EVALUATING MANAGEMENT STRATEGIES THROUGH ECONOMIC MODELING OF HEAVY EQUIPMENT FLEETS

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ABSTRACT: State transportation agencies utilize fleets of heavy equipment to construct and maintain roadways. Equipment cost models can be developed to forecast economic life, which is the point at which the average unit cost to date reaches a minimum. A calculated economic life and cost models can be used to quantify the impacts of management strategies applied to a fleet.

The purpose of this research was to develop an accurate method of quantifying the results of management strategies applied to a fleet of heavy construction equipment. The strategies evaluated are related to the annual usage of the fleet and the size of the fleet. More specifically the methodology is used to adjust the economic model to consider a limit to the annual decline in machine usage and a reduction in the number of machines in the fleet. When limiting annual machine usage, a specified rate is applied to the usage of the fleet, while total usage is held constant. This causes aging at a modified rate. A reduction in fleet size also causes a change to the usage of a fleet as the fleet must use fewer machines to produce the same total usage.

Keywords: Construction Equipment; Heavy Equipment; Fleet Management; Equipment Economics

1. INTRODUCTION

Heavy construction equipment is utilized in almost all divisions of the construction industry today. Areas that are often considered to be equipment intensive can include mining, earth moving, paving operations, and large vertical construction. Departments of transportation (DOTs) make substantial capital investments in heavy equipment for construction and maintenance of state controlled roadways. Therefore, it is imperative that effort be invested into accurately tracking and forecasting equipment costs, as well as making informed and economically sound decisions regarding the management of equipment fleets.

The effective management of construction equipment requires a number of processes that begin when machines are purchased, must be implemented throughout the life of the machine, and continue until the machine leaves the fleet at the conclusion of its economically productive life. These processes include, but are not limited to, purchasing machines at an appropriate price, applying an accurate depreciation method, having an adequate preventative maintenance program, and selling the machines at the most financially beneficial time. The economic life of a machine is the point at which the average unit cost to date reaches a minimum [1]. Estimates of economic life are based on an analysis of historical equipment cost and usage data.

Through the utilization of appropriate fleet historical data, economic models can be developed to represent the average usage and cost of a fleet. Theoretically, the economic model of the fleet can then be applied to a typical machine within the fleet in an attempt to predict the cost and usage a machine will experience at a given age. These two models, along with historical information about the fleet, can then be used to develop a fleet life unit cost model. The unit cost model developed can then be utilized to determine the minimum average life-to-date cost for the fleet of machines.

Several operational strategies can be applied to the economic model of a fleet. This research attempts to quantify the impacts and results of changes caused by applying operational strategies. The operational strategies will include reducing the variability in annual usage over the course of machine life and reducing the number of machines in the fleet, while maintaining a constant level of fleet output. These strategies have the potential to result in changes to the timing and performance of the fleet at economic life.

2. PRIOR RESEARCH

2.1 Equipment Owning and Operating Cost

In general, there are two types of cost associated with equipment, owning and operating costs. Equipment managers may track these cost separately, but ultimately the two costs are combined when a decision is to be made regarding replacement of the machine. Owning costs are costs that will be incurred by the owner as a result of keeping the machine in the fleet, regardless of whether it is used or not. Owning include purchase price, cost of financing, insurance, depreciation cost and a negative cost resulting from residual value.

Operating costs are costs that occur as a result of using the machine to perform work. These costs are largely proportional to the amount of time the equipment is operated. Operating costs will include the cost of repairs, preventive maintenance, wear parts, tires or tracks, and the cost of consumable items i.e. fuel. For contractors in the heavy civil construction industry, the cost of owning and operating equipment is a key part of doing business in a profitable manner [2].

The purchase price of a machine and the resulting capital recovery is a large component of owning cost. After the initial bare price, acquisition value can include everything from sales tax, the cost of extra equipment, the cost of shipping or the cost of assembly [1].

Depreciation is a key element of estimating the owning costs of equipment; it is the difference in value that the machine experiences over its life. Depreciation has commonly been calculated using three different methods: the Straight-Line Depreciation method, the Sum-of-Years'-Digits Depreciation method and the Double-Declining Balance Depreciation method [1].

