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ANALYTICAL FRAMEWORK FOR LIFE CYCLE AND PERFORMANCE ASSESSMENT OF EQUIPMENT PROGRAMS

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RESEARCH

Keeping Utah Moving
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16. Abstract

In this project, we analyzed the optimal life cycles for three types of trucks for the Utah Department of Transportation (UDOT) using a macro-level approach. The types of truck include loaders, graders, and sweepers. The life cycle analysis follows a similar procedure with respect to the optimal life cycle analysis for Class 8 snowplow trucks that was conducted in 2019. Currently, UDOT has managed these trucks since 1988. The increase of service span leads to lower performance efficacy and higher maintenance costs. To this end, we performed a data-driven approach for optimal life cycle analysis. The numerical results indicated different replacement cycles for the three types of trucks. Specifically, the optimal life cycle for sweepers is 4 years due to its relatively lower purchase price and high maintenance cost. In contrast, the optimal life cycles for loaders and graders are 8 and 9 years, respectively. Moreover, we analyzed the life cycles and total costs under different scenarios, and subsequently provided appropriate time windows for truck replacement.

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AVL	Automatic Vehicle Location
DB	Declining Balance
UDOT	Utah Department of Transportation
PMPC	Post-Manufacturing Product Cost
PSM	Peurifoy and Schexnayder Method

EXECUTIVE SUMMARY

In this project, we analyzed the optimal life cycles for three types of trucks including sweepers, loaders, and graders. The life cycle analysis follows a similar approach conducted on Class 8 snowplow trucks by the research team in 2019. In this study, the optimal life cycle for these types of trucks are determined separately considering their varying purchase price and functionalities. Sweepers are the type of vehicles that are equipped with brooms, water sprays, and collection bins to clean debris on streets. Loaders are the heavy equipment trucks used in construction to load and move materials such as sand and rock, etc. Graders are commonly used in maintenance and construction of road pavement. Currently, the Utah Department of Transportation (UDOT) is managing these three types of trucks for a variety of functioning purposes. According to the purchase records of the managed trucks, the earliest service data can be traced back to 1989. Yet with the increase of service span, malfunctions occur more frequently and could lead to higher maintenance expenditures. For instance, problems such as inoperative lift-and-tilt cylinders and transmission issues for loaders are more likely to occur with increased service years, and are generally expensive to fix (Ahrens 2009). The main purpose of this project is to apply a data-driven approach to evaluate the optimal life cycles for sweepers, loaders, and graders, respectively. Suggestions are made on service range for each type of truck.

1.0. Introduction and Data Examination

1.1. Background

The main equipment programs that will be evaluated via performance assessment in this research project are as follows:

- **Sweeper**: Street sweepers keep the streets clean and litter free. Conventional sweeper trucks are equipped with a jet that sprays water around the truck to prevent dust flying around. The cylinder brushes at both sides of the truck sweep the dust and debris into the storage container. Some sweeper trucks use a vacuum to replace the cylinder brushes to remove the debris.
- **Loader**: A loader truck is equipped with a loader (tractor). There are multiple types of loaders, depending on the application and design. The major components for a loader include an engine, hydraulic components (such as pump), and transmission components. Loader trucks are mainly used for moving stockpiled materials from the ground level, such as dirt, snow, gravel, and others.
- **Grader**: A grader is also referred to as a road grader, which normally is equipped with a blade to flatten the surface of the road during the grading process. Graders are commonly used for constructing and maintaining dirt and gravel roads. During construction, a grader works to create a flat surface on which to place the road surface.

The general appearance of each equipment type is shown in Figure 1.

(a) (b)

(c)

Figure 1 Pictures of (a) Sweeper; (b) Loader; and (c) Grader from Wikipedia

1.2 Review of Class 8 Snowplow Truck Life Cycle Analysis

In this project, the goal is to perform life cycle analysis for sweepers, loaders, and graders, separately to obtain the corresponding optimal replacement cycle for each type of equipment. To this end, we come up with the potential data required for such analysis based on a previous similar study for Class 8 snowplow truck analysis. We first identify crucial parameters from the Class 8 snowplow truck life cycle assessment project, and then review literature regarding life cycle analysis for heavy-duty equipment. Lastly, we summarize the potential dataset required to perform a cost-benefit analysis for the specified equipment programs.

In reference to the class 8 snowplow truck project, the following variables are deemed essential for benefit-cost analysis:

- **Service span:** Indicate how long the machine has serviced roads since the beginning of purchase. Surplus value is an important parameter when performing cost-benefit analysis. For an asset, the surplus value varies with its service years. Hence, service span is an essential variable to evaluate a machine's current surplus value.
- **Purchase price** (including purchase data and corresponding model): The purchase price may change by time and model. Trucks' surplus values are also determined by their purchase price.
- **Resale price:** The resale price is used to estimate the depreciation value of the assets.
- **Maintenance costs:** Maintenance costs refer to the expenses of any required repairs as well as the costs of preventive maintenance during the service span. Maintenance cost is

one of the major investments in an asset. Cumulative maintenance costs generally mount up with the service span.

- **Working mileage:** Daily working mileage records can reflect the workload of trucks, and are indispensable for calculating their optimal life cycle. Depending on the functionality of those trucks, the working mileage may vary over time. Analyzing the working pattern and general workload can help us better understand the relationship between workload and maintenance.

- **Fuel consumption records:** Fuel consumption data is consistent with the working mileage data. We utilize fuel consumption data to calculate trucks' working efficiency (mpg). This enables us to examine if their performance goes down with the increase of service years.

In addition to the aforementioned data, the following data are also preferred for the purpose of conducting micro-analysis with finer granularity:

- **Working regions:** We like to know if trucks service a specific region. In this case, the truck may be labeled by their working region. This allows us to find discrepancies in truck performance across regions.
- **Maintenance records in detail**: In general, the maintenance records only contain the costs and date for each event. However, the reason for maintenance can be different. Since these trucks have a specified functionality, the malfunction could be associated with a certain type of job (e.g., the repair of cylinder brushes, replacement of the loader, etc.). Consequently, if detailed reasons for maintenance can be accessed, we can analyze if their functionalities can cause certain malfunctions excessively.
- **GPS data**: We are able to identify trucks' working regions, average speed, working frequency, and the like. Meanwhile, by locating their working regions, we can evaluate their working conditions as well.

Based on the aforementioned analysis of the Class 8 snowplow truck project and previous studies, we summarize the data that might be required for the life cycle analysis in the table below. The data are categorized into two classes: *Essential Data* and *Granular-Level Data*. *Essential Data* documents the indispensable data in performing cost-benefit analysis; while *Granular-Level Data* enables us to refine the model and conduct analysis in finer granularity.

Table 1 Essential Dataset Required for Life Cycle Analysis

Essential Data
• Purchase/Resale records (including the price, date, and model) • Maintenance records (including the repair costs and corresponding reasons, if any) • Mileage records (data obtained from odometer) • Type of Engine (Diesel/Gasoline for Sweeper/Grader/Loader respectively)

Table 2 Granular-Level Data Required for Life Cycle Analysis

• Current replacement strategy, budget allocation, and expected future plans • Working regions (Labels and corresponding denotations) • Fuel cost and interest rate in different time periods (Can be tracked online) • GPS data from automatic vehicle location (AVL) • Labor cost data • Explanation of major tasks for street sweepers/loaders/graders

1.3 Literature Review

The dataset described above is mainly utilized to analyze Class 8 snowplow trucks exclusively, whose primary function is winter activities. However, sweepers, loaders, and graders have significantly different functionality and working patterns. As a result, a literature review in terms of cost-benefit analysis of general heavy-duty vehicles enables a better understanding of this project. Gransberg and Connor (2015) conducted life cycle cost analysis of major equipment for the Minnesota Department of Transportation (MnDOT). The authors applied the Peurifoy and Schexnayder method (PSM) to calculate life-cycle costs for equipment. In addition to the inputs we used for Class 8 snowplow trucks, tire costs and tire cost repair are also taken into consideration. Moreover, given the uncertainty and fluctuation of market value, the stochastic approach is implemented for evaluating life cycle cost. Specifically, the parameters “fuel price” and “interest rate” are randomly generated through Monte Carlo simulation, and subsequently fed into cost-benefit analysis. The framework of this combined method is illustrated in Fig 2.

