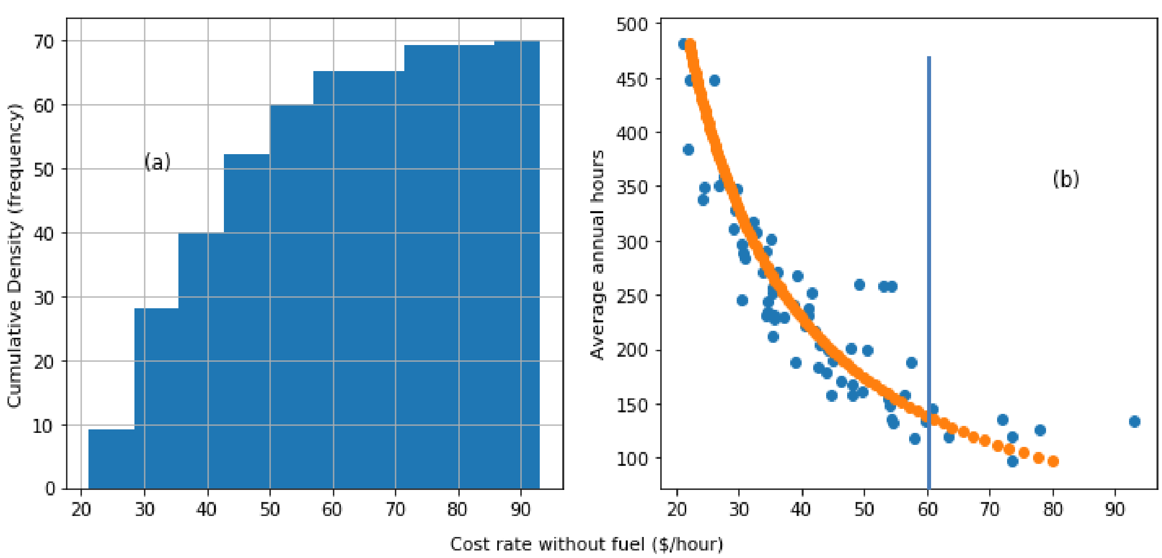
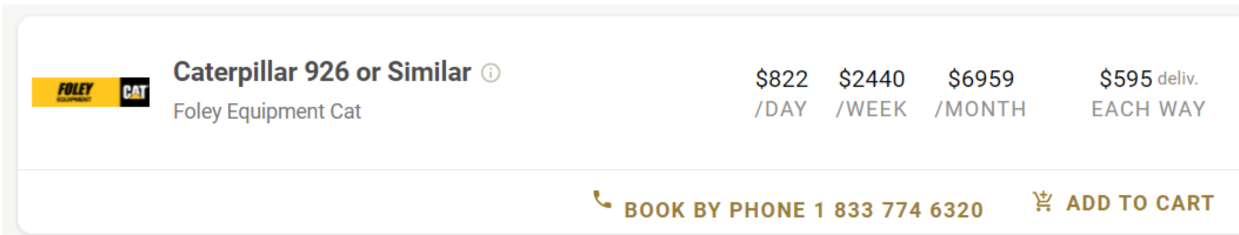
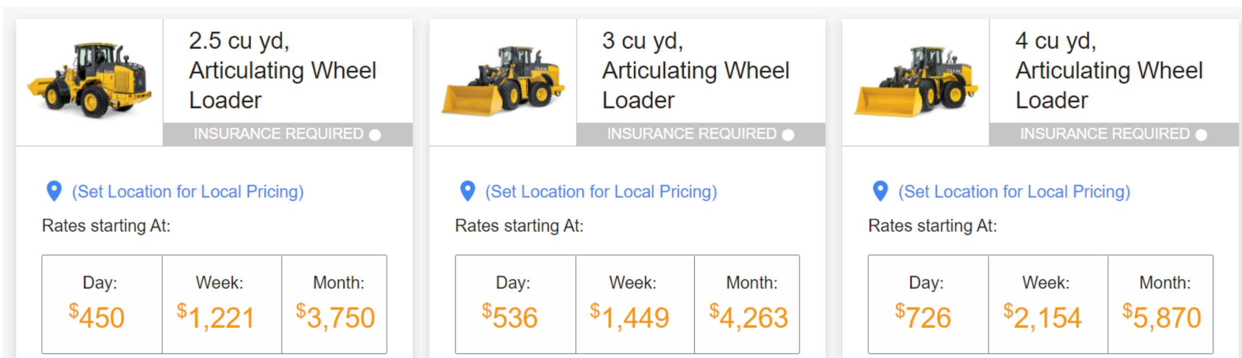


Figure 24. Cumulative density function of cost rates (a) from equipment in class code 5355 and the correlation between average annual hours versus cost rates (b). Blue line represents the average rental price quote from dozr.com and bigrentz.com for 2/2.5 YD Front End Loaders

When usage less than 150 hours per year, cost rate without fueling could be greater than $60/hour and rent could be considered for these equipment pieces with such low usage. 10% of current equipment in class code 5355 could be considered for renting. The screen shots below shows the rental prices from different agencies online for reference (Figure 25).



https://dozr.com/rent/wheel-loader/2-yds/Oklahoma_City-OK/2021-05-12/2021-05-13



https://www.bigrentz.com/equipment-rentals/earthmoving/wheel-loader

Product	2Hour	Daily	Weekly
FRONT END LOADER, BOBCAT S130	$60.00	$180.00	$540.00
FRONT END LOADER, DINGO WALK BEHIND	$44.00	$132.00	$528.00
FRONT LOADER TRACKS, BOBCAT T450	$72.00	$216.00	$648.00

https://adarental.com/equipment.asp?action=category&category=94

Figure 25. Screen shots or price tables from various website sources for the rental price for Front End Loaders.