The residual value of a single piece of construction equipment is one of the most difficult costs to estimate in regards to owning cost of equipment. Although the value of an equipment sell can seem minute when compared to the remainder of owning costs, the residual value can produce a substantial amount of cash inflow upon the sell. Residual value can be defined as 'the price for which a piece of used equipment could be sold in the market at a particular time'. It is the value that remains after losses 'related to the equipment itself or the economic situation have been considered [7].

Consumable costs for equipment are costs for items that are consumed by a machine at a relatively constant rate, regardless of the age of the equipment. Consumables typically include: fuel, oil and grease, tires and tracks, and any ground engaging equipment. The cost of fuel is a chief component of the operating cost of a machine. The elements that make up the cost of fuel include the actual cost per gallon of the fuel itself and the cost of managing the fuel inventory, the cost of dispensing the fuel and the cost associated with maintaining fuel records.

Preventive maintenance costs will include the cost of all parts and labor required for routine maintenance of machinery. These costs include the cost of all oil, grease and filters applied to the machine.

A paramount component of operating costs is the cost associated with repairing a piece of machinery when it breaks down. The subcomponents of repair cost include all tangible parts required for the repair as well as the cost of skilled labor to perform the maintenance. Unlike operating costs as a whole, the costs of repairs are not directly proportional to the amount of hours a machine has accumulated. Machines tend to require repairs due to usage rather than simply passage of time [8].

2.2 Modeling Equipment Cost

Equipment costs have been modeled and estimated using a number of different methods. The cost minimization model [3] develops a total average cost curve from an owning cost curve and an operating cost curve. The developed model is then used to determine the minimum value of average total cost and the time at which the minimum occurs.

The repair limit model [4] utilizes a repair cost curve to track the cumulative cost of repairs and evaluate disposal decisions based on a pre-determined repair limit. The repair limit is the point at which it is economically sound to repair a machine rather than replace. Therefore once a machine surpasses the repair limit it is replaced.

The cumulative cost model [5] develops a cost curve to model all costs associated with equipment. The curve is used to derive the minimum point of the average costs of ownership, which is the optimum economic life.

Kaufmann [6] utilizes linear regression of equipment age versus unit cost to produce a representative cost curve to predict operating cost and use at various machine ages. Cost curves as a function of machine age were developed for six classes of machines. The develop cost curves were analyzed to determine an optimum disposal period for each class.

Mitchell et al. [8] looked at two different methodologies for forecasting equipment repair costs: the life-to-date repair costs model and the period-cost-based model. One methodology requires the use of all repair cost information for the given machine in its lifetime; hence the name life-to-date repair costs. Therefore the life-to-date repair cost model can only be utilized on machine in which the required data has been collected since the time of its purchase. This model is used determine the relationship between the age of a machine and the amount of cost incurred for repairs by the machine.

The period cost based methodology is also used to determine the relationship between age and repair cost for a given machine or given class of machines. The difference between the two methods is that the period cost based methodology can be used on machines that may only have cost data for a given period rather than data for the entire life of the machine.

A process developed by Mitchell [9] attempted to produce equations that could estimate repair costs using collected field data. Data was collected from four separate construction firms that all had differing numbers of machines in their fleets. For this study Mitchel defined an equipment fleet as "a group of machines of the same size and type within the same company". The classes and categories utilized during the study were meant to represent fairly common categories and classes of equipment throughout the industry. One of the constraints of this process was that the data collected for the machines had to include all data from the machines time of purchase to the time of analysis. Mitchell stated that "A mathematical relationship exists between repair costs and age of heavy earth moving equipment [9]." The mathematical relationship described attempted to relate the direct costs of maintenance and repair to cumulative hours of use.

2.3 Determining Economic Life

The two main types of costs accrued by equipment during its lifetime will often follow a parabola shaped cost curve, consisting of an increasing operating cost curve and a decreasing owning cost curve. The owning unit costs of a machine will start high with the purchase price and decrease as the amount left to pay on the machine diminishes. The operating costs for equipment will do just the opposite; operating costs start low when the machine is new and requires little or no repairs and operates at its peak performance and will gradually increase as the machine ages and requires repairs. When attempting to determine the most beneficial time to dispose of a machine, owners and equipment managers will look for the point at which total owning and operating cost required for the machine reaches a minimum. A graphical representation of the three cost curves and the determination of economic life are shown in Figure 1.