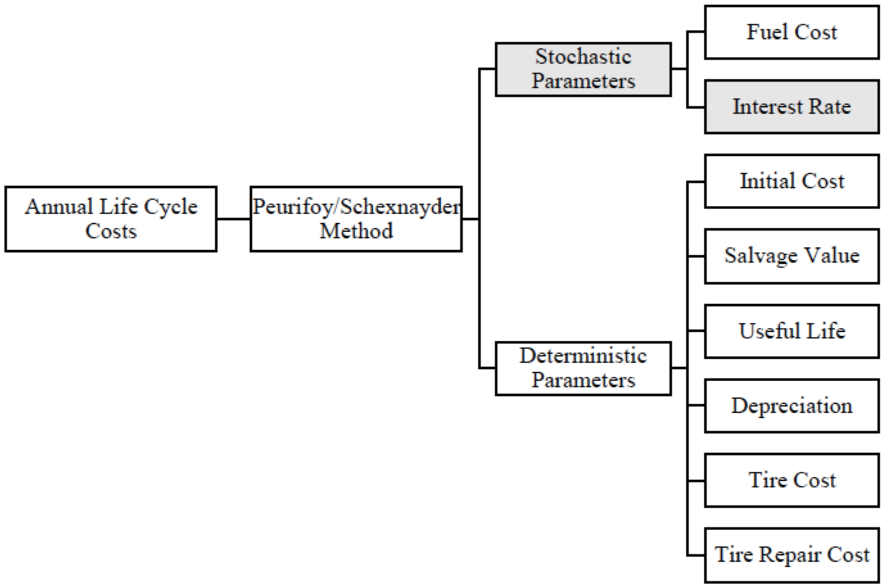

Figure 2 The Flow Chart of Stochastic PSM Method

Deterministic (PSM) and stochastic (PSM with Monte Carlo simulation) models were both developed to calculate the optimal life cycle. Four specific types of equipment are studied in this project (i.e., 2002 Sterling LT9500 Dump Truck, 2012 Loader, 2006 Volvo Loader), and the optimal replacement cycles derived by both models are recorded in Table 3.

Table 3 Optimal Life Cycle Results of Different Equipment Fleets

Equipment	Deterministic Economic Life (yrs)	Stochastic Economic Life Range (yrs)
2002 Dump Truck	13	11-14
2012 Loader	4	3-8
2006 Loader 2.5 yd	4	3-7
2005 Loader 5 yd	4	5-8

In Table 3, it is found that loaders generally have a shorter life cycle than a dump truck, which ranges between 3 to 8 years using the stochastic method. Compared to the deterministic model, the stochastic model allows the fleet manager to forecast several years in advance of the need for equipment replacement for the entire fleet, and therefore to generate a rational replacement strategy with relatively increased confidence that the decisions can be justified.

Total cost is one of the major sources in calculating the optimal life cycle costs. Yet, the definition of total cost can vary significantly for different equipment. Chen and Keys (2009) defined a general Post-Manufacturing Product Cost (PMPC) model to analyze the total costs of heavy equipment in its utilization stage. In this study, the authors pointed out that the costs of heavy equipment generally contain two parts: ownership costs and operating costs, where operating costs are normally much bigger than ownership costs. Ownership costs refer to the purchase cost and depreciation cost in cost-benefit analysis; whereas the operating costs are more complicated to define since such costs depend on the specified job performed by the heavy equipment truck. For example, when studying the total costs for haulers, the activities need to be broken down into several segments (namely wait for loading, run on the road with load, dump, and return with empty load) in order to analyze its fuel costs. Moreover, the PMPC model also includes labor costs and energy source consumption.

For energy source consumption, in addition to fuel consumption, many researchers take environmental impact into consideration when building the life cycle model. This is due to the fact that the diesel engine can generate emissions and pollutants such as CO_2, CO, HC, NO_X, and PM (Pang 2008). For example, Bartolozzi et al. (2018) performed a life cycle inventory assessment for street sweeping services (including sweeper vehicles and manual labor) to evaluate the environmental impact from street sweeping. Specifically, fuel consumption of vehicles, electricity for vehicle recharging, equipment (e.g., brushes, dustpans, etc.), waste and emissions are included in the model to evaluate the impact on climate change, ozone depletion, land use, etc. This provides an insight of taking environmental impact into account in the total costs when building life cycle models.

2.0. Data Analysis and Preprocessing

2.1. Basic Information

UDOT provides information on currently managed trucks in the format of a .csv file. The basic information contains the date of their in-service start time, acquisition price, the annual maintenance cost, etc. Detailed information is shown in the table below.

Table 4 The Basic Information of Truck Records

Information	Description
Total # of equipment	186
Service time span	1998-2020
Entry information	Annual mileage/Annual fuel cost/Annual repair cost records
Column features	1. Year 2. Equipment ID 3. Maintenance Class 4. Model Year+Model+Company of Manufacturer 5. Acquisition Cost 6. In-Service Date 7. Annual Fuel Quantity & Fuel Cost 8. Annual Repair Cost/PM Part Costs/Commercial Labor/Commercial Parts/Commercial PM Labor Cost/PM Commercial Part Costs

2.2. Truck Information

The data file does not document the type of each equipment. Based on information from the manufacturer and confirmation with UDOT, the research team compiled the following manufacturer information.

Table 5 Manufacturer and Corresponding Type of Trucks

Make	Type of Trucks
CAT	Grader
CATERPILLAR	Grader
CHAMPION	Grader
GALION	Grader
CASE	Loader
GEHL	Loader
INGERSOL-RAND	Loader
JCB	Loader
JOHN DEERE	Loader
KOMATSU	Loader
ALLIANZ	Sweeper
BROCE	Sweeper
ELGIN	Sweeper
GLOBAL	Sweeper
JOHNSTON	Sweeper
SCHWARZE	Sweeper
SUPERIOR BROOM	Sweeper
SWEEPRITE	Sweeper
SWEEPSTER	Sweeper
WALDON	Sweeper

It is noted from Table 5 that the majority of the equipment is loaders, and Table 6 shows the type split across all of the equipment.

Table 6 Equipment Classified by Types

Type of Trucks	Count of Eqp#
Grader	23
Loader	102
Sweeper	61
Grand Total	186

Table 7 Manufacturer and Model Information for All Equipment

Row Labels	ALLIANZ	BROCE	CASE	CAT	CATERPILLAR	CHAMPION	ELGIN	GALION	GEHL	GLOBAL	INGERSOLL-RAND	JCB	JOHN DEERE	JOHNSTON	KOMATSU	SCHWARZE	SUPERIOR BROOM	SWEEPRITE	SWEEPSTER	WALDON	Grand Total
135H				2	2																4
140H					8																8
140M					1																1
140M 6X6					1																1
20572M												1									1
3203L															2						2
4000	1																				1
444H													10								10
544GH													1								1
544H													4								4
621B			5																		5
621C			5																		5
621D			24																		24
621E			17																		17
624													1								1
624EH													1								1
624G													7								7
624H													1								1
670CH													1								1
710A						1															1
721D			1																		1
724K													1								1
770D													2								2
772D													1								1
821E			3																		3
821F			1																		1
830								2													2
850								5													5
850C								1													1
A9																1					1
BOBCAT 773											1										1
DT80CT																	9				9
DT80K																	5				5
EAGLE							21														21
ES351														5							5
GD650															5						5
M 4										1											1
ROAD WIZARD							9														9
RTC350		5																			5
SK1026															1						1
SL3615									1												1
SP96																			1		1
SR3300F																		1			1
SWEEPMASTER																				2	2
WA180															1						1
WA3203MC															1						1
WA380															3						3
Grand Total	**1**	**5**	**56**	**2**	**12**	**1**	**30**	**8**	**1**	**1**	**1**	**1**	**30**	**5**	**13**	**1**	**14**	**1**	**1**	**2**	**186**

2.3. Acquisition Price Distribution for Equipment

The price of equipment varies based on the type of truck, manufacturer, and model. We further analyze the price distribution for each type of truck. For graders, the price varies widely by their manufacturers and models from $50,000 to $250,000. The price of most loaders is concentrated around $100,000. As for the sweeper, it can be grouped into two categories - acquisition price below $100,000 and acquisition price over $100,000.