Similarly, the cumulative density function of cost rate from equipment for class code 5385 and the strong correlation between average annual miles and cost rates is shown in Figure 26. Compared to the relationship between cumulative annual miles and cost rates in Figure 19a, the correlation between average annual miles and cost rates is much higher here (Figure 26b). When usage less than 5000 miles per year, cost rate without fueling could be greater than $0.75/mile (U-haul rate for 8 ft pickup truck: 0.59/mile + $19.95/day) and rent would be considered for these equipment pieces with such low usage. Less than 1% (12 out of 449) of current equipment in class code 5385 could be considered for renting.

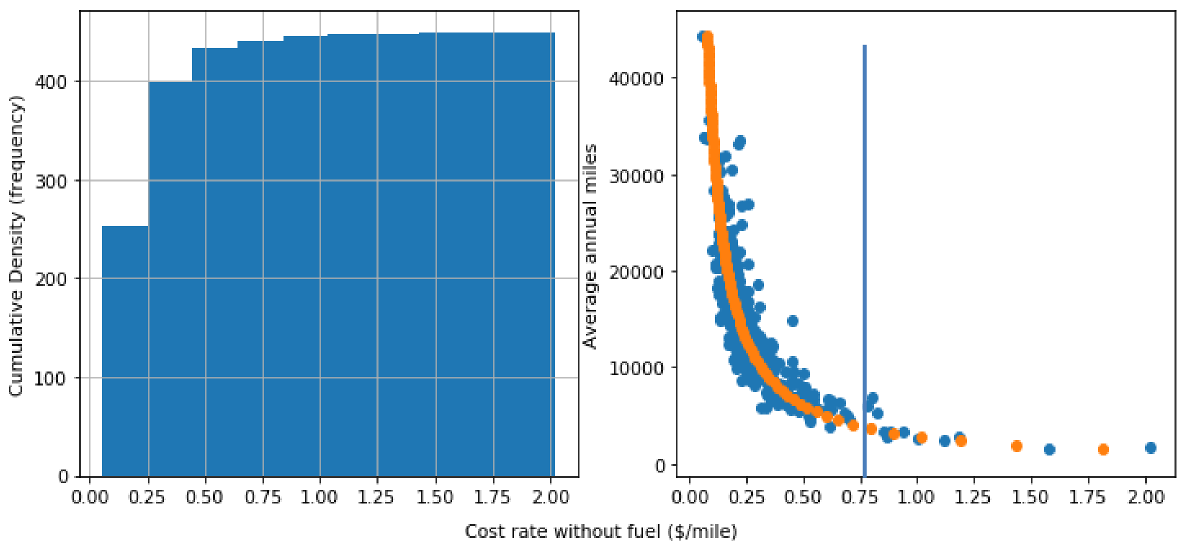


Figure 26. Cumulative density function of cost rates (a) from equipment in class code 5385 and the correlation between average annual miles versus cost rates (b). Blue line represents the rental price quote from U-Haul for 8 ft pickup truck

CHAPTER V

CONCLUSION

Using the data recorded in ODOT Agile Assets equipment fleet management system, this research directly addresses the need of ODOT to strategically improve its equipment management practices. Database and SQL procedures and function were developed to facilitate data transfer and transformation between MySQL workbench and Python Jupiter Notebook. Machine learning techniques such as exploratory data analysis, data imputation, important measures, and anomalies detection were used to investigate the cost rate ($/hour or $/mile) and its affecting factors of cumulative total costs, operation hours/miles, fuel efficiency, and ages for selected equipment classes 5355 (Front End Loaders) and 5385 (1/2 ton Fleetside Pickups). Life cycle economic analysis was used to determine the best time to replace equipment in its life cycle. Dynamic programing models, specifically deterministic dynamic programing, were developed to determine best replacement policy for each piece of equipment in these two class codes. In addition, own-rent strategy comparison was also carried out so that manager could better decide if it is better to own or rent equipment pieces for these two class codes. The results and recommendations for equipment management practices are included:

1. Life cycle cost analysis shows that cost rate of equipment class 5355 decreases very fast in the first five years of life span with both Straight_Line and DDB depreciation methods. Cost rate keeps decrease from age 5 to age 10 in the DDB while mostly keeps constant in the Straight-Line method. This suggests that it is economic to keep the equipment until

the end of useful life. Cost rate decreases with increases of both cumulative hours and cumulative total costs, which suggests that equipment in this class tend to be used more frequently in their later ages. The cumulative hours are more correlated with cost rate than cumulative total cost and should be considered as a more important factor in equipment management. In addition, fuel efficiency also plays some positive role in cost rate. Therefore, it would be wiser to improve equipment utilization when they are young and function well.

2. Life cycle cost analysis for class code 5385 suggests that cost rate of this class keep decreasing when aging no matter which depreciation methods were used. There are very similar cost-age patterns between the two classes of 5355 and 5385 except that cost rate keeps constant after age 5 in 5355 while it keeps decreasing in 5385 with the Straight-Line depreciation method. Therefore, a similar suggestion would apply to class 5385 that it is better to keep the equipment until the end of useful life for economic purpose. Fuel efficiency also shows correlation with cost rate, so it is beneficial to use the equipment more at their young ages when equipment function well.
3. Although both class codes 5355 and 5385 are suggested to be kept until the end of useful life with life cycle cost analysis, the dynamic programing approach suggests that there should be different policies for different equipment pieces. 17% (12/70) and 27% (123/449) of equipment in class 5355 and 5385, respectively, are suggested to have replacement policies with Straight-Line depreciation. No equipment in class 5355 and only 8 pieces equipment are suggested for replacement with Double Declining Balance. These results from the two different depreciation methods are consistent with life cycle cost analysis. For the equipment with replacement, with the Straight-Line depreciation,

cumulative total cost could be reduced on average by roughly $ 7,000 and $8500 for the class code 5355 and 5385, respectively, within the period from 2011 to 2019. Dynamic programing also indicates that replacement occurs when significant amount of maintenance/repair cost incurred for the specific equipment pieces in their mid-life to which management should pay attention for cost reduction.