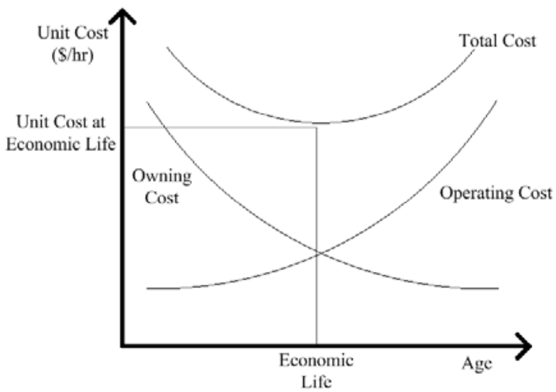

Figure 1: Equipment Costs and Economic Life.

The cost minimization model is an economic model that can be used to graphically track equipment owning and operating costs [7]. The model consists of three different cost curves: average ownership cost, average operating cost and average total cost. Intuitively the first two curves are summed to develop the total cost curve. Although each of these curves is described by different equations, they are all developed from four basic parameters: purchase price, expenditures for the period being analyzed, salvage value and machine age. This model is used to determine the optimum age to dispose of a machine, which is the age at which the average life-to-date total cost reaches a minimum.

The cumulative cost model [5] can be used to determine the optimum disposal point for equipment. The model is developed from cumulative life-to-date costs of equipment. The optimum economic life on the cumulative cost curve is the point when a straight line drawn from the origin is tangent to the curve.

Models developed by Kaufmann [6] attempt to estimate operating cost and use as a function of equipment age. Through the determination of the minimum equivalent uniform annual cost (EUAC), an optimum disposal period can be calculated from cost and usage models.

2.3 Development of the Economic Model

In order to develop economic models of the fleet, various historical data must be obtained. For this application, the necessary historical information included operating usage for one year and the resulting cost for one year of operation. There are two models developed to represent the annual usage and cost of the fleet. The usage model developed was produced by performing a linear regression on the age of the machines in the fleet against the usage each machine experienced at the corresponding age. An example of a developed usage model for a fleet of motor graders is shown below in Figure 2.

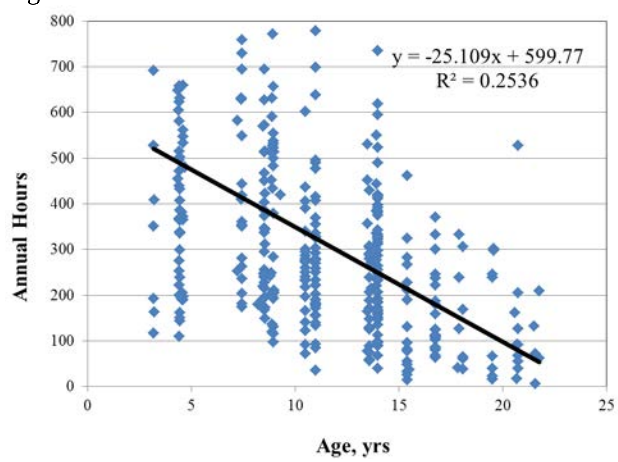

Figure 2: Fleet Usage Model

The model developed to represent the annual usage of the fleet produces a trend line that represents all the data considered. The resulting line is in a linear form and produces the following equation:

$$Y = Ax + B \qquad \text{Eq. 1}$$

Where:

- Y = Average annual usage experience by a machine x years old
- B = Average initial usage of a machine in the fleet
- A = Annual decline in usage for a machine in the fleet
- x = Age of the machine

The cost model developed requires the input of the total annual cost for each machine and the annual usage. A unit cost is calculated for each machine by dividing total annual cost by the annual usage. The result is a cost per unit of work each machine experienced during the observed year of operation. The cost model is developed by performing a regression on machine age against corresponding unit cost. The resulting model is an exponential function representing fleet cost behavior over machine life. An example of a developed unit cost curve is shown below in Figure 3.