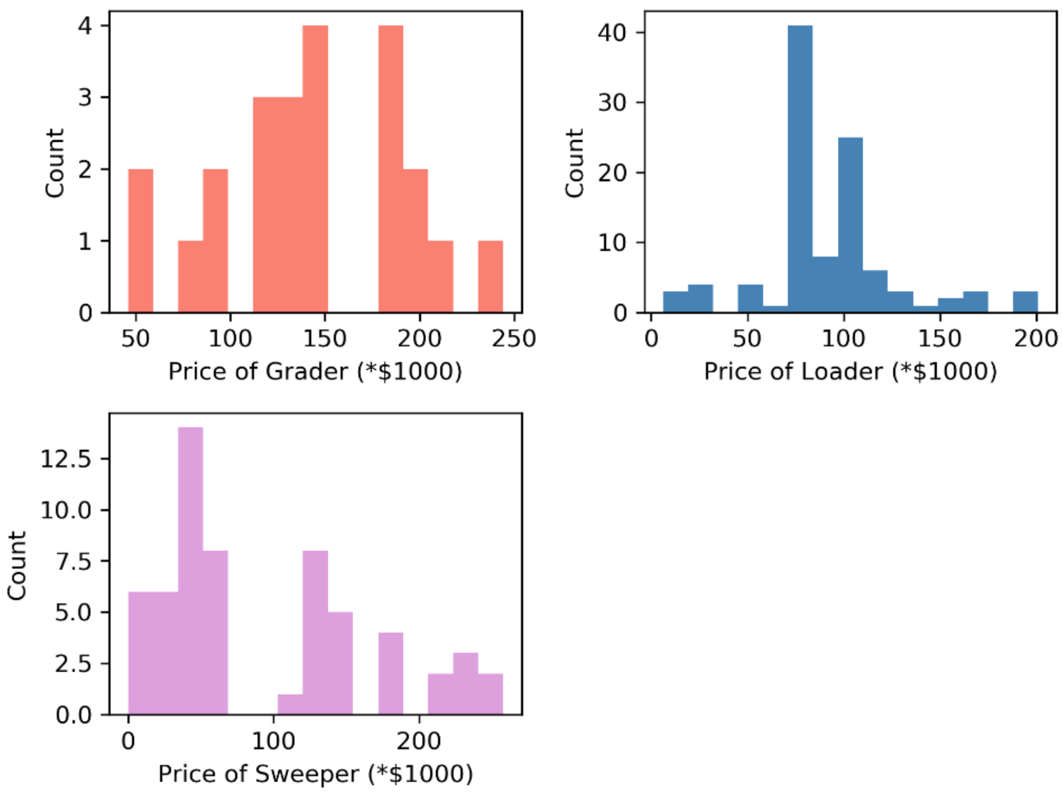

Figure 3 Histogram Plot for the Acquisition Price of Each Type of Vehicle

2.4. Maintenance Cost

There are six different categories of maintenance costs, including repair parts costs, commercial parts costs, commercial labor costs, PM parts costs, PM commercial parts costs, and PM commercial labor costs. We visualized the split of total maintenance costs in Figure 4.

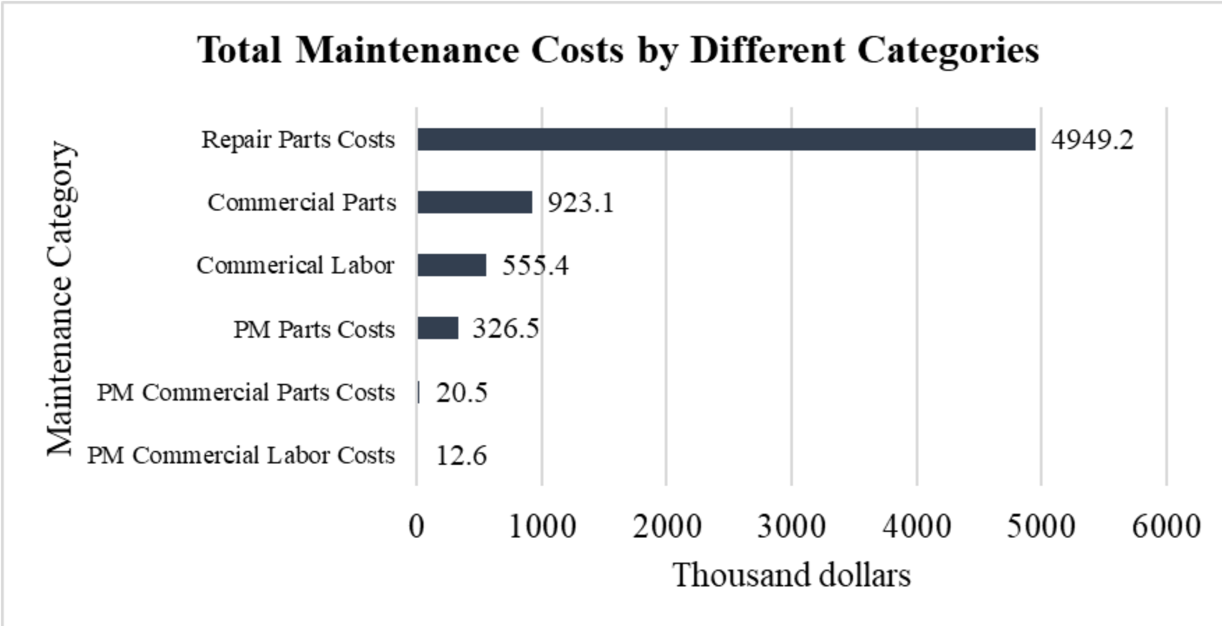

Figure 4 Maintenance Costs by Different Categories

It is observed that the dominant factor that contributes to maintenance costs is parts repair. Besides that, commercial parts costs, commercial labor costs, and PM parts costs account for a fair share of total maintenance costs. On the contrary, PM commercial parts costs and PM commercial labor costs only contribute marginally. This split indicates that repair parts cost is a main category we might focus our analysis on.

In order to better understand the average maintenance cost for each truck and its trend along the time horizon, we calculate the maintenance cost per truck in each year from 1998 to 2020. The result is displayed in Figure 5. Back in 1998, there were only 48 trucks (including sweepers, loaders, and graders) in service. From 1999 to 2020, the number of trucks in service kept stable between 172 and 186. However, we notice that the average cost in 1998 is 0. It could be either because the maintenance record is missing or because the trucks were brand new and not much maintenance was needed. It is also noted that there has been a significant surge in maintenance costs since 2011. Before 2011, the average maintenance cost was below $1,500 per truck every year. After 2011, the average annual maintenance costs in most years were above $2,500 per truck. Such a contrast indicates a large increase in maintenance requirements for trucks after a certain period of service. In addition, the significant reduction of average maintenance costs in 2020 might be due either to the influence of COVID-19 or only partial data availability (until July 2020). In either case, we removed the 2020 records from our life cycle analysis.

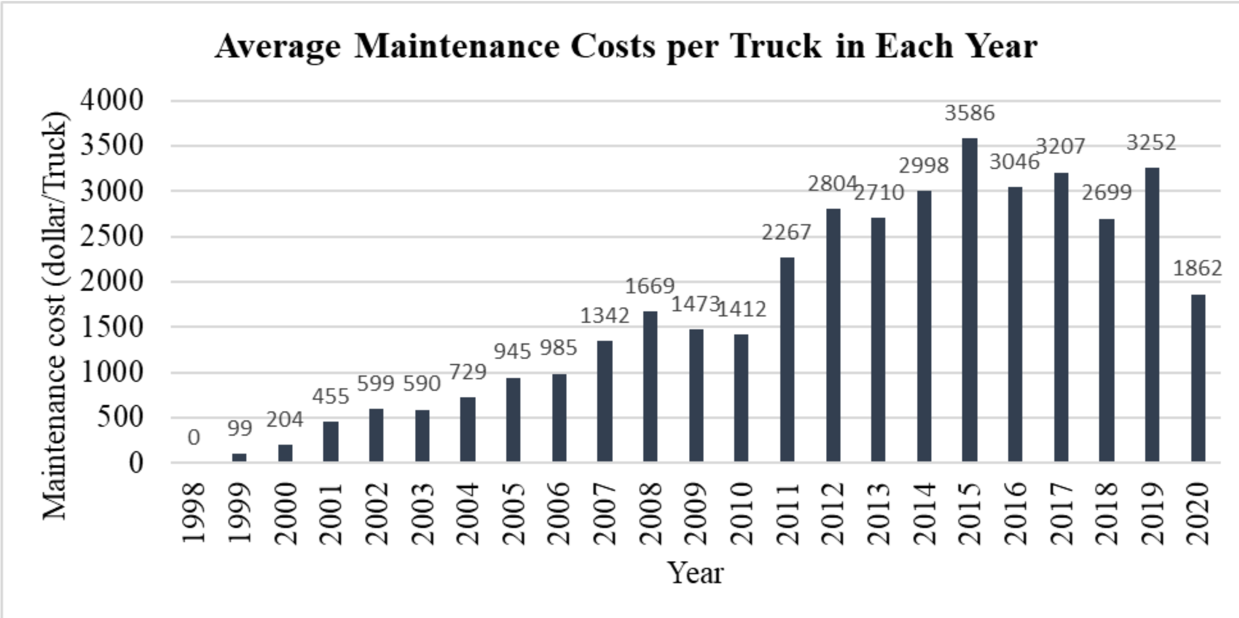

Figure 5 The Average Maintenance Cost in Each Year

2.5. Working Mileage and Fuel Consumption

Working mileage and fuel consumption are two important indicators to quantify trucks' utilization. In our previous research for Class 8 snowplow trucks, we used working mileage to quantify the trucks' workload, since snowplow trucks are moving while working. In this project, however, each type of truck functions differently. For example, sweepers operate in a similar fashion to snowplow trucks. As a result, the workload of sweepers might be proportional to the running mileage. Yet loaders generally work in a specific region, suggesting a potentially much lower range of working mileage than sweepers. However, their fuel consumption could be high due to the loading process. For this reason, we consider both the working mileage and fuel consumption as options for quantifying trucks' workload, and separate the analysis by the type of truck.