4. Though cumulative annual miles/hours (better than other factors of cumulative cost, age, and fuel efficiency) can be a good predictor of cost rate, the correlation between average annual miles/hours and cost rates is much stronger. Thus, average annual usage (miles/hours) should be the most important factor in identifying anomaly equipment with exceptionally high cost rate in replacement or rent considerations.
5. For class code 5355, when usage less than 150 hours per year, cost rate without fueling could be greater than $60/hour and rent could be considered for these equipment pieces with such low usage. By comparison of the rental prices from different online agencies, 10% of current equipment in class code 5355 could be considered for renting.
6. For class code 5385, When usage less than 5000 miles per year, cost rate without fueling could be greater than $0.75/mile (U-haul rate for 8 ft pickup truck: 0.59/mile + $19.95/day) and rent would be considered for these equipment pieces with such low usage. Less than 1% (12 out of 449) of current equipment in class code 5385 could be considered for renting.
7. Although detailed study focusing on class code 5355 and 5385, the rest equipment classes were also investigated, and their rental rates (including both ownership cost and operation cost) were calculated with error removal. Further study for these equipment classes are needed in order to provide comprehensive management decisions for the whole fleet.

REFERENCES

AhireSanjay, L., and MillerDavid, M. (1997). "Maximizing the Effectiveness of a Preventive Maintenance System." Management Science.

Ávila-Godoy, G., Brau, A., and Fernández-Gaucherand, E. "Controlled Markov chains with discounted risk-sensitive criteria: applications to machine replacement." Proc., Proceedings of the 36th IEEE Conference on Decision and Control, IEEE, 1115-1120.

Baldin, A., Furlanetto, L., Roversi, A., and Turco, F. (1988). "Manuale della Manutenzione degli Impianti Industriali e servizi." Milano: Editorial Franco Angeli.

Barringer, H. P., and Weber, D. P. "Life cycle cost & reliability for process equipment." Proc., 8th Annual Energy Week Conference and Exhibition. Houston, Texas, 1-22.

Bengtsson, M., and Kurdve, M. (2016). "Machining equipment life cycle costing model with dynamic maintenance cost." Procedia Cirp, 48, 102-107.

Chang, P.-T. (2005). "Fuzzy strategic replacement analysis." European Journal of Operational Research, 160(2), 532-559.

Czajkiewicz, Z. J., and Reddy, N. H. R. (1985). "Simulation models and some applications to maintenance and repair systems." SIGSIM Simul. Dig., 16(2), 31–34.

Dohi, T., Ashioka, A., Osaki, S., and Kaio, N. (2001). "Optimizing the repair-time limit replacement schedule with discounting and imperfect repair." Journal of Quality in Maintenance Engineering, 7(1), 71-84.

Douglas, J. (1978). "Equipment costs by current methods." Journal of the Construction Division, 104(2), 191-205.

Eilon, S., King, J., and Hutchinson, D. (1966). "A study in equipment replacement." Journal of the Operational Research Society, 17(1), 59-71.

Fan, W., Machemehl, R. B., & Gemar, M. D. (2012a). "Optimization of Equipment Replacement:Dynamic Programming-Based Optimization." Transportation Research Record, 2292(1), 160-170. doi:10.3141/2292-19

Fan, W., Machemehl, R., Gemar, M., and Brown, L. (2012b). "A Stochastic Dynamic Programming Approach for the Equipment Replacement Optimization with Probabilistic Vehicle Utilization." Proceedings of the 91st Annual Meeting of the Transportation Research Board, 2012b.

Flynn, J., and Chung, C.-S. (2004). "A heuristic algorithm for determining replacement policies in consecutive k-out-of-n systems." Computers & Operations Research, 31(8), 1335-1348.

Gransberg, D. D., and O′Connor, E. P. (2015). "Major equipment life-cycle cost analysis." Minnesota Department of Transportation, Research Services & Library.

Gransberg, D. D., Popescu, C. M., and Ryan, R. (2006). Construction equipment management for engineers, estimators, and owners, CRC Press.
Hargreaves, B. (2002). "To rent or buy?: That is the question." New Zealand Property Journal, 21-26.
Hartman, J. C., and Rogers, J. (2006). "Dynamic programming approaches for equipment replacement problems with continuous and discontinuous technological change." IMA Journal of Management Mathematics, 17(2), 143-158. doi:10.1093/imaman/dpi032
Hopp, W. J., and Nair, S. K. (1994). "Markovian deterioration and technological change." IIE transactions, 26(6), 74-82.
Hritonenko, N., and Yatsenko, Y. (2007). "Optimal equipment replacement without paradoxes: a continuous analysis." Operations Research Letters, 35(2), 245-250.
Johnson, R. W., and Lewellen, W. G. (1972). "Analysis of the lease-or-buy decision." The journal of Finance, 27(4), 815-823.
National Academies of Sciences, Engineering, and Medicine (2020). "Guide to Calculating Ownership and Operating Costs of Department of Transportation Vehicles and Equipment: An Accounting Perspective." Washington, DC: The National Academies Press. https://doi.org/10.17226/25700
Popescu, C. M. (1992). "Managing Construction Equipment, 1st ed." Austin, TX: C&C Consultants Inc., p. 2.1–2.17.
Peurifoy, R., Ledbetter, W., and Schexnayder, C. (2002). "Construction, planning, equipment, and methods, McGraw-Hill." New York.
Sarache Castro, W. A., Castrillón, O. D., Gonzales, G., and Viveros Folleco, A. (2009). "A multi-criteria application for an equipment replacement decision." Ingeniería y Desarrollo(25), 80-98.
Sinuany-Stern, Z., David, I., and Biran, S. (1997). "An efficient heuristic for a partially observable Markov decision process of machine replacement." Computers & operations research, 24(2), 117-126.
US Army Corps of Engineers (2003). "Construction Equipment Ownership and Operating Expense Schedule, Region VI". Document EP 1110–1–8, Vol. 2. Washington D.C.: US Army Corps of Engineers.

