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Green and Economic Fleet Replacement Modeling: Part I

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Green and Economic Fleet Replacement Modeling Part I

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GREEN AND ECONOMIC FLEET REPLACEMENT MODELING

Final Report – Part I

OTREC-RR-11-03

by

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16. Abstract

The purpose of this study was to gain a better understanding of how equipment replacement decisions are supported with data collection and quantitative models at state DOTs, and to determine if models found in the research literature offer any better decision support when applied to realistic fleet usage and cost data. This study also addressed the current state of equipment replacement at state DOTs with respect to using measurable "green" criteria in replacement decisions, and the development of new quantitative replacement models utilizing such criteria.

The responses from 25 state DOTs indicates that there is little consistency in the criteria used by state DOTs to support replacement decisions and the way that these criteria are used. There are also no measurable "green" criteria utilized. However, most state DOTs maintain an information system where cost and usage data is recorded, stored, and utilized as part of the replacement process. To investigate if a particular modeling approach offers better performance than the variety of approaches used in practice, a simulation study was conducted. Simulation models were used to evaluate the effectiveness of replacement models for prioritizing equipment replacement. The models evaluated come from the research literature and were compared to a simple replacement model that is similar to those used by state DOTs. Results indicate that the simple models used in practice provide similar results to the best model from the research literature.

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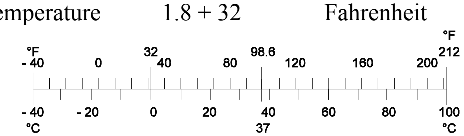
SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	millimeters squared	mm^2
ft^2	square feet	0.093	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometers squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celsius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	Meters	3.28	feet	ft
m	Meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
ha	Hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	Liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
g	Grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8 + 32	Fahrenheit	°F



* SI is the symbol for the International System of Measurement

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DISCLAIMER

GREEN AND ECONOMIC FLEET REPLACEMENT MODELING

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EXECUTIVE SUMMARY

The purpose of this study was to gain a better understanding of how equipment replacement decisions are supported with data collection and quantitative models at state DOTs, and to determine if models found in the research literature offer any better decision support when applied to realistic fleet usage and cost data. This study also addressed the current state of equipment replacement at state DOTs with respect to using measurable "green" criteria in replacement decisions, and the development of new quantitative replacement models utilizing such criteria.

The responses from 25 state DOTs indicates that there is little consistency in the criteria used by state DOTs to support replacement decisions and the way that these criteria are used. The most common criterion utilized is equipment age, followed by usage (mileage or hours). There are also no measurable "green" criteria utilized and no data collected for green criteria (e.g., emissions). Some states utilize "threshold" values for criteria to identify equipment replacement candidates, and some states compute simple measures from various criteria to prioritize equipment replacements. While there is little consistency in replacement criteria and how they are used, most state DOTs maintain an information system where cost and usage data is recorded and stored. This data is used as part of the replacement process if cost and usage are factored into the replacement decisions.

A simulation study was conducted to investigate whether a particular modeling approach offers better performance than the variety of approaches used in practice. Simulation models were used to evaluate the effectiveness of applicable replacement models from the research literature. A simple model similar to those used by state DOTs to prioritize equipment replacement was also evaluated and compared to the more complex models from the literature. The simple model utilized equipment age exceeding a fixed threshold value as a measure of replacement priority. One component of the simulation consisted of a module that simulated equipment usage. Regression models fit (as functions of equipment age and usage) to Oregon DOT data were then used to generate realizations of equipment costs. Different fixed replacement budgets were also included as part of the simulation.

Two different classes of vehicles were simulated (sedans and heavy diesel trucks), and two models from the research literature were evaluated. One model from the literature takes a mathematical optimization approach, and the other model uses an approach that is similar to life-cycle cost analysis. The experimental results show that the simple DOT model and the optimization approach are similar in effectiveness, with the second model from the literature being less effective. These results indicate that the current practice of using simple replacement models will not be significantly improved by adopting a more complex procedure.

1.0 INTRODUCTION

All DOTs maintain large fleets of equipment for the maintenance and upkeep of roads and highways. An important and difficult part of managing such a large amount of equipment is deciding what equipment should be replaced and when. Such decisions have a clearly documented economic impact, and also affect the fleet's ability to provide required equipment when needed. However, interactions with several state DOTs indicate that there may be very little consistency in how DOTs across the nation make replacement decisions. Furthermore, as more DOTs are explicitly considering their environmental impact, it is not known if some DOTs have considered the use of other criteria besides cost, such as greenhouse gas emissions and equipment energy sources, as a basis for making replacement decisions. The research documented in this report focuses on equipment replacement decisions at state DOTs and addresses the current state of practice, improvements to the current state of practice, and future methods for supporting equipment replacement decisions.