2.5.1. Removing Anomalous Data

The dataset records the annual information for each truck from 1998 to 2020. Nevertheless, the mileage data from 1998 to 2000 have negative values for some trucks. An example of erroneous records is displayed in the figure below. Moreover, the negative mileage occasionally occurs in other years as well.

Cost Yea	Eqp #	Maint Cla	Model Ye	Make	Model	Acquisition Amour	In Service Da	Meter 1 Readi	Meter 2 Readi	Sum of Fuel C	Sum of Fuel Cos
1998	SR05039	0502	1995	GALION	850	$ 132,710.00	01/01/95	-728	0	0.0	$ 3,765.54
1999	SR05039	0502	1995	GALION	850	$ 132,710.00	01/01/95	4,956	0	459.8	$ 399.97
2000	SR05039	0502	1995	GALION	850	$ 132,710.00	01/01/95	-3,944	993	325.3	$ 362.41
2001	SR05039	0502	1995	GALION	850	$ 132,710.00	01/01/95	116	0	159.0	$ 201.17
2002	SR05039	0502	1995	GALION	850	$ 132,710.00	01/01/95	302	0	265.3	$ 297.86
2003	SR05039	0502	1995	GALION	850	$ 132,710.00	01/01/95	5	0	369.1	$ 439.23

Figure 6 Example of a Truck Containing Anomalous Records

In order to obtain reasonable results, we only consider the working mileage and fuel consumption from 2001 to 2020, with additional filtering to remove negative mileage values.

2.5.2. Working Mileage Data

Figure 7 below shows the average annual mileage from 2001 to 2020 for each type of truck.

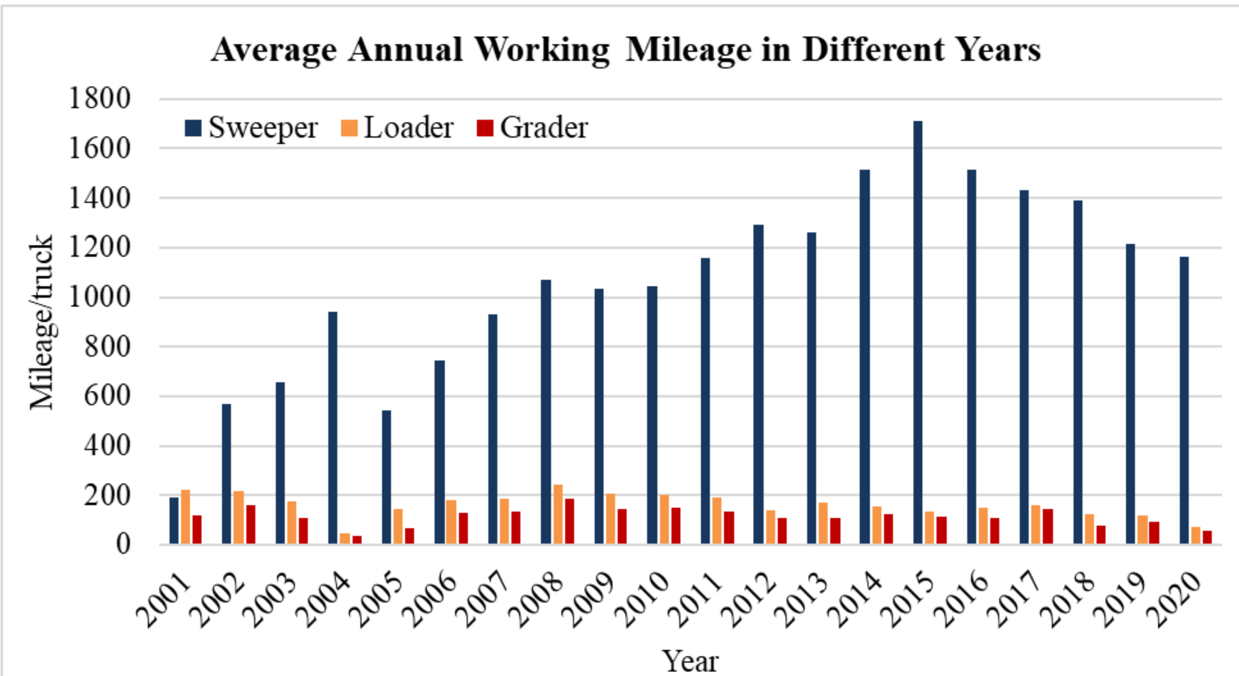

Figure 7 The Average Annual Working Mileage in Different Years

The average annual mileage for a loader/grader is below 200 miles, while the range of average mileage for sweepers varies between 200 to 1,800 miles per year. As expected in the aforementioned analysis, sweepers have much higher average working mileage than loaders or graders. Due to the difference in functionalities, working mileage might not be able to fully capture the workload for all types of trucks. This finding suggests that it is necessary to define the optimal life cycle separately. Another observation is that for sweepers, the average mileage is relatively low prior to 2010. In contrast, the trend for graders and loaders has been quite stable. This implies an increasing demand for sweepers. In the next step, we present the average fuel consumption variation from 2001 to 2020 in Figure 8.

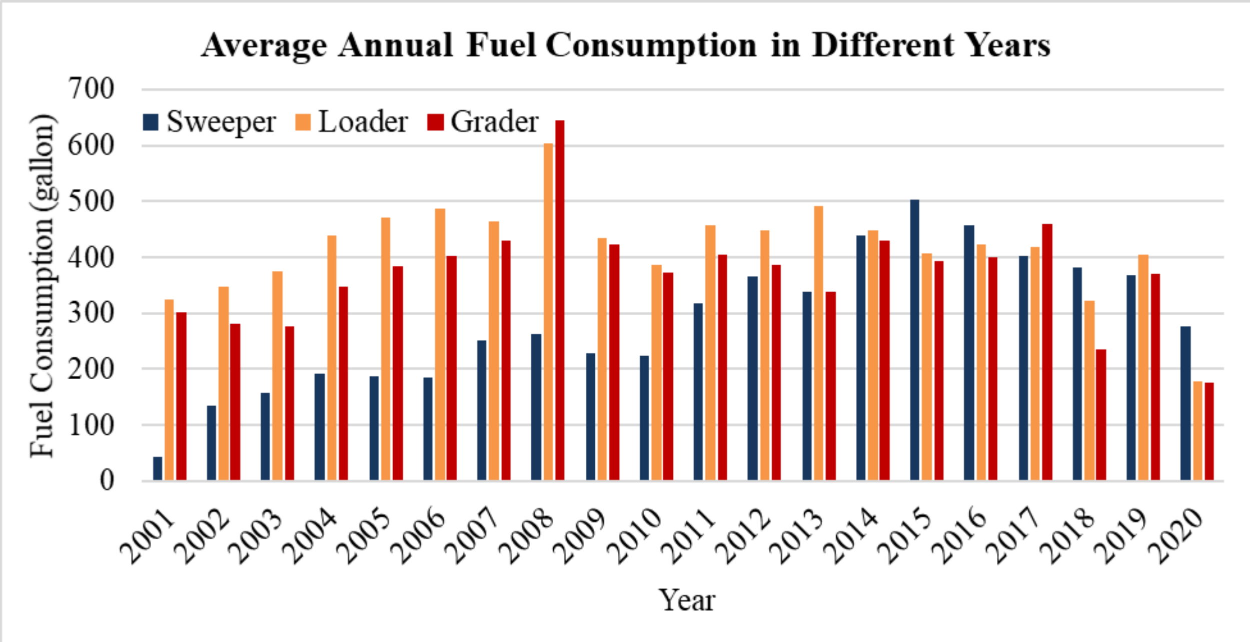

Figure 8 The Average Annual Fuel Consumption in Different Years

Fuel consumption reveals a very different perspective compared with working mileage. Sweepers appeared to be utilized more intensively post-2010. Both Figures 7 and 8 show a significant reduction in 2020, which might be caused by the incomplete records of the year or the COVID-19 pandemic.