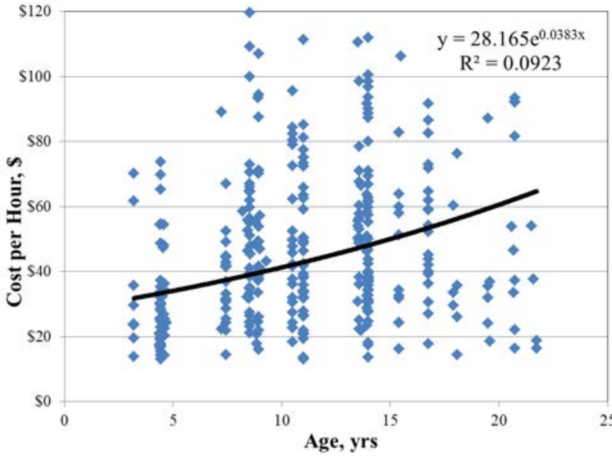

Figure 3: Fleet Unit Cost Model

The equation of the resulting model is shown below in Equation 2.

$$Y = k\,e^{xt} \qquad \text{Eq. 2}$$

Where:

Y = Average operating rate for a machine, x years old
k = Initial operating rate of the machine
x = Annual cost factor
t = Age of the machine

3. RESEARCH METHODOLOGY

This methodology begins after the determination of a sound economic model to represent the fleet. The full model is a result of the usage of the fleet and the behavior of fleet unit cost during one year of production. These two components both have models associated with them that are used to predict the usage and unit cost for various ages of machines.

There are two operational strategies that can be applied to a fleet to alter the usage model. One strategy changes the calculated annual decline in usage measured for the fleet to a specified percentage of initial use, while keeping total output of the fleet constant. This strategy will result in a new initial usage and slope for the usage model. This process requires the calculation of adjusted parameters of a usage model. These parameters include adjusted initial annual use and an adjusted annual decline in usage as a result of the specified slope percentage. The actual formula used to calculate the adjusted initial usage is shown in Equation 3.

$$I = 2T / N\,(2+PR) \qquad \text{Eq. 3}$$

Where:

I = Initial Annual Usage
T = Total Fleet Usage
N = Number of Machine in Fleet
P = Percent Decline in Use
R = Target (Productive) Life

The annual decline in usage resulting from the adjusted initial use is calculated by multiplying the applied percentage decline in usage and the adjusted initial use. This calculation produces the amount, in units of production that the usage of the machines in fleet is decreased each year. A graphical representation of an observed usage model changed to an adjusted usage model can be seen in Figure 4.

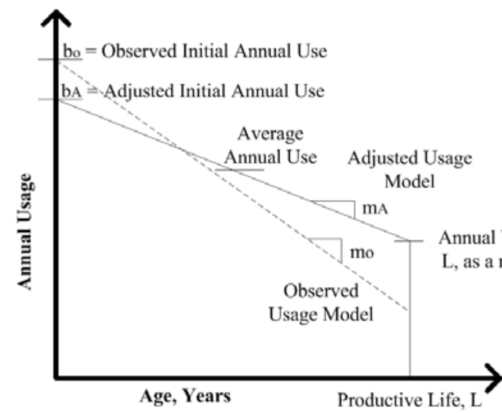

Figure 4: Original and Adjusted Usage Models

Another operational strategy that can be applied to the usage model of fleet entails reducing the amount of machines by which the total fleet usage is applied to. This strategy can be applied with or without the application of the other operational strategy. The process is carried out using the same equations utilized during the other strategy, but with an adjustment made to the number of machines in the fleet. The result of this application is the production of another adjusted usage model. Due to the fact that the same amount of production output must be performed with a lower number of machines, this strategy will always result in higher annual usages for the fleet.

As a result of machines experiencing higher usages, individual machines will acquire more life-to-date usage in a shorter time span. The effect on the fleet can be described as a "modified aging" process due to the fact that, during this strategy, a younger aged machine will experience the same life-to-date usage as an older machine under the measured usage model. A graphical representation of the usage experienced at various fleet reductions is shown in Figure 8.

3.1 Calculating Economic Life of the Fleet

The fleet management strategies will be evaluated by changes in timing and magnitude of the calculated economic life for the fleet. The economic life of a machine is the point at which the average unit cost to date reaches a minimum [1]. Calculating the economic life of a fleet of machines requires the calculation of a life-to-date unit cost model across the life of the machine. The life-to-date unit cost model includes owning and operating costs for a generic machine in the fleet. The operating cost during each year of life is calculated through the use of the developed fleet usage model and operating cost model. The owning cost during each year of life is calculated by an economic analysis of the total owning cost. Each cost associated with equipment is calculated into an equivalent uniform annual cost (EUAC). The EUAC for owning or operating cost is calculated using an annuity equation. Both costs are calculated using different inputs and start from different values.