This research has three main focus areas:

1. An attempt to gain a better understanding of the state of equipment replacement at DOTs throughout the nation, and to determine if any DOTs are using, or moving towards "green" criteria, as a basis for making replacement decisions.
2. An evaluation of different general categories of replacement models used in practice and found in the literature, when applied to real DOT equipment cost and usage data. The objective of this evaluation is to make recommendations to DOTs with respect to how they use collected data to help make replacement decisions.
3. The development of replacement models specifically for use with greenhouse gas emissions and equipment energy sources as replacement criteria.

A survey of state DOTs was conducted to gain a better understanding of equipment replacement practices at DOTs throughout the country. The objective was to obtain information from at least 25 state DOTs.

The comparative study of the effectiveness of different replacement models included simple prioritization ranking models, optimization methods presented in the research literature, and life-cycle cost analysis. Evaluations were conducted using a simulation model of a multi-equipment class fleet with cost and usage values generated so that they reflect historical cost and usage (Oregon DOT cost and usage data was used).

The research focusing on a model using greenhouse gas emissions and equipment energy sources as replacement criteria will start with a review of existing emissions models and an evaluation of their data needs. Although DOT information systems collect a wide array of vehicle usage data, some emission models require detailed information regarding vehicle speeds, engine temperature range, environmental temperature and engine technology.

1.1 REPORT ORGANIZATION

The three focus areas of this research are related but concentrate on topics providing enough independence that the results of each area will be presented in separate sections. Section 2 will present the results of an extensive survey of state DOTs conducted to gain an understanding of the current state of practice in equipment replacement. Section 3 will present results of applying both “state-of-the-art” equipment replacement models found in the research literature, and models currently used by DOTs to actual DOT cost and usage data..

2.0 REPLACEMENT PRACTICES AT STATE DOTS

The examination of existing replacement methods and green replacement criteria used at DOTs in the United States aimed to obtain information from at least 25 state DOTs. More than 25 DOTs were contacted since not all DOTs responded to requests for information. A request for an interview was sent to DOTs via email. Those states that responded to the email request were contacted via phone to collect more specific information about their current replacement methods and green replacement criteria. A standard list of questions was developed to maintain consistency in the information collection process.

This section begins with a review of the states that were contacted and the process used to collect information. This will be followed by a state-by-state summary of the results from each state that provided information. Next, a summary of the information and conclusions drawn from this information will be presented. The results of the state-by-state summary lead to an examination of how standards or "threshold values" are established. These values are used to identify pieces of equipment that are candidates for replacement.

2.1 STATES CONTACTED

A total of 39 states were contacted and responses were received from 25. Contact was first attempted with fleet managers listed in the directory of the American Association of State Highway and Transportation Officials. If no manager was listed for a state, contact was attempted with a director or assistant director of the department managing the state's equipment fleet.

Contact was first made through email and followed up with telephone calls if no email response was received. For those states responding, phone interviews were scheduled and held.

A list of DOT personnel who provided information and their contact information is provided in Appendix A.

2.2 QUESTION LIST

The following standard list of questions was prepared and asked during each telephone interview:

1. How many pieces of equipment are in your fleet and what is the general composition of equipment type?
2. Is there a specific quantitative criteria used to determine when a piece of equipment needs to be replaced? Examples of such criteria are:
    a. Mileage/Hours
    b. Age
    c. Repair Cost

   d. Operating Cost
   e. Purchase Value
   f. Physical Assessment
3. When multiple pieces of equipment are eligible to be replaced, what methods are used to prioritize replacements?
4. What personnel are involved in determining what equipment is replaced?
5. Is there any automated data collection and processing that is part of the replacement process? Is there a manual data collection and processing?
6. Are there any environmental criteria such as CO2 emissions or other measurable criteria utilized when making replacement decisions?

2.3 SUMMARY OF STATE REPLACEMENT PRACTICES

For each state, information regarding equipment fleet size, criteria used to make replacement decisions, environmental replacement criteria, and information systems used to store and organize data is presented. The states are listed in alphabetical order.

2.3.1 Alaska

Fleet size: Not provided.