3. Life Cycle Analysis

The optimal life cycle for trucks are mainly driven by their depreciation value (or surplus value) and the total maintenance cost (Scheibe, Nilakanta, and Ragsdale, 2017; Wyrick and Erquicia, 2008) In this section, we estimate the trucks' optimal replacement cycle for loaders, sweepers, and graders, respectively.

3.1. Loaders

3.1.1. Depreciation Cost for Loaders

There is a total of 102 loaders servicing between 1998 and 2020. The average acquisition price is $94,505. Depreciation refers to the decrease in asset value in response to time. For loaders, sweepers, and graders, their values start to decrease as they begin to function. The depreciation cost for every service year is accumulating with the increase of service span. That means the assets' surplus value is decreasing accordingly, as the sum of surplus value and cumulative depreciation value in a certain year equals to the acquisition price.

However, in most cases, the surplus value is not available and is usually estimated empirically. To this end, we use the declining balance (DB) method to predict trucks' depreciation value. The DB method is an accelerated depreciation method, in which the depreciation expense is the highest in the initial year and declines over service span (Mayer 1947). The formula for the DB method is expressed as follows:

$$p = 1 - \sqrt[n]{\frac{s}{c}} \tag{1}$$

where p is the annual depreciation rate; n is the number of years of useful life; s is the surplus value at the n^{th} year; and c is the original purchase cost. Once the percentage of annual depreciation rate p is derived, the annual depreciation cost at a given service year (k) can be calculated based on the method as:

$$\mathrm{dep}_k = c * (1 - p)^k \tag{2}$$

Finally, the cumulative depreciation costs from the start of service to the k^{th} service year can be derived as:

$$\mathrm{c\_dep}_k = \sum_{i=1}^{k} dep_i \tag{3}$$

In general, to obtain the percentage of depreciation p in Equation 1, we usually use the acquisition price and average resale price for estimation. Nevertheless, the original dataset does not contain the resale price of trucks. To resolve this issue, we use the Class 8 snowplow trucks' annual depreciation rate as reference (which is 0.17), and we therefore set three different rates (namely p=0.15, p=0.2, and p=0.25) in our analysis representing three scenarios of slow, medium, and high depreciation rate, respectively (Liu and Yi 2019). Figure 9 illustrates the loaders' cumulative depreciation costs and surplus value under different p values from service year 1 to 20.

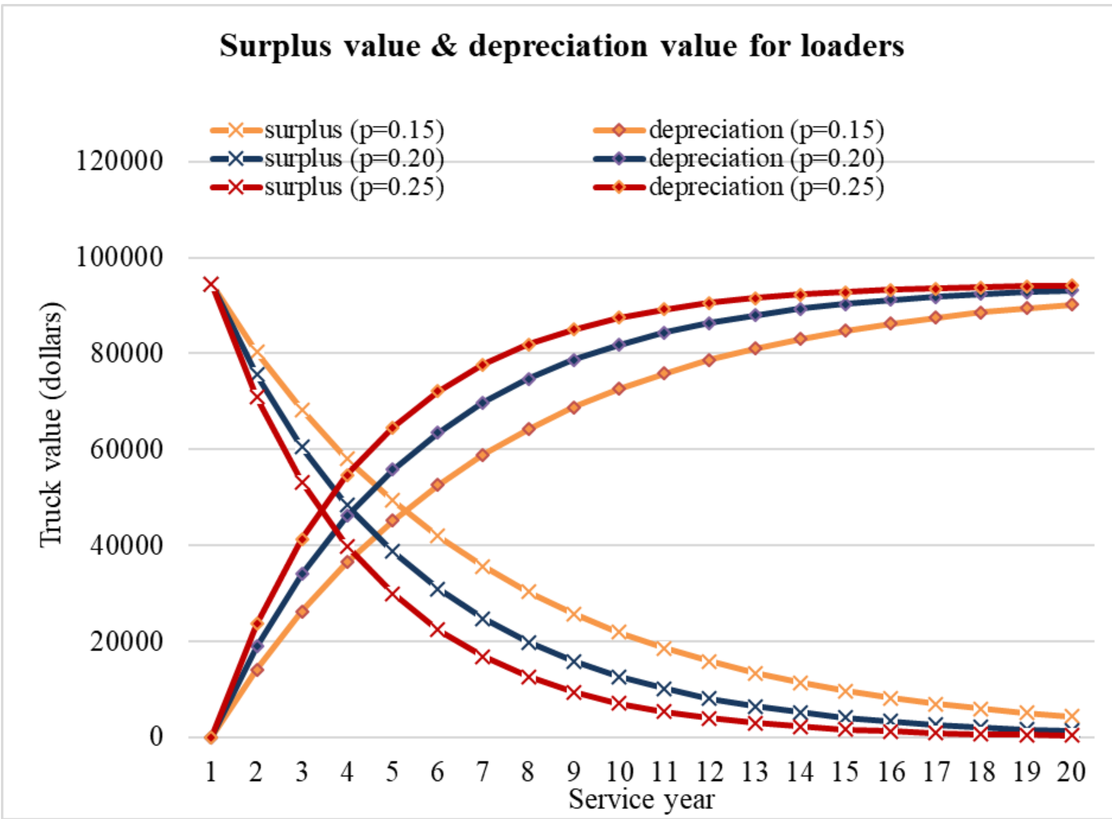

Figure 9 Cumulative Depreciation Costs and Surplus Value Curves for Loaders with Different Annual Depreciation Rates

Note that service year is defined as the number of years that the truck has already been in service, and that the trucks' surplus value drops abruptly after the first several service years. The rate then becomes mild when the surplus value itself is relatively low. Correspondingly, the cumulative depreciation curve in the figure presents a reverse trend. In Figure 9, the three p values correspond to different scenarios, where the larger p value represents the scenario of a more aggressive reduction in surplus value. However, with the increase of service span, the gap of surplus values for different p values becomes smaller.

3.1.2. Maintenance Cost for Loaders

In the next step, we calculate the maintenance cost in every service year. The maintenance cost is defined as the sum of all repair costs, including repair parts costs, commercial parts costs, commercial labor costs, PM parts costs, PM commercial parts costs, and PM commercial labor costs. The average annual cost and cumulative cost with the increase of service years for a loader are shown in Figure 10.