The owning cost EUAC is calculated based on the purchase price, interest rate, and the market value of the machine during the calculated year. The market value of a machine in the fleet at a given year is determined by use of the sum-of-years digits method of depreciation and a specified deprecation term. The owning cost EUAC requires the calculation of two annuity payments; one for the initial purchase price of the machine and one for the remaining value of the machine. The purchase price annuity payment utilizes the present value of the machine, the specified interest rate and the number of payments to take place. The remaining value annuity payments takes into account the future value of the machine, the specified interest rate, and the number of payments to take place. Therefore the owning EUAC is difference between the annuity payment of the purchase price to the calculation year and the annuity payment of the value of the machine during the calculation year. The two equations utilized for annuity calculations and the combination of the two to determine owning EUAC are shown below.

$$\text{Purchase Price EUAC} = \frac{r\,(PV)}{1-(1+r)^{-n}} \quad \text{Eq. 4}$$

Where:

r = Interest rate
PV = Present value of the machine
n = Number of payments

$$\text{Machine Value EUAC} = \frac{(FV)\,r}{(1+r)^{n}-1} \quad \text{Eq. 5}$$

Where:

r = Interest rate
FV = Future (machine) Value
n = Number of payments

Owning EUAC = Purchase Price EUAC – Machine Value EUAC Eq. 6

In order to calculate the operating cost EUAC, the annual operating cost must first be calculated through utilizing the usage model and operating cost model of the fleet. The operating cost for a given year is calculated by inputting the annual miles into the equation of operating cost model. The equation used to calculate operating cost utilizing the fleet operating rate model is shown below in Equation 7.

$$\text{Op Cost} = U(I^{NA})(1 + INF)^{N} \quad \text{Eq. 7}$$

Where:

Op Cost = Total Annual Operating Cost
U = Total Annual Usage (miles/hours)
I = Initial Operating Unit Cost
N = Age of Machine (years)
A = Annual Cost Factor

The operating cost present value is calculated from the previously determined operating cost. An operating cost EUAC is then calculated for the operating cost present value. This calculation is performed using the same equation as utilized for the EUAC of machine purchase price during the owning EUAC determination, but with different inputs. Instead of the present value being the purchase price, as utilized during the owning EUAC calculation, for operating cost EUAC the value used for present value is the sum of all annual operating costs to date e.g. total life-to-date operating costs. The equation utilized for operating cost EUAC is shown below in Equation 7.

$$\text{Operating Cost EUAC} = \frac{r\,(PV)}{1-(1+r)^{-n}} \quad \text{Eq.8}$$

Where:

r = Interest rate
PV = Present value of life-to-date operating costs
n = Number of payments

Once an EUAC is calculated for each type of costs, the two costs are combined into a life-to-date EUAC. The life-to-date rate is calculated by finding the present value of the life-to-date EUAC and dividing the value by the life-to-date usage acquired by the machine. The final result of this calculation is life-to-date cost per unit of usage in dollars per mile or dollars per hour. The economic life for the fleet of machines being analyzed is year that returns the minimum life-to-date cost per unit of usage.