Replacement criteria: The light-duty vehicle replacement criterion is age. Light-duty vehicles are usually replaced between seven and 10 years of age, with mileage less than 100,000 and total maintenance costs less than 100 percent of the original purchase value. Vehicles are amortized by their expected useful life. Heavy assets are usually replaced between 10 and 15 years of age, with usage hours less than 10,000 and total maintenance costs less than 100 percent of the original purchase value. As with light-duty vehicles, heavy-duty vehicles are amortized by using historical life data to estimate expected life. When replacing equipment, an assessment is made as to whether or not the unit is still providing adequate service. Questions asked to complete this assessment may include: Does it still support the mission requirements? Is a smaller or larger piece of equipment needed? Should the agency just rent a unit due to low usage?

Environmental replacement criteria: No specific criteria are utilized. However, the tradeoff between the cost of alternative fuel vehicles vs. regular gas/diesel is examined when considering replacement. Alaska is somewhat hampered in that biodiesel, ethanol and compressed natural gas alternatives are not currently available.

Information system: Alaska uses a computerized system to tracks all the assets, maintenance records, billing records, federal fees, etc. It is used to determine what units are considered for replacement during the year. Fleet users are also contacted as part of the process.

2.3.2 Arizona

Fleet size: 4,400 assets.

Replacement criteria: Arizona uses a Code Program Replacement Schedule based on age and usage. Codes change as time elapses.

Environmental replacement criteria: Emissions compliance is the only green-related criteria utilized.

Information system: AssetWorks software tracks all functions related to the maintenance of vehicles and equipment - including repair, preventive maintenance and operating expenses - and offers billing and tracking of vehicle and equipment usage.

2.3.3 California

Fleet size: Not provided.

Replacement criteria: CalTrans uses a model to categorize its fleet into condition classes based on three variables: repair cost, usage and time in service. The first priority criterion is repair cost. The second priority criterion is a combination of repair cost, usage and time in service. Units with the worst rankings have the highest replacement priority.

Environmental replacement criteria: Compliance with air-quality emissions standards. Approximately one-third of the fleet uses alternative fuels.

Information system: Not provided.

2.3.4 Colorado

Fleet size: 7,500 assets.

Replacement criteria: Age and usage are compared to the expected life and expected annual usage. A score is given based on differences greater than the expected age and usage. Equipment with high scores has a higher replacement priority.

Environmental replacement criteria: Colorado's governor has issued two executive orders mandating a reduction in petroleum usage among state agencies. Part of the Colorado DOT's goal in support of this mandate is to acquire flex-fuel powered vehicles and hybrid vehicles. Colorado's DOT uses some biodiesel and E85 in flex-fuel vehicles, and this amount is growing each quarter.

Information system: Colorado downloads listings from a SAP system, loads this data into Excel spreadsheets, and manually manipulates the data. Meter entries are collected manually and entered into the Excel spreadsheet, then the data is re-sequenced for highest meter and age.

2.3.5 Florida

Fleet size: Not provided.

Replacement criteria: Depending on the type of vehicle, Florida uses two replacement models. For cars and light trucks (up to and including one-ton pickup trucks), replacement eligibility is determined by using the Replacement Eligibility Factor (REF) calculation. The REF calculation takes into account the following replacement criteria: age, miles, condition of the vehicle in the last 12 months, days down, and maintenance and acquisition costs. All other vehicle classes must use the standard units (i.e., miles or hours) and age (in months) table (pre-determined age and usage standards).

Environmental replacement criteria: No green criteria for equipment replacement are considered.

Information system: Not provided.

2.3.6 Georgia

Fleet size: Not provided.

Replacement criteria: Georgia uses age and miles as criteria for replacement.

Environmental replacement criteria: No green criteria for equipment replacement are considered.

Information system: Not provided.

2.3.7 Hawaii

Fleet size: Not provided.

Replacement criteria: Hawaii uses time, mileage and repair cost as criteria for replacement. Once a vehicle's repair cost reaches 75 percent or more of the actual acquisition cost, it becomes a candidate for replacement. Light vehicles up to one-ton load capacity have replacement threshold values of 10 years or 100,000 miles.

Environmental replacement criteria: Hawaii complies with federal and state regulations.

Information system: Not provided.

2.3.8 Idaho

Fleet size: 1,400 assets.

Replacement criteria: Idaho uses a model based on age, mileage and repair cost. A threshold for each criterion has been determined from historical data.

Environmental replacement criteria: No green criteria for equipment replacement are considered.

Information system: Developed in-house. The system tracks operational costs and the inventory of equipment.

2.3.9 Indiana

Fleet size: 4,500 assets

Replacement criteria: Indiana uses a life-cycle cost minimization approach. Replacement candidates are selected primarily based on age.