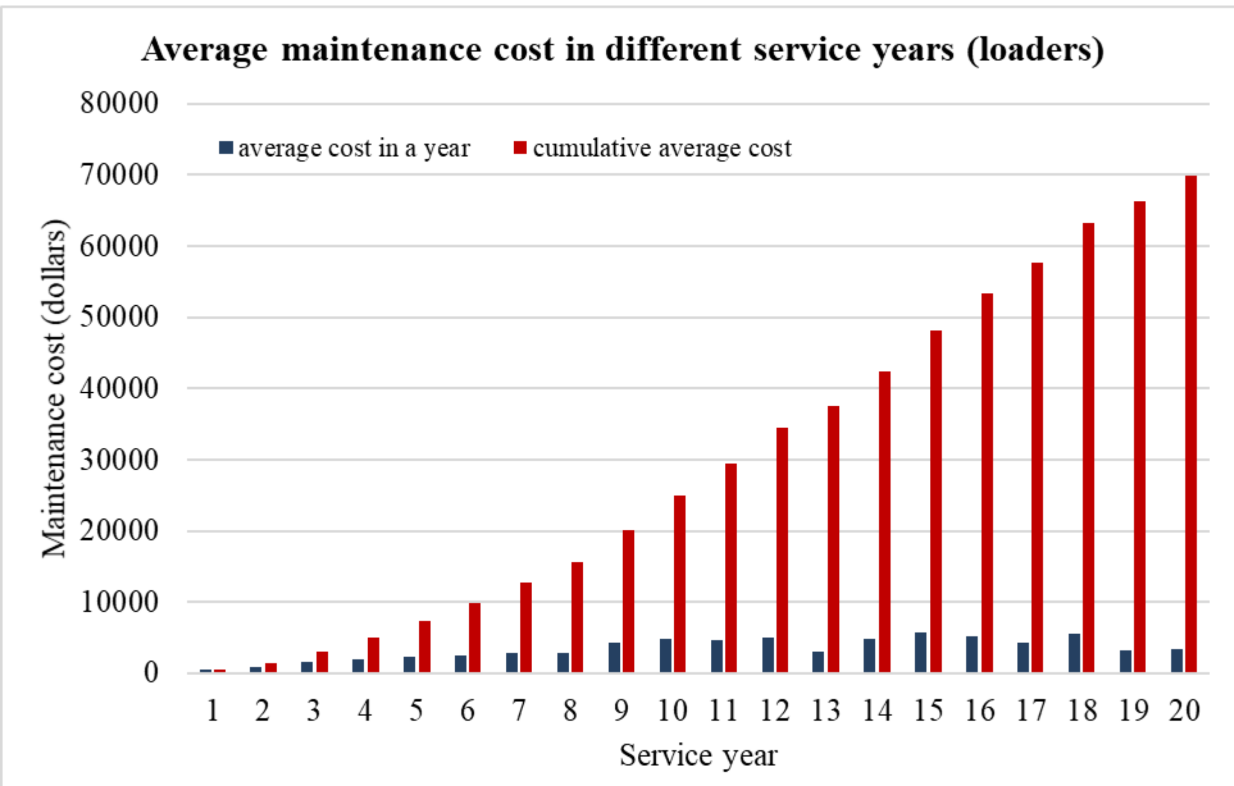

Figure 10 The Average Maintenance Cost in Different Service Years for One Loader

In Figure 10, we notice that the maintenance cost keeps within a low range (below $3,000 every year) when the service year does not exceed 8 years. However, when the loaders service over 9 years, the average annual maintenance cost is over $4,000. At this point, the aging of trucks can lead to more frequent repairs. After we obtained the estimated surplus value and average maintenance cost for a loader, in the next subsection, we overlap the two curves to identify the optimal life cycle for loaders.

3.1.3. Optimal Life Cycle Analysis for Loaders

The optimal life cycle for loaders under different depreciation rates are shown in Figure 11.

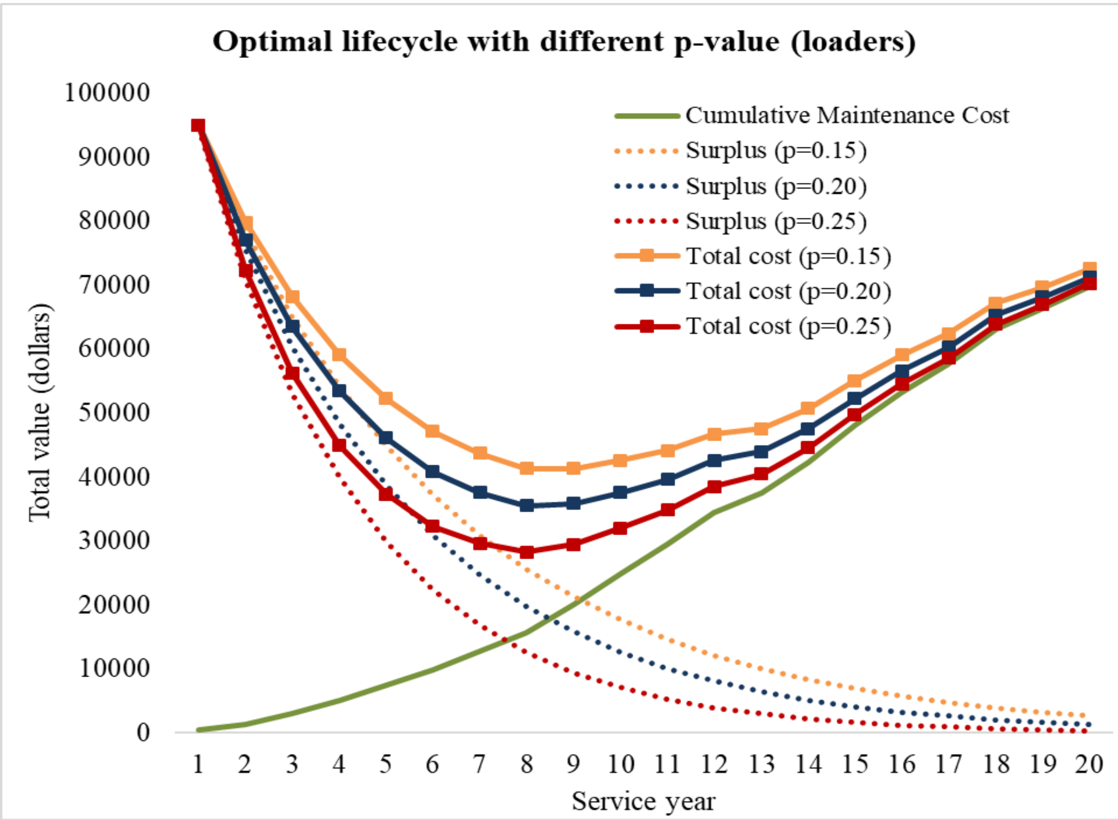

Figure 11 Total Cost Curves for a Loader with Different p Values

Fig 11 not only shows the total costs for different p values, it also displays the cumulative maintenance cost and surplus values at corresponding service years. The total costs of a loader will decrease first due to low maintenance and fast depreciation, and then it will increase. The increase is caused by higher maintenance costs along their service span. We can observe that by setting different p values, we obtain different optimal life cycles. We notice that the optimal life cycles are the same (8 years) under different p values. As mentioned earlier, we set different p values to estimate the surplus value for the following reasons:

- Because the loaders managed by UDOT consist of different models and purchase prices, the average acquisition price may not truly reflect the price for a certain brand or model;

- Since we do not have the resale price for the trucks, it is difficult to set a precise p value for the life cycle estimation. If we had the resale price data, it might still cause bias to the results given the small sample size of loaders (102).

Therefore, setting a time window for fleet replacement appears to be more appropriate here. The suggested cycle to replace the loader would be 7 to 11 years based on the historical dataset.

3.2. Sweepers

3.2.1. Depreciation Cost for Sweepers

Sixty-one sweepers were purchased between 1998 and 2020, with the average acquisition price being $95,440. The most expensive one cost $257,665 and the cheapest sweeper cost $29,400. We calculate the cumulative depreciation costs and surplus value in the same way we calculated for a loader. Likewise, depreciation rate p is set as 0.15, 0.2, and 0.25, respectively. The results are displayed in Figure 12.

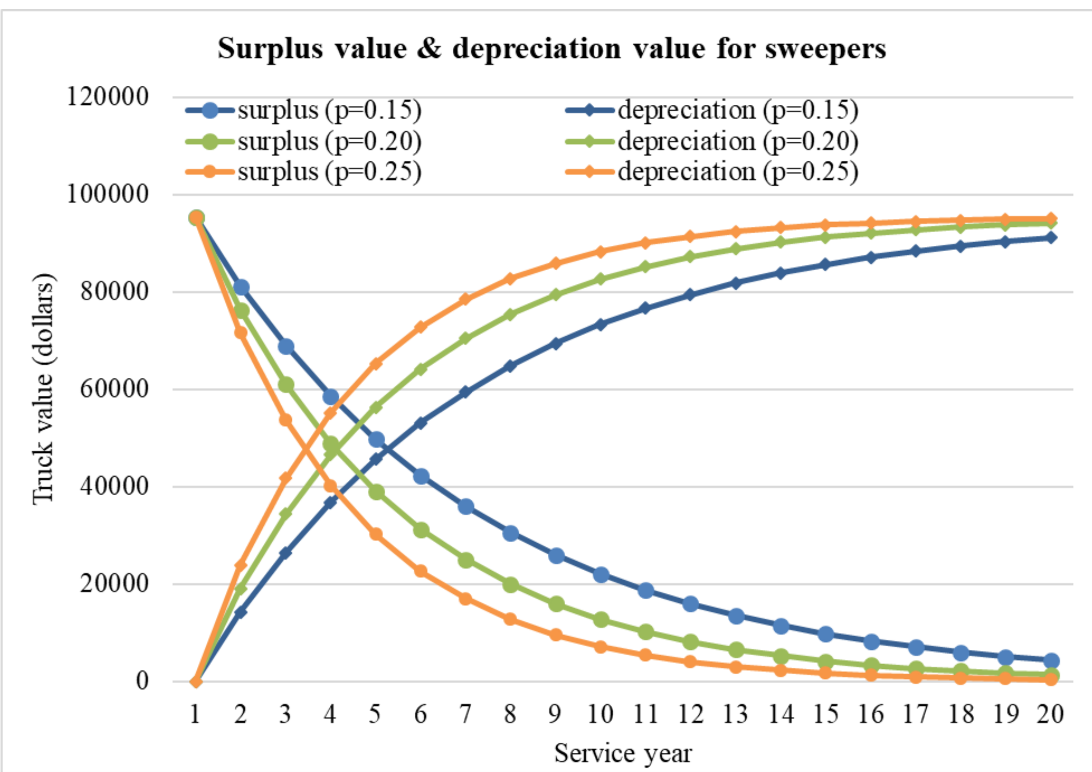

Figure 12 Cumulative Depreciation Costs and Surplus Value Curves for Sweepers with Different Annual Depreciation Rates

It is noticed that the depreciation trend for sweepers follows a similar trend as loaders, since their average acquisition prices are very close. When the service year surpasses 10, the depreciation rate becomes relatively slow. Meanwhile, the truck's surplus has been decreased over 75% to 80% depending on different depreciation rates.