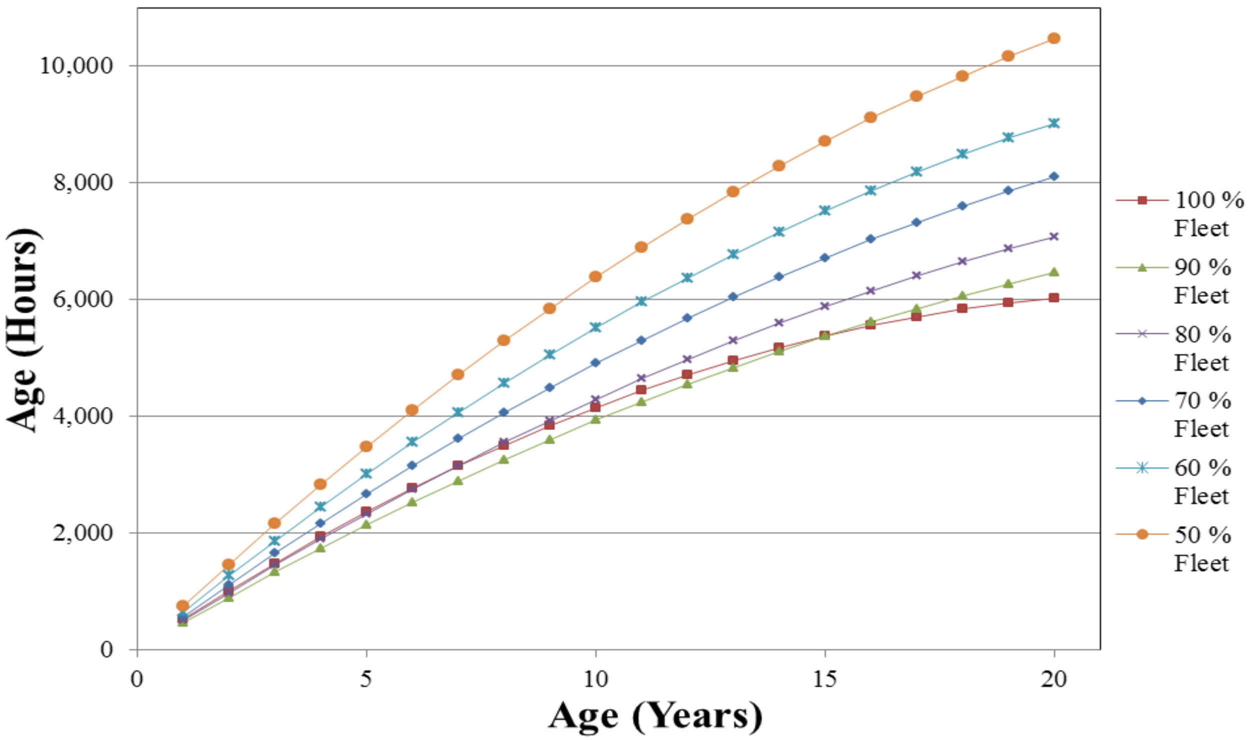

Figure 8: Modified Aging

4. RESULTS

The operational strategies can cause a number of effects to the timing and magnitude of economic life. These changes can be observed by calculating the year at which economic life occurs, the accumulated amount of usage, and the unit cost of the fleet at that point. These values can be compared across various usage reduction percentages to determine which applications cause change. Graphical representations of resulting changes from applying various usage reductions can be seen in Figures 5 thru 8.

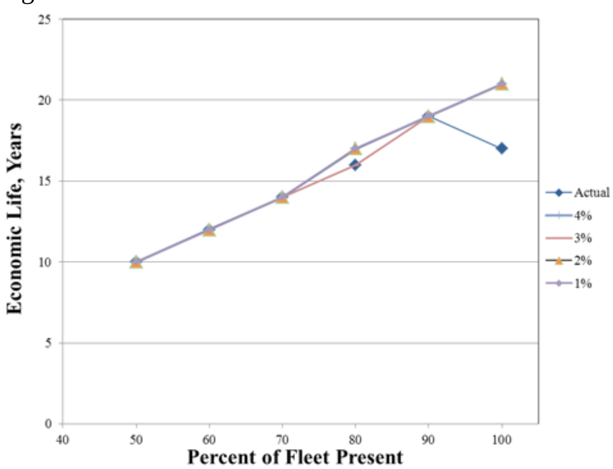

Figure 5: Economic Life across Usage Percentages

As can be seen in Figure 5, variation in the year that economic life occurs is not as much affected by the annual usage decline applied but rather by the reduction in fleet size. With the exception of the calculated economic life at one hundred percent fleet and a variation at eighty percent fleet, the economic life does not change across usage percentages. The variation at one hundred percent fleet is due to the utilization of observed data, rather than modeled data, when calculating economic life. At eighty percent of present fleet, there is one year of variation in economic life from actual fleet usage to modeled fleet usage. A graphical depiction of this is shown in Figure 5. As stated, the annual decline in usage for the fleet does not cause much change in the year at which economic life occurs. However, when applying a reduction in fleet size, considerable changes can be seen at various reductions. As can be seen in Figure 5, the year at which economic life occurs varies from eighteen years at ninety percent fleet to ten years at fifty percent fleet.