Environmental replacement criteria: Hybrid vehicles are purchased, but no specific criteria are utilized.

Information system: A database is maintained to keep track of inventory, work orders, historical data and maintenance.

2.3.10 Kansas

Fleet size: Not provided.

Replacement criteria: Detailed records for each piece of equipment are kept in a computer system. Equipment is grouped by equipment category code. Initial recommendations for replacement of equipment within each category code are based on age and a usage (i.e., miles or hours) threshold. The final decisions on replacement also consider an evaluation of the actual equipment condition and budget priorities.

Environmental replacement criteria: Only regulatory restrictions are considered.

Information system: Not provided.

2.3.11 Maine

Fleet size: Not provided.

Replacement criteria: Maine uses time and mileage as criteria for replacement. Both criteria should be met in order to consider replacing a piece of equipment. Threshold values are determined from historical data.

Environmental replacement criteria: Fuel economy is considered.

Information system: Not provided.

2.3.12 Minnesota

Fleet size: 3,800 assets.

Replacement criteria: Minnesota uses a model where the equipment is classified by class or type of vehicle. Within a class, the replacement criterion is months in service.

Environmental replacement criteria: Following orders from the governor of Minnesota, alternative fuel vehicles have been acquired, but no specific criteria are used in a model.

Information system: A centralized system maintains records of repairs and costs.

2.3.13 Nebraska

Fleet size: 1,500 assets.

Replacement criteria: Nebraska uses a model based on age, hours in service and mileage. Threshold values used for replacement criteria are based on manufacturer's information.

Environmental replacement criteria: For small vehicles, equipment that employs alternative fuels is considered. For heavy equipment, standard emissions regulations are followed.

Information system: Uses Enterprise Asset Management software to track purchase cost, maintenance, work orders, warranty records, and other data. It was implemented about four years ago.

2.3.14 New Mexico

Fleet size: 6,400 assets.

Replacement criteria: New Mexico uses time in service and mileage as criteria for equipment replacement.

Environmental replacement criteria: Hybrid vehicles are considered, although they are not preferred. Hybrids do not usually work well for the type of maintenance work the state performs. No specific quantitative criteria are considered.

Information system: Not provided.

2.3.15 New York

Fleet size: 8,000 pieces.

Replacement criteria: New York uses a model in which age, downtime and utilization are the criteria used to determine when to replace an asset. Replacement candidates are then reviewed by managers, and there are three possible outcomes: keep the asset one more year (if all criteria are met, but the unit does not have many problems); rent a similar unit (if it is old; has a lot of downtime but has minimum utilization); or replace the asset.

Environmental replacement criteria: 2010 Emissions Standards are adhered to and alternative fuel vehicles, such as biodiesel-fueled vehicles, are considered when replacing.

Information system: Not provided.

2.3.16 North Carolina

Fleet size: 2,600 pieces.

Replacement criteria: North Carolina uses life-cycle cost analysis for determining the equipment with the highest replacement priority. There is also physical inspection of some equipment.

Environmental replacement criteria: Purchases vehicles that utilize biodiesel and ethanol as fuel.

Information system: SAP.

2.3.17 Ohio

Fleet size: 6,000 assets.

Replacement criteria: Ohio conducts asset replacement in cycles. The criteria used to prioritize equipment replacement are age, mileage and cost. If a piece of equipment meets or exceeds set standards for the above criteria, an inspection is performed and a decision to replace is based on the outcome of this inspection.

Environmental replacement criteria: There are no specific environmental criteria utilized. However, the following items are considered when replacements are made: 2010 emissions standards, alternative fuel vehicles, and green-certified dump trucks.

Information system: Not provided.

2.3.18 Oklahoma

Fleet size: 6,000 assets.

Replacement criteria: Oklahoma uses cumulative miles or hours as a measure when prioritizing equipment to replace.

Environmental replacement criteria: Oklahoma considers whether new pickup trucks and cars use ethanol or can be converted to use CNG.

Information system: A mainframe program is used to track equipment usage (miles or hours used).

2.3.19 Oregon

Fleet size: 5,000 assets.

Replacement criteria: Oregon uses age, cumulative miles or hours, and repair costs as criteria for replacement. A model is used that computes a replacement measure based on how much the criteria exceed equipment class-specific threshold values.

Environmental replacement criteria: No specific criteria, but hybrid vehicles and alternative fuel vehicles are considered.

Information system: They use a mainframe program to track equipment usage (miles or hours used), operating costs and repair costs.

2.3.20 Pennsylvania

Fleet size: 9,000 pieces.

Replacement criteria: Pennsylvania uses three criteria for replacing equipment: average age, maintenance cost and hours of use.

Environmental replacement criteria: Alternative fuel vehicles are considered when acquiring replacement equipment. Larger vehicle classes must have 5 percent of the class using biodiesel.

Information system: SAP.

2.3.21 Rhode Island

Fleet size: 1,000 assets.

Replacement criteria: Rhode Island uses a model solely based on age. Their replacement plan is to replace 10 trucks per year, so that by 2014, there are no trucks older than 10 years.

Environmental replacement criteria: No specific criteria other than adhering to 2007 emissions standards.

Information system: Invoice Tracking Software is a program that is used to store and track fleet operation and equipment costs.

2.3.22 Tennessee

Fleet size: 4,500 assets.

Replacement criteria: Tennessee has a list of minimum miles/hours and/or months for each class of equipment that must be exceeded before replacement. Assets are not automatically candidates for replacement when they reach these criteria. Assignment of candidates is at the discretion of the regional maintenance engineer to whom the equipment is assigned.

Environmental replacement criteria: No specific criteria are used other than adhering to federal and state mandates that apply to light-duty vehicles.

Information system: Not provided.

2.3.23 Vermont

Fleet size: 650 assets.

Replacement criteria: Vermont only uses equipment age as a criterion for replacement decisions.

Environmental replacement criteria: Vermont tries to maintain a modern fleet. No particular green criteria are utilized.

Information system: AssetWorks software tracks all functions related to the maintenance of vehicles and equipment - including repair, preventive maintenance and operating expenses - and offers billing and tracking of vehicle and equipment usage.

2.3.24 Virginia

Fleet size: Not provided.

Replacement criteria: The Virginia DOT uses a model based on three replacement criteria: age, miles/hours and maintenance cost. A vehicle becomes a candidate for replacement when at least two of the three criteria exceed established thresholds. Specific values for threshold values are established based on experience.

Environmental replacement criteria: No specific criteria are used. Environmental Protection Agency (EPA) standards and biodiesel-powered vehicles are considered when replacing equipment.

Information system: Not provided.

2.3.25 Wisconsin

Fleet size: Not provided.

Replacement criteria: Wisconsin DOT buys almost no equipment. Unlike other states, WisDOT does not have its own employees performing routine maintenance work, emergency work, pavement marking or signing. Instead, WisDOT contracts with counties to perform these services, and the 72 individual counties employ their own replacement practices.

Environmental replacement criteria: Not specified.

Information system: Not provided.

2.3.26 Wyoming

Fleet size: 3,300 assets.

Replacement criteria: Wyoming uses a model that prioritizes equipment for replacement based on usage, age and repair costs. The most important criterion is usage, followed by age. If the usage threshold has not been met but the unit is fully depreciated and the age is significant, then the vehicle is disposed of. The last criterion is the "problematic" unit. If repair costs exceed the value of the unit and the usage criteria has not been met, the piece is considered for replacement.

Environmental replacement criteria: No specific criteria are used, but they consider hybrid vehicles when purchasing replacements.

Information system: A web-based system that connects with PeopleSoft and Interface is a solution that provides the capability to monitor and maintain assets during their useful life.

2.4 STATE DOT EQUIPMENT REPLACEMENT PRACTICES - SUMMARY AND CONCLUSIONS

The state-by-state summary indicates that there are many different replacement procedures/processes utilized by state DOTs to support replacement decisions. The processes/procedures differ in the replacement criteria considered and how these criteria are utilized. Table 2.1 is a summary of the different replacement criteria considered by different state DOTs. The most utilized replacement criterion is age, followed by usage (typically mileage or hours).

Many states utilize standard values or threshold values to identify candidates for replacement. A number of states compute an overall "replacement measure" that utilizes threshold values (e.g., Oregon, Nebraska and others). Although the replacement measure formulas used were not explicitly communicated, these formulas differ since different criteria are utilized and threshold values utilized by states typically differ.

Other states use values for different criteria directly (i.e., no comparison to a threshold value) to rank equipment for replacement (e.g., California, Oklahoma, Rhode Island and others). Indiana and North Carolina claim to use life-cycle cost analysis.

The most obvious conclusion from the state-by-state summary is that there is little consistency in how different state DOTs support their replacement decisions. The most consistent criterion utilized is equipment age, used by all states that provided information except Wisconsin which does not have a centralized replacement function. Another common practice is the use of standard or threshold values for different criteria.

With respect to green replacement criteria, no state currently uses any specific green criteria such as greenhouse gas emissions. However, multiple states consider the use of hybrid vehicles and alternative equipment energy sources. Multiple states also responded to the use of green criteria by indicating that they explicitly adhere to governmental emissions regulations. Table 2.2 is a summary of state responses to the use of green criteria when making equipment replacement decisions.

Given the inconsistency in how replacement decisions are supported within various state DOTs, Section 3 documents a comparison of different models that have been used to prioritize equipment replacement. The objective will be to determine if one method performs better when applied to realistic fleet usage and cost data. The results may then lead to more consistency in how state DOTs support replacement decisions. The next subsection examines how threshold values are established, which is another area of inconsistency among DOTs and agencies that utilize these values in their replacement processes and procedures.

Table 2.1: Replacement criteria used by state DOTs.

State	Mileage/Hours	Time in Service	Operating Cost	Repair Cost	Usage	Purchase Value	Ability to Provide Service	Days Down	Physical Inspection	Life-cycle Cost Analysis	Threshold Values Used
Alaska	x	x		x		x					
Arizona		x			x						
California		x			x						
Colorado		x			x						x
Florida	x	x		x		x	x	x			x
Georgia	x	x									x
Hawaii	x	x		x							
Idaho	x	x		x							
Indiana		x								x	
Kansas	x	x									x
Maine	x	x									x
Minnesota		x									
Nebraska	x	x									x
New Mexico	x	x									
New York		x			x			x			
North Carolina	x	x	x						x		
Ohio	x	x	x						x		x
Oklahoma	x	x									
Oregon	x	x	x								x
Pennsylvania	x	x		x							
Rhode Island		x									
Tennessee	x	x									
Vermont		x									x
Virginia	x	x		x							x
Wisconsin											
Wyoming	x	x		x							x

Table 2.2: State response to the use of green criteria when making equipment replacement decisions.

State	Hybrid and Alt Fuel Vehicles Considered	Emissions Compliance	Fuel Economy
Alaska	x		
Arizona		x	
California		x	
Colorado	x		
Florida			
Georgia			
Hawaii			
Idaho			
Indiana	x		
Kansas		x	
Maine			x
Minnesota	x		
Nebraska	x	x	
New Mexico	x		
New York	x	x	
North Carolina	x		
Ohio	x	x	
Oklahoma	x		
Oregon	x		
Pennsylvania	x		
Rhode Island		x	
Tennessee		x	
Vermont			
Virginia	x	x	
Wisconsin			
Wyoming	x		

2.5 ESTABLISHING REPLACEMENT CRITERIA STANDARD VALUES (THRESHOLD VALUES)

The survey of state DOTs shows that many states utilize “standard values” or “threshold values” as a means for identifying and prioritizing candidates for equipment replacement. If a piece of equipment exceeds a pre-specified threshold value, it is identified as a candidate for replacement. State DOTs utilize threshold values for different criteria, and these values will also typically differ for the same criteria for different equipment classes. Appendix B shows different threshold values for life and usage used by the Minnesota DOT for different equipment classes.

The classes of equipment shown in Appendix B for the Minnesota DOT have age threshold values that range from five to eight years. The same equipment, which is all categorized as "Light Fleet" by the Oregon DOT, each has an Oregon DOT age threshold value of eight years. It is understandable that differing climatic conditions will lead to different service lives (and thus different threshold values) for vehicles such as sedans and light pickup trucks in Minnesota and Oregon. However, other organizations maintain threshold values for the same types of equipment that may differ substantially from the values used by Minnesota and Oregon. For example, the Federal Highway Administration uses an age threshold of three years and mileage threshold of 60,000 miles for sedans and station wagons (Federal Highway Administration, 2004).

Since threshold values are commonly used and have an impact on equipment replacement decisions, an examination of how standard or threshold values can be quantitatively established was conducted. This examination focused on establishing an age standard since all of the states that provided replacement practice information considered equipment age an important replacement criterion. Also, the age criterion allows for a straightforward consideration of the time value of money. Establishing threshold values for other criteria can follow a similar approach, but the time value of money must be dealt with differently.

One approach to establishing an age standard is to set the age standard to the age that minimizes long-run total costs (acquisition, maintenance, operating costs) for a fleet of the same type of equipment (e.g., sedans). This approach requires acquisition, maintenance and operating cost data over time and is often referred to as life-cycle cost analysis. Life-cycle cost analysis is not new and is actually the single-asset replacement analysis approach described in Terbough (1949) that is included in many engineering economics texts. For establishing an age standard, the "single asset" represents the average vehicle with respect to acquisition, maintenance and operating costs. Wagner (2010) and popular engineering economics textbooks such as Park (2006) contain examples of the analysis.

Wagner (2010) has shown that the life-cycle cost analysis approach is effective for an equipment fleet when the equipment is utilized in a "random" manner. This implies that there is no preference as to which piece of equipment is utilized to complete/support a task. This equipment utilization practice results in equipment of different ages having the same expected annual utilization. However, Wagner (2008), Kriett (2009), and Wagner (2010) have shown that equipment in the Oregon DOT fleet is not utilized equally over time. Their analysis clearly shows that equipment utilization decreases on average as equipment ages. They have explained this to be the result of a "newest first" utilization practice, where newer equipment is utilized (or preferred) more than older equipment. This occurs even if older equipment is equally capable when compared to newer equipment. Other researchers have also noted this phenomenon of decreasing usage as equipment ages (Dietz & Katz, 2001; Redmer, 2005; and Buddhakulsomsiri and Parthanadee, 2006).

Under the "newest first" utilization practice, equipment utlization and equipment replacment decisions are dependent. For example, if five new vehicles are aquired to replace the five oldest vehicles in a fleet, these new vehicles will be the most highly utilized and all other vehicles will realize a decrease in average utilization. Wagner (2010) has shown that under a "newest first" uttilization practice, additional models of the utlization interdependency are required to find the age standard that minimizes long-run total costs. First, a model that provides expected utilization as a function of the number of pieces of equipment of each age is needed. Secondly, a model that provides estimates of equipment costs as a function of equipment utilization is required. Wagner (2010) applies a Markovian queuing model to estimate equipment utilization, and a regression model (fit to Oregon DOT data) that predicts equipment costs as a function of equipment utilization. Wagner (2010) demonstrates through an example that ignoring the impact of the age standard on equipment utilization and costs results in an age standard that is too large.

The results in Wagner (2010) imply that quantitatively establishing age standards for state DOTs that precisely account for "newest first" utilization practices may be inaccessible since the utilization and cost-prediction models may not be available. However, if a model for costs as a function of utilization (a regression model) can be developed, it may be possible to assume a random utilization practice and apply the life-cycle cost analysis approach. Preliminary evidence indicates that the resulting age standards may be close enough to use either in practice. However, this is a topic that will require additional research.

3.0 EVALUATION OF EQUIPMENT REPLACEMENT PROCEDURES

The ability of several equipment replacement procedures to minimize total fleet-wide cost was compared using a simulation based on actual Oregon DOT (ODOT) data. An overview of the simulation structure is shown in Figure 3.1.

The simulation is presented in the context of a fleet of vehicles, but is applicable to other types of equipment. The simulation generates requests for vehicles and the newest available vehicle in the fleet is assigned to each request. Each simulation run uses one replacement procedure to control fleet replacement decisions. The fleet portion of the simulation tracks data on each vehicle in the virtual fleet, including age, annual usage (mileage), and lifetime usage for each vehicle.

A regression model based on actual ODOT cost data is then used to transform the vehicle usage data into estimated operating and maintenance (O&M) costs. Replacement procedures were compared based on annual equivalent cost (AEC) of operating the virtual fleet over a period of 100 years.

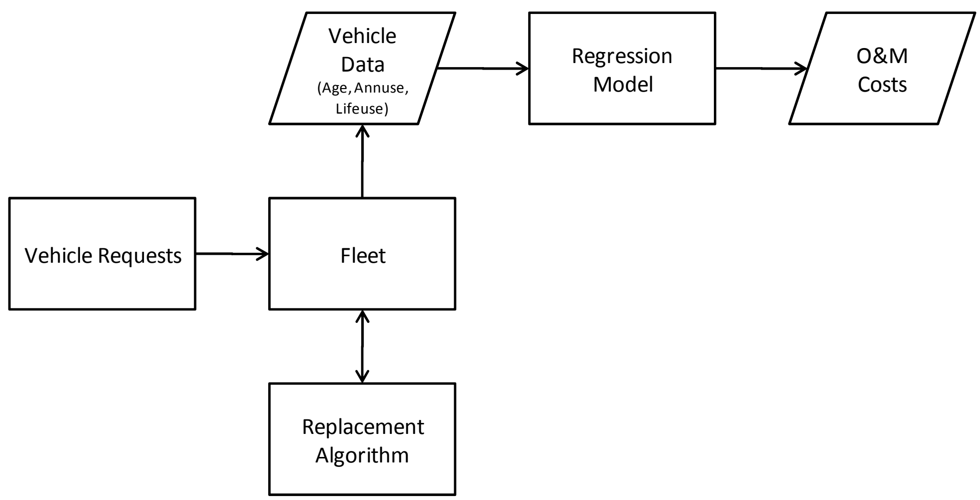

Figure 3.1: Structure of the simulation to evaluate procedures supporting replacement decisions.

This section will begin with a review of the replacement model literature and the models selected for evaluation. A description of the comparison methodology and its components is presented next. The main components of the methodology, which include the fleet simulation, replacement procedure implementation, and the regression model for costs, are each described. The experimental design and results are presented, followed by conclusions for this part of the project.

3.1 REVIEW OF REPLACEMENT PROCEDURES

Nine replacement procedures from the literature were reviewed for potential inclusion in the experiment. Procedures described by Dietz and Katz (2001) and Hartman (2000) met the following criteria for inclusion:

- Ability to evaluate decisions on a fleet-wide basis (i.e., not solely on an individual-vehicle basis)
- Ability to determine replacement decisions within a reasonable period of time (i.e., less than one hour)

An age standard replacement procedure was also included for comparison (Kriett, 2009). This procedure identifies vehicles that are above a certain threshold value as candidates for replacement, and proceeds to replace as many candidates as permitted by a fixed budget. This procedure was included to represent the simple replacement measure models used at a number of state DOTs (see section 2.2). Table 3.1 summarizes the nine replacement methodologies from the research literature that was considered.

Table 3.1: Summary of replacement procedure features.

Replacement Procedure	Capital Budget Ability	Multi-vehicle Ability	Multi-class Ability	Solution Method	Incorporation of Vehicle Utilization	Comments
Bellman 1955	No	No	No	Dynamic programming	Static	**No multi-vehicle ability.** Classic dynamic programming approach.
Waddell 1983	No	No	No	Dynamic programming	Indirect/static	**No multi-vehicle ability.** Similar to Bellman 1955.
Jones et al. 1991	No	Yes	No	Dynamic programming solved as LP	Indirect/static	**Multi-vehicle ability is based solely on fixed charge.**
Karabakal et al. 1994	Yes	Yes	Yes	Binary integer programming	Indirect/static	**Too computationally intense.**
Hartman 2000	Yes	Yes	No	Binary integer programming (small number of binary variables)	Indirect/static	Optional fixed charge.
Dietz & Katz 2001	Yes	Yes	Yes	Score (based on age and estimated maintenance) and rank	Static	
Hartman 2001	No	No	No	Stochastic dynamic programming	Probabilistic, discrete increments	**No multi-vehicle ability.**
Hartman 2004	No	Yes	No	Dynamic programming	Decision variable, discrete increments	**Too computationally intense.** Uses probabilistic demand. Optional fixed charge.
Keles & Hartman 2004	Yes	Yes	No	Integer programming	Indirect/static	**Similar to Hartman 2000.** Mostly sensitivity analysis.

Bellman (1955) describes a classic approach employing dynamic programming, but only evaluates replacement decisions for one asset at a time. Waddell (1983) uses a similar dynamic programming approach and also does not consider the operation of multiple assets simultaneously.

Jones et al. (1991) do consider multiple assets, but only in the context of a fixed charge. A fixed charge may represent time spent completing paperwork or requesting bids, or delivery fees or other work, that is required regardless of how many new assets are purchased in a time period. It is one way to introduce interdependence of replacement decisions within a fleet – without any interdependence, replacement decisions for each asset can be solved as separate problems. However, the replacement procedure described by Jones et al. (1991) was not suitable for inclusion because the investigation was focused on interdependence introduced by capital constraints on asset utilization.

The binary integer programming approach of Karabakal et al. (1994) proved to be too computationally intense to include, as was the dynamic programming approach of Hartman (2004), which included asset utilization as a discrete decision variable. On the other hand, the binary integer approach of Hartman (2000) could be solved in a reasonable amount of time due to the relatively small number of binary variables. The inclusion of capital constraints ensured that the optional fixed charge in this model was not the only source of interdependence, so the model was selected for inclusion. Asset utilization (an important factor that is observed to vary with age in ODOT data) is not directly incorporated into the model. However, asset utilization by age can be indirectly incorporated into the model since cost inputs are specified with respect to asset age. The procedure of Hartman (2001) was not included because the model only analyzes one asset at a time. The model described by Keles and Hartman (2004) was excluded due to strong similarity to the Hartman