3.2.2. Maintenance Cost for Sweepers

The maintenance costs for sweepers are aggregated by service years from 1 year to 20 years. Figure 13 indicates the maintenance costs for sweepers, including repair costs, labor costs, and parts costs.

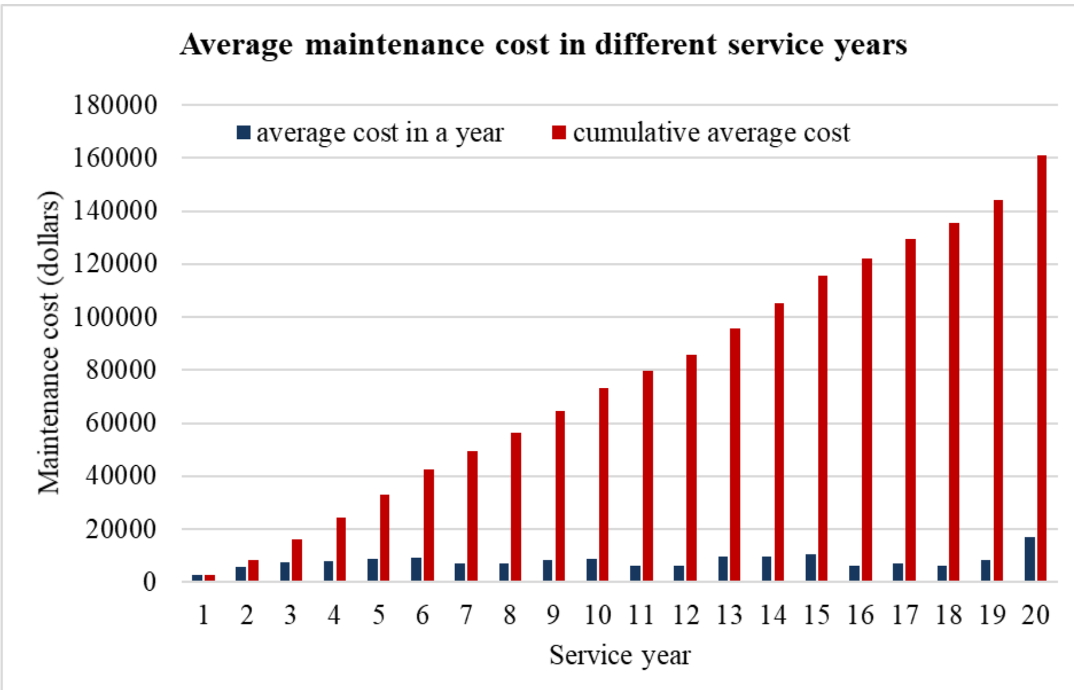

Figure 13 The Average Maintenance Cost in Different Service Years for One Loader

In general, the average maintenance costs are relatively less in the first service year. With the increase of service years, average annual maintenance costs fluctuate between $5,000 and $10,000 for a sweeper. Cumulative average costs (red bars in Fig 13) also indicate a steady linear increase with service years. Note that the average cost for the 20 service years is $17,135. However, the records show that only 6 sweepers functioned over 20 years. For this reason, $17,135 might be a biased number to indicate the maintenance cost for 20 service years. In the next step, we calculate the optimal life cycle for sweepers combining the depreciation cost and maintenance costs.

3.2.3. Optimal Life Cycle Analysis for Sweepers

Figure 14 demonstrates the life cycle trends of sweepers under different depreciation rates.

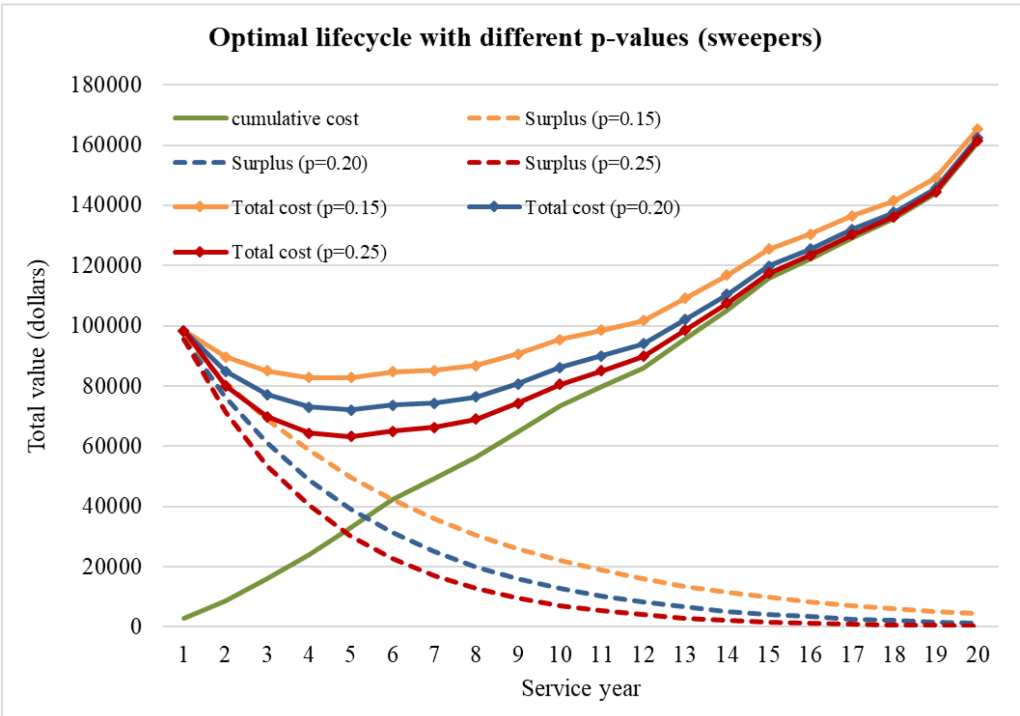

Figure 14 Total Cost Curves for a Sweeper with Different p Values

The life cycle trend for sweepers has a different trend than loaders. One major reason is that sweepers have more expensive maintenance costs on average. This distinction leads to a decrease in the optimal life cycle for sweepers. As observed in Figure 14, the optimal life cycle for a sweeper is 4 years if depreciation rate p is 0.15, and 5 years if depreciation rate p is 0.2 or 0.25. When the service years exceed 8, total costs start to spike significantly. When the sweepers have been servicing over 11 years, the total price exceeds the acquisition price. In this situation, the sweepers are not appropriate to continue working further.

3.3. Graders

3.3.1. Depreciation Cost for Graders

The average acquisition price for the existing 23 graders is $142,555. Surplus values and depreciation costs under different depreciation rates are displayed in Figure 15.

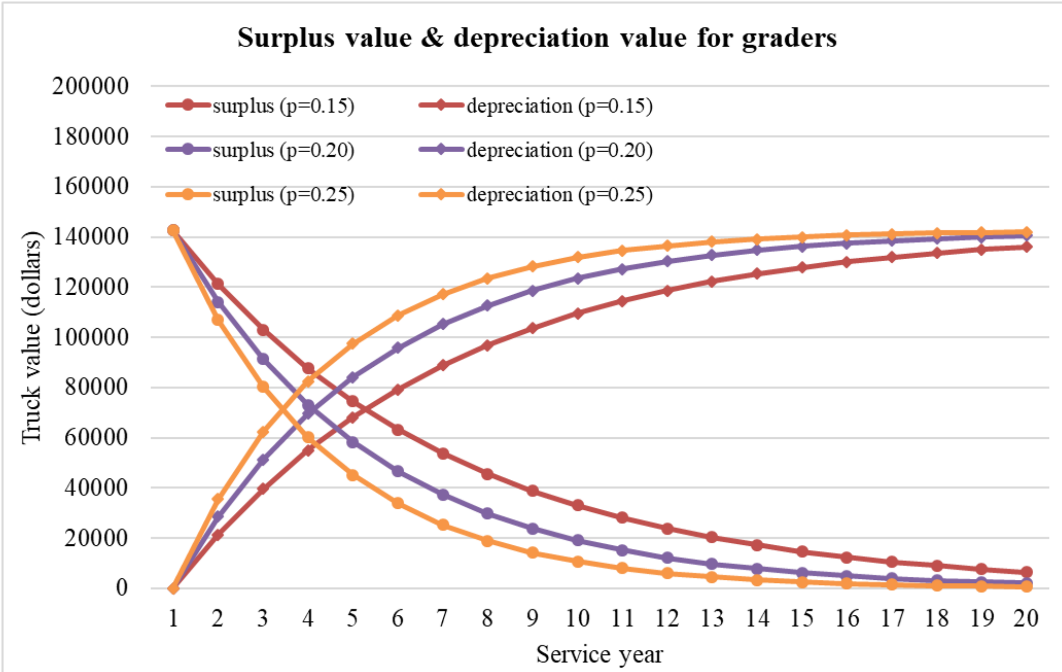

Figure 15 Cumulative Depreciation Costs and Surplus Value Curves for Graders with Different Annual Depreciation Rates

The rate of depreciation speed depends on the p value. A larger p value produces a faster decrease in surplus value. When p is set as 0.15, the truck maintains half surplus value around the 6th service year. In contrast, when p is set as 0.25, it only takes approximately 3.5 years to decrease to half surplus value. The depreciation rate starts to flatten at the 8th service year. In the next step, we observe the maintenance cost for graders.