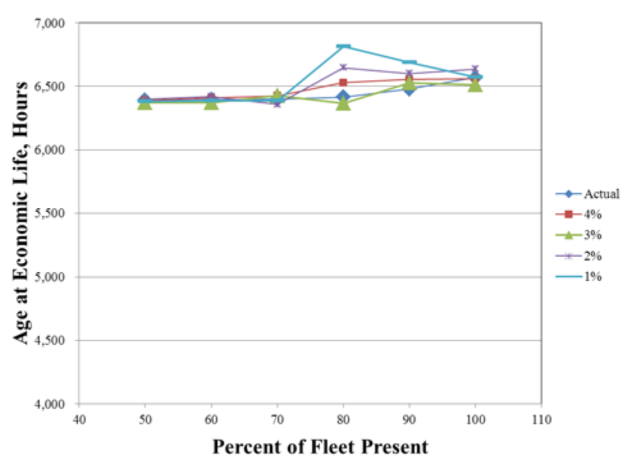

Figure 6: Age (Hours) at Economic Life across Usage Percentages

Due to the fact that total fleet usage is held constant during the application of the various annual usage reductions, the accumulated amount of use at economic will not vary greatly. The largest amount of variation can be observed at an eighty percent fleet reduction and one percent annual decline in usage as shown in Figure 6. The age value at eighty percent is within five hundred hours of the other applied annual usage declines. All other combinations are within one hundred hours, which is less than one year of use.

The age at economic life is the highest while applying a one percent annual decline in usage and operating at eighty percent of the current fleet. The next highest age at economic life occurs when applying a one percent annual decline in usage at ninety percent fleet size. The lowest ages at economic life and the combination of applied strategies are shown in the table below.

Table 1: Lowest Ages at Economic Life and Corresponding Applied Strategies

Age (Hours)	Annual Decline in Usage (%)	Fleet Reduction (%)
6,356	2	70
6,368	3	80
6,370	3	50
6,372	3	60
6,380	1	50

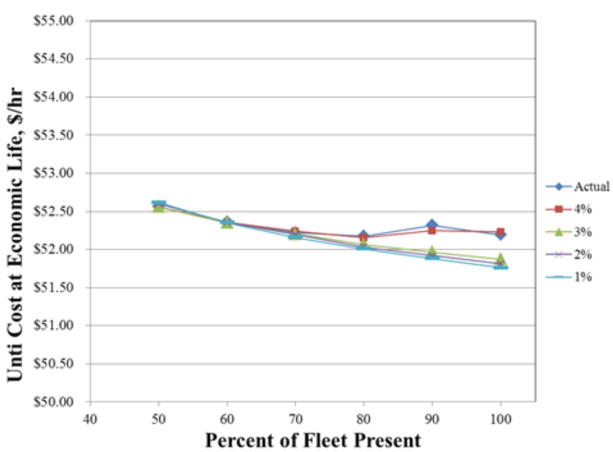

Figure 7: Unit Cost ($/hr) at Economic Life across Usage Percentages

The total average rate calculation for a specified usage reduction and/or fleet reduction is calculated by dividing the present value of life-to-date annual total cost by the life-to-date hours. Therefore changes in the unit cost at a given year are a result of adjusted total operating cost and the adjusted age, in hours, at the determined economic life year. Variations across reduction percentages will be caused by an adjusted usage model and the corresponding total cost. A can be seen in Figure 7, the largest variations are between actual and four percent usage at ninety and one hundred percent of fleet size.

4. Conclusion

The determination of economic life is an important task for equipment managers. For a fleet of machines, economic models can be developed to predict the usage and resulting cost machines of that fleet should experience during a productive lifespan. Fleet economic models can be utilized to determine the year of machine life that it is the most beneficial to be disposed of (economic life). This economic life year has a corresponding accumulated usage, and unit cost.

The application of operational strategies to the economic models of a fleet can result in changes in the characteristics of economic life as well as the manner in which economic life is reached. The resulting changes can be observed through a number of calculations that change usage models and the ages associated with an accumulated use.

The main variations observed across applied operational strategies were seen when applying a reduction in fleet size, rather than a specified annual usage decline.

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