APPENDICES

Query 1: Procedure "load_dp" for depreciation rate calculation

```
CREATE DEFINER=`root`@`localhost` PROCEDURE `Load_dp`()
begin
DECLARE counter,odo_yr,odo_mon,odo_day INT DEFAULT 1;
DECLARE dt,eq,byr,ul,ov,q,actv int DEFAULT 1;
declare ddb,bv,slv double default 0;
select count(*) from equip_info into dt;
loop1: WHILE counter <= dt DO
      select EQUIPMENT_ID,Buy_Year, if(USEFUL_LIFE <> 0,
USEFUL_LIFE,0),ORIGINAL_VALUE,Actual_Value,year(ODOMETER_DATE),
month(ODOMETER_DATE),day(ODOMETER_DATE) from equip_info where RowID =
counter into eq, byr,ul,ov,actv, odo_yr,odo_mon,odo_day;
      if (ul=0) then
        set counter = counter + 1;
        iterate loop1;
                  end if;
      set q = byr+ul-1;
      set bv = ov;
       while byr <= q and byr<=odo_yr do
                                set ddb = bv*2/ul;
           set bv = bv-ddb;
           set slv = actv/ul;
           if byr=odo_yr
           then set ddb = ddb*(odo_mon*30+odo_day)/365; # adjust last year depreciation value
if sold early
              set slv = actv/ul*(odo_mon*30+odo_day)/365;
           end if;
                           insert into
equip_depreciation(EQUIPMENT_ID,YEAR_DP,Deprec1,Deprec2)
           values(eq,byr,slv,ddb);
           set byr = byr + 1;
                   end while;

     SET counter = counter + 1;

END WHILE loop1;
End
```

Query 2: Procedure "dp_to_all_costs" for operation costs time series calculation according to ownership costs

```
CREATE DEFINER=`root`@`localhost` PROCEDURE `dp_to_all_costs`()
begin
### create a table to store annual cost time series
drop table if exists equip_all_cost_series;
Create table equip_all_cost_series
### first import depreciation table
select tab1.*, fueling1_cost,
fueling2_cost,maint1_cost,maint2_cost,fueling1_amount,fueling2_amount,
ifnull(Deprec1,0)+ifnull(fueling1_cost,0)+ifnull(fueling2_cost,0)+ifnull(maint1_cost,0)+ifnull(maint2_cost,0) as
total_cost1,ifnull(Deprec2,0)+ifnull(fueling1_cost,0)+ifnull(fueling2_cost,0)+ifnull(maint1_cost,0)+ifnull(maint2_cost,0) as total_cost2, ifnull(fueling1_amount,0)+ifnull(fueling2_amount,0) as
total_fuel from
(select * from equip_depreciation) as tab1
### join in comdata fueling tabel - fueling only part
left join
(select  EQUIPMENT_ID,sum(FUEL_AMOUNT) as fueling1_amount, sum(FUEL_COST) as
fueling1_cost, FUEL_PRODUCT_CODE_NAME,
FUEL_PRODUCT_CODE_DESC,Year(if(length(FUEL_DATE) = length('29-OCT-14
00:00:00'),str_to_date(FUEL_DATE,'%d-%b-%y %H:%i:%s'),str_to_date(FUEL_DATE,'%Y-%m-%d %H:%i:%s'))) as Year1
from comdata_fueling_all_1
where FUEL_RATE < 4 and if(length(FUEL_DATE) = length('29-OCT-14
00:00:00'),str_to_date(FUEL_DATE,'%d-%b-%y %H:%i:%s'),str_to_date(FUEL_DATE,'%Y-%m-%d %H:%i:%s')) <= ODOMETER_DATE
group by EQUIPMENT_ID,Year1) as fueling1
on tab1.EQUIPMENT_ID=fueling1.EQUIPMENT_ID AND tab1.YEAR_DP = fueling1.Year1
### join in equipment_fueling table
left join
(select  EQUIPMENT_ID,sum(FUEL_AMOUNT) as fueling2_amount, sum(FUEL_COST) as
fueling2_cost,Year(if(length(FUEL_DATE) = length('29-OCT-14
00:00:00'),str_to_date(FUEL_DATE,'%d-%b-%y %H:%i:%s'),str_to_date(FUEL_DATE,'%Y-%m-%d %H:%i:%s'))) as Year1
from equipment_fueling_all_1
where if(length(FUEL_DATE) = length('29-OCT-14
00:00:00'),str_to_date(FUEL_DATE,'%d-%b-%y %H:%i:%s'),str_to_date(FUEL_DATE,'%Y-%m-%d %H:%i:%s')) <= ODOMETER_DATE
group by EQUIPMENT_ID,Year1) as fueling2
on tab1.EQUIPMENT_ID = fueling2.EQUIPMENT_ID and tab1.YEAR_DP = fueling2.Year1
### join in maintenance data from setup_project table
left join
(select  EQUIPMENT_ID,sum(COMPLETED_COST) as maint1_cost,
Year(if(length(DATE_COMPLETED) = length('29-OCT-14
00:00:00'),str_to_date(DATE_COMPLETED,'%d-%b-%y %H:%i:%s'),str_to_date(DATE_COMPLETED,'%Y-%m-%d %H:%i:%s'))) as Year1
from setup_project_all_1
```

```
where if(length(DATE_COMPLETED) = length('29-OCT-14
00:00:00'),str_to_date(DATE_COMPLETED,'%d-%b-%y %H:%i:%s'),str_to_date(DATE_COM
PLETED,'%Y-%m-%d %H:%i:%s')) <= ODOMETER_DATE
group by EQUIPMENT_ID,Year1) as maint1
on tab1.EQUIPMENT_ID = maint1.EQUIPMENT_ID and tab1.YEAR_DP = maint1.Year1
### join in maintenance data from comdata_fueling table
left join
(select  EQUIPMENT_ID,sum(FUEL_COST) as maint2_cost, Year(if(length(FUEL_DATE) =
length('29-OCT-14
00:00:00'),str_to_date(FUEL_DATE,'%d-%b-%y %H:%i:%s'),str_to_date(FUEL_DATE,'%Y-%
m-%d %H:%i:%s'))) as Year1
from comdata_fueling_all_1
where FUEL_RATE >= 4 and if(length(FUEL_DATE) = length('29-OCT-14
00:00:00'),str_to_date(FUEL_DATE,'%d-%b-%y %H:%i:%s'),str_to_date(FUEL_DATE,'%Y-%
m-%d %H:%i:%s')) <= ODOMETER_DATE
group by EQUIPMENT_ID,Year1) as maint2
on tab1.EQUIPMENT_ID = maint2.EQUIPMENT_ID AND tab1.YEAR_DP = maint2.Year1
order by EQUIPMENT_ID, YEAR_DP;

end
```

Query 3: Procedure “dollar_per_mile” for cost rate calculation of mile based equipment

```
CREATE DEFINER=`root`@`localhost` PROCEDURE `dollar_per_mile`(in equip_id int)
begin
declare t_odo,Class_Code int default 0;
declare t_fuel,mpg double default 0;
SELECT sum(total_fuel) FROM `odot-database3`.equip_all_cost_series where
EQUIPMENT_ID=equip_id into t_fuel;
Select CURRENT_ODOMETER,EQUIPMENT_CLASS_CODE_ID from equip_info where
EQUIPMENT_ID=equip_id into t_odo,Class_Code;
set mpg = t_odo/t_fuel;
set @msum1 :=0;
set @csum1 :=0;
set @msum2 :=0;
set @csum2 :=0;
# create a temporary table to store cost time series
drop table if exists temp1;
create temporary table temp1
SELECT *, mpg, Class_Code, total_fuel*mpg as annual_miles , (@csum1 := @csum1 +
total_cost1)/(@msum1 := @msum1 + total_fuel*mpg) as dollar_per_mile1_cum, (@csum2 :=
@csum2 + total_cost2)/(@msum2 := @msum2 + total_fuel*mpg) as dollar_per_mile2_cum
FROM `odot-database3`.equip_all_cost_series where EQUIPMENT_ID=equip_id;
# creat a temporary table to store annual average of the time series
#drop table if exists temp2;
#create temporary table temp2
#SELECT EQUIPMENT_ID,Class_Code, sum(total_cost1)/sum(annual_miles) as
rental_rate1,sum(total_cost2)/sum(annual_miles) as rental_rate2, mpg as mile_per_hour,
avg(annual_miles),count(*) as Current_age FROM `odot-database3`.temp1;
End
```

Query 4: Procedure "dollar_per_hour" for cost rate calculation of hourly based equipment

```
CREATE DEFINER=`root`@`localhost` PROCEDURE `dollar_per_hour`(in equip_id int)
begin
declare t_hours,Class_Code int default 0;
declare t_fuel,hpg double default 0;
declare odo_date text;
SELECT sum(total_fuel) FROM `odot-database3`.equip_all_cost_series where
EQUIPMENT_ID=equip_id into t_fuel;
Select ODOMETER_DATE,EQUIPMENT_CLASS_CODE_ID from equip_info where
EQUIPMENT_ID = equip_id into odo_date,Class_Code;
Select sum(TOTAL_HOURS) from work_orders_equipment_dc where
EQUIPMENT_ID=equip_id and DATE_WORK<=odo_date into t_hours;
set hpg = t_hours/t_fuel;
set @msum1 :=0;
set @csum1 :=0;
set @msum2 :=0;
set @csum2 :=0;
# create a temporary table to store cost time series
drop table if exists temp1;
create table temp1
select a.*,b.annual_hours,(@csum1 := @csum1 + a.total_cost1)/(@msum1 := @msum1 +
b.annual_hours) as dollar_per_hour1_cum, (@csum2 := @csum2 + a.total_cost2)/(@msum2 :=
@msum2 + b.annual_hours) as dollar_per_hour2_cum,total_fuel*hpg as annual_hours_on_feul
from
(SELECT *, hpg as hour_per_gallon, Class_Code FROM `odot-database3`.equip_all_cost_series
where EQUIPMENT_ID=equip_id) as a
left join
(Select Year(DATE_WORK) as Year1, sum(TOTAL_HOURS) as annual_hours from
work_orders_equipment_dc where EQUIPMENT_ID=equip_id and DATE_WORK<=odo_date
group by Year1) as b
on a.YEAR_DP = b.Year1;
# creat a temporary table to store annual average of the time series
#drop table if exists temp2;
#create table temp2
#SELECT EQUIPMENT_ID, Class_Code, sum(total_cost1)/sum(annual_hours) as
rental_rate1,sum(total_cost2)/sum(annual_hours) as rental_rate2,hpg as hour_per_gallon,
avg(annual_hours),count(*) as Current_age FROM `odot-database3`.temp1;
End
```

Query 5: Procedure "class_code_cost", a loop call to calculate cost rates for each piece of equipment based on their charge types (either miles or hourly based)

```
CREATE DEFINER=`root`@`localhost` PROCEDURE `class_code_cost`( in charge_types int)
begin
declare equip_id,counter,len_of_table, equip_charge_type int default 1;
SELECT count(*) FROM `odot-database3`.equip_info into len_of_table;
drop table if exists equip_dollar_per_mile_time_series;
if charge_types =2 then
create table equip_dollar_per_mile_time_series
(EQUIPMENT_ID int ,
YEAR_DP int,
Deprec1 double,
Deprec2 double ,
fueling1_cost double ,
fueling2_cost double ,
maint1_cost double ,
maint2_cost double ,
fueling1_amount double ,
fueling2_amount double,
total_cost1 double ,
total_cost2 double ,
total_fuel double ,
mile_per_gallon double ,
Class_Code int,
annual_miles double ,
dollar_per_mile1 double ,
dollar_per_mile2 double);
#drop table if exists equip_dollar_per_mile_stats;
#create table equip_dollar_per_mile_stats
#(EQUIPMENT_ID int ,
#Class_Code int,
#Rental_Rate1 double,
 #Rental_Rate2 double,
 #Mile_per_gallon double,
 #Avg_annual_miles double,
 #Current_Life int);
else
drop table if exists equip_dollar_per_hour_time_series;
create table equip_dollar_per_hour_time_series
(EQUIPMENT_ID int ,
YEAR_DP int,
Deprec1 double,
Deprec2 double ,
fueling1_cost double ,
fueling2_cost double ,
maint1_cost double ,
maint2_cost double ,
fueling1_amount double,
fueling2_amount double,
```

```
total_cost1 double ,
total_cost2 double ,
total_fuel double ,
hour_per_gallon double ,
Class_Code int,
annual_hours double ,
dollar_per_hour1 double ,
dollar_per_hour2 double,
annual_hours_on_fuel double);
#drop table if exists equip_dollar_per_hour_stats;
#create table equip_dollar_per_hour_stats
#(EQUIPMENT_ID int ,
#Class_Code int,
#Rental_Rate1 double,
#Rental_Rate2 double,
#Hour_per_gallon double,
#Avg_annual_hours double,
#Current_Life int);
end if;
loop1: while counter <= len_of_table do
        SELECT EQUIPMENT_ID,EQ_CHARGE_TYPE FROM `odot-database3`.equip_info
where RowID=counter into equip_id, equip_charge_type;
   if equip_charge_type = 2 and  charge_types =2 then
   call dollar_per_mile(equip_id);
   insert into equip_dollar_per_mile_time_series
   select * from temp1;
        #insert into equip_dollar_per_mile_stats
   #select * from temp2;
   end if;
   if equip_charge_type = 1 and  charge_types =1 then
        call dollar_per_hour(equip_id);
   insert into equip_dollar_per_hour_time_series
   select * from temp1;
   #insert into equip_dollar_per_hour_stats
   #select * from temp2;
   end if;
   set counter = counter +1;
end while loop1;
end
```

Table A1. An Example Equipment with Whole Historical Costs in Fueling, Maintenance, and Depreciation (Stright-Line depreciation)

EQUIPMENT_ID	Years	Age	Fueling Cost, $	Maintenance Cost, $	Depreciation, $	Original Total Cost, $
1081414	2016	1	409.76	202.51	3218.90	3831.17
1081414	2017	2	504.25	338.34	3218.90	4061.49
1081414	2018	3	897.24	1086.38	3218.90	5202.52
1081414	2019	4	1700.66	2329.40	3218.90	7248.96
						In total: 20344.14

Table A2. Costs Optimized with Decisions from the Dynamic Programming Model (Straight-Line depreciation) for the Equipment in Table A1

EQUIPMENT_ID	Years	State (ages)	Decisions	Fueling Cost, $	Maintenance Cost, $	Depreciation, $	Optimal Total Cost, $
1081414	2016	1	Keep	409.76	202.51	3218.90	3831.17
1081414	2017	2	Replace	504.25	338.34	3218.90	4061.49
1081414	2018	1	Keep	897.24	202.51	3772.74	5230.37
1081414	2019	2	Keep	1700.66	338.34	3772.74	6169.61
							In total: 19292.64

Table A3. An Example Equipment with Whole Historical Costs in Fueling, Maintenance, and Depreciation (Double Declining Balance)

EQUIPMENT_ID	Years	Age	Fueling Cost, $	Maintenance Cost, $	Depreciation, $	Original Total Cost, $
1081414	2016	1	409.76	202.51	5403.36	6015.63
1081414	2017	2	504.25	338.34	4322.688	5165.29
1081414	2018	3	897.24	1086.38	3458.15	5441.77
1081414	2019	4	1700.66	2329.40	2766.52	6796.58
						In total: 23419.26

Table A4. Costs Optimized with Decisions from the Dynamic Programming Model (Double Declining Balance depreciation) for the Equipment in Table A3

EQUIPMENT_ID	**Years**	**State (ages)**	**Decisions**	**Fueling Cost, $**	**Maintenance Cost, $**	**Depreciation, $**	**Optimal Total Cost, $**
1081414	2016	1	Keep	409.76	202.51	5403.36	6015.63
1081414	2017	2	Keep	504.25	338.34	4322.688	5165.29
1081414	2018	3	Keep	897.24	1086.38	3458.15	5441.77
1081414	2019	4	Keep	1700.66	2329.40	2766.52	6796.58
						In total: 23419.26	

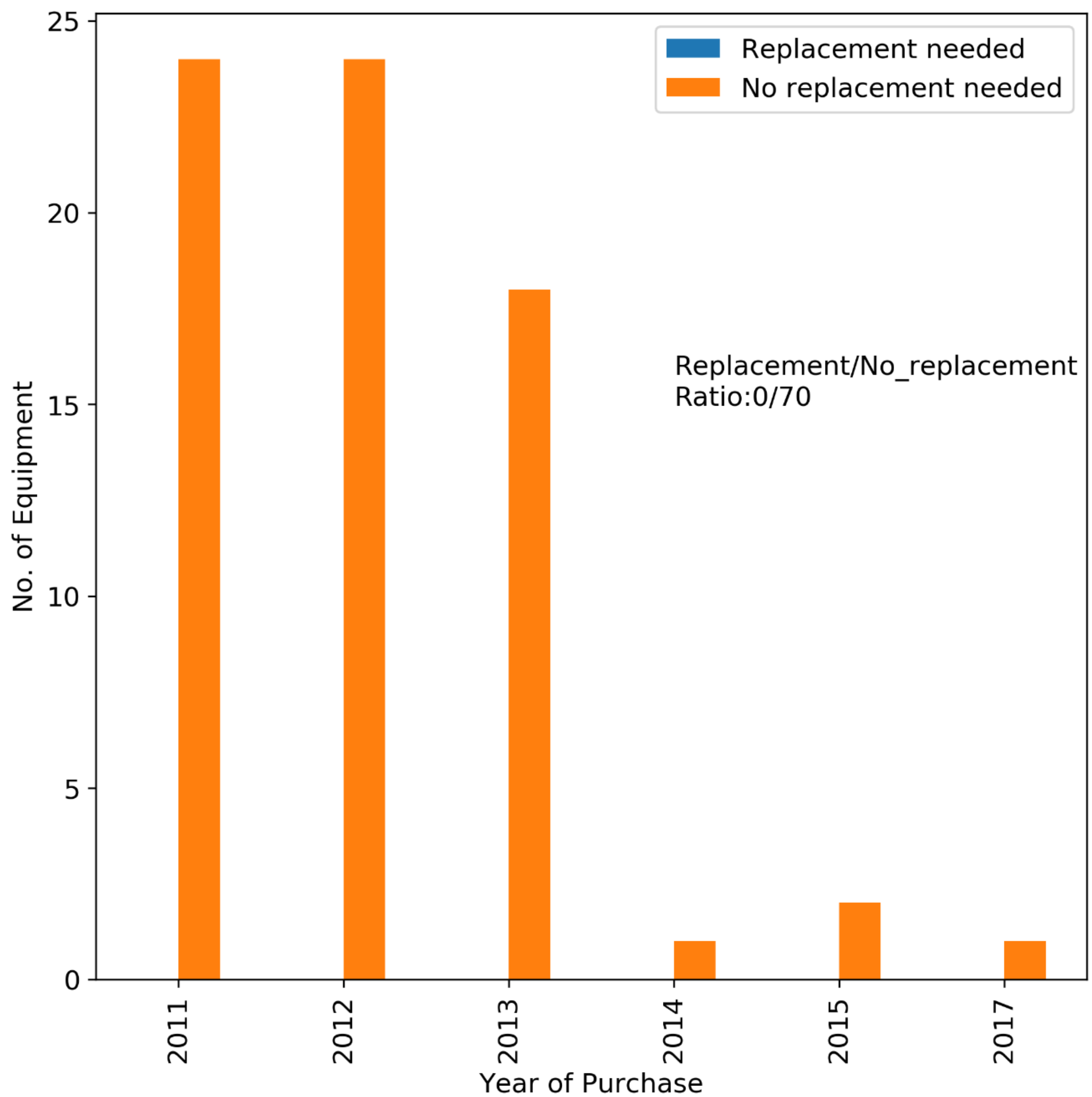


Figure A1. Numbers of equipment with replacement suggestions vs. no replacement suggestions with the years of purchase for the class code 5355. Depreciation is calculated from Double Decline Balance method

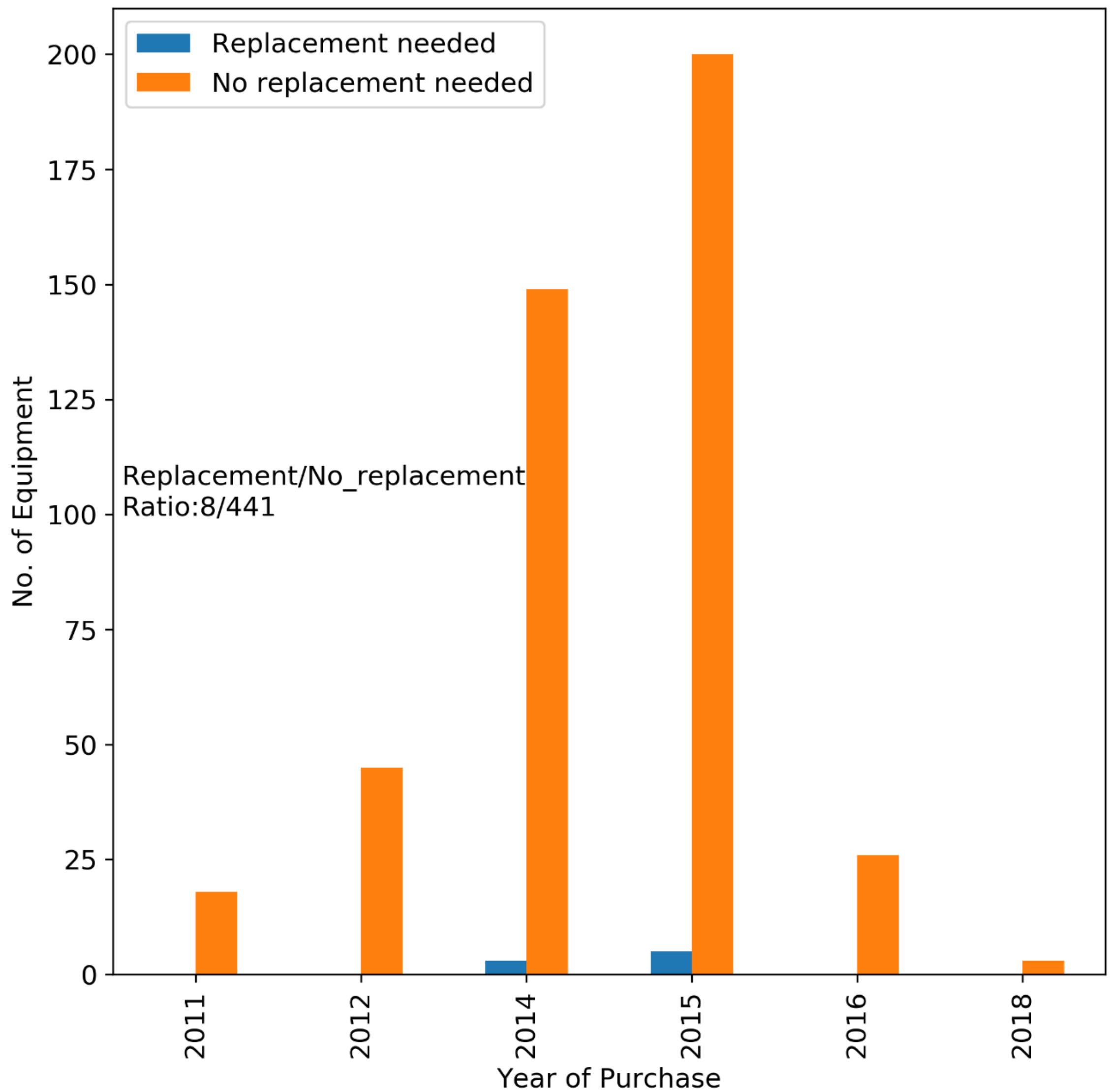


Figure A2. Numbers of equipment with replacement suggestions vs. no replacement suggestions with the years of purchase for the class code 5385. Depreciation is calculated from Double Decline Balance method

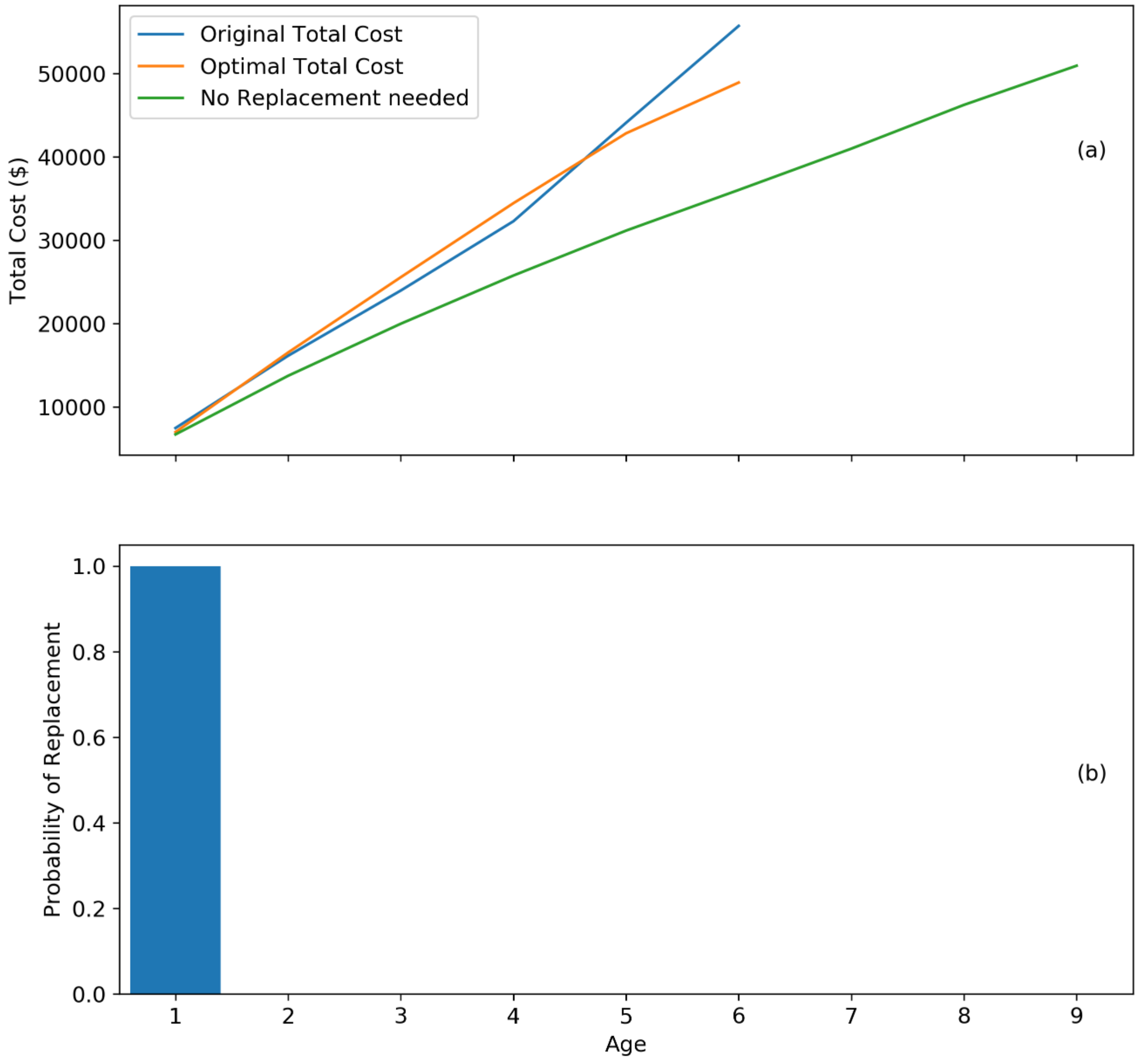


Figure A3. Numbers of equipment with replacement suggestions vs. no replacement suggestions with the years of purchase for the class code 5385. Depreciation is calculated from Double Decline Balance method

VITA

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