3.3.2. Maintenance Cost for Graders

The maintenance costs for graders across different service years are displayed in Figure 16.

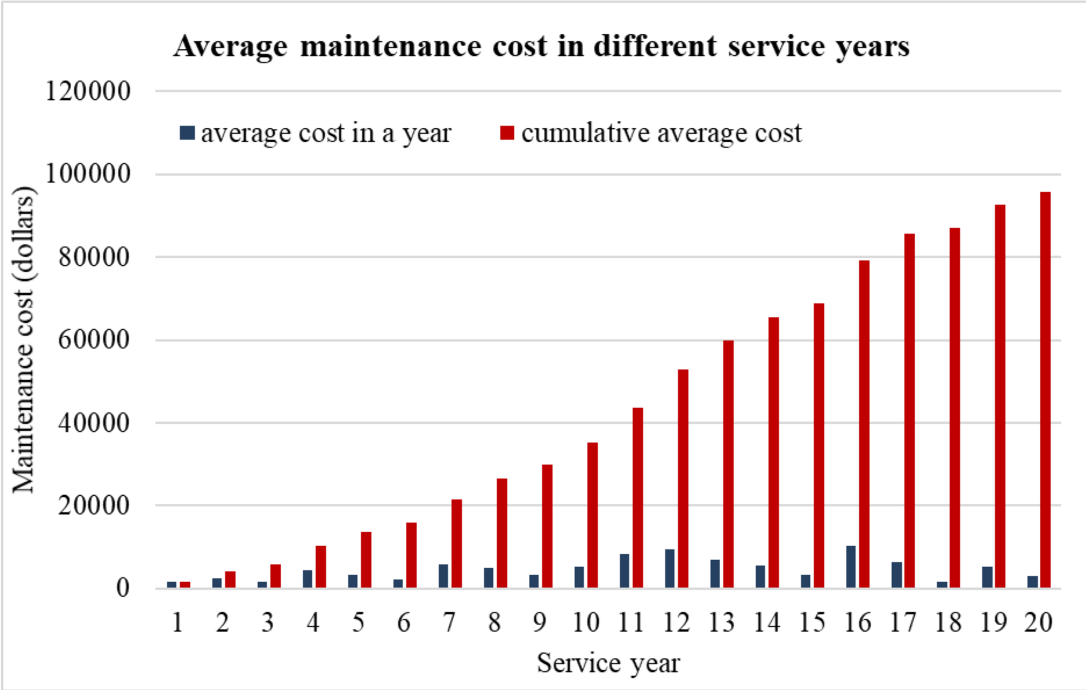

Figure 16 The Average Maintenance Cost in Different Service Years for a Grader

Compared to sweepers, the maintenance cost of graders is relatively low. The average annual cost stays low for the first 6 service years. Peak maintenance cost happens between 10 to 14 years with the highest annual maintenance cost reaching $9,355 for each grader.

3.3.3. Optimal Life Cycle Analysis for Graders

The optimal life cycle trends for graders are displayed in Figure 17. The optimal life cycle for graders is 9 years. Compared to sweepers and loaders, the life cycle trend for graders is different. When the service year exceeds the optimal point, the increase rate of total costs is slow. This can be attributed to two reasons. First, the purchase price for a grader is high. Second, the maintenance cost is relatively low compared to sweepers. According to the trend of life cycle curves, we recommend that graders can function for 8 to 11 years.

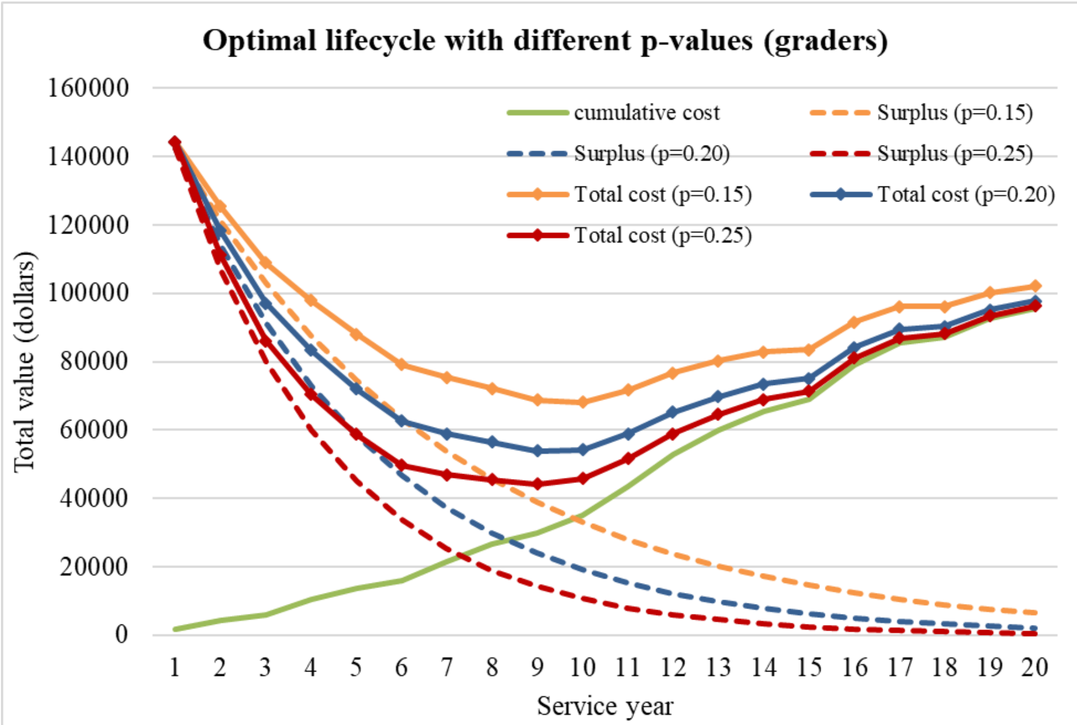

Figure 17 Total Cost Curves for a Grader with Different p Values

4. Conclusion

In this project, we applied a macro-level life cycle analysis for loaders, sweepers, and graders currently managed by UDOT. The analysis is a purely data-driven approach. In other words, the results are obtained from the historical records provided by UDOT. The optimal life cycle decision may shift based on factors such as the number of historical records, data quality, estimation of depreciation cost, and so on. For this reason, we not only calculated the optimal life cycle year for each type of truck, we also provided the appropriate range for replacing trucks under different depreciation estimations. The numerical results indicate that the optimal life cycle varies significantly among different types of trucks due to the different acquisition prices and levels of maintenance cost.

The optimal life cycles for loaders are all 8 years under different depreciation rates. However, we noticed that the total cost of depreciation and maintenance were kept to a low level when the service years range from 7 to 11. Consequently, it is suggested that loaders should function no more than 11 years.

For sweepers, the average purchase price is approximately $100,000, which is close to the price of loaders. However, the annual average maintenance costs for sweepers are much higher than loaders. Based on the historical data, it is found that the low repair cost period only lasts for the 1st and 2nd service years. After the sweepers service three years, annual maintenance cost increases significantly. The optimal life cycle for sweepers is identified as 4 years. We suggest that sweepers be replaced more frequently than loaders, generally between 3 to 6 years.

Lastly, graders have the highest average acquisition prices (approximately $140,000) but a low maintenance cost compared to sweepers. Hence, graders can be serviced longer than sweepers. The optimal life cycle for graders is 9 years, and the suggested replacement cycle is between 8 to 11 years. However, it is noted that there are only 23 graders documented in the historical records. Therefore, the annual maintenance cost estimation might be less convincing than that of sweepers and loaders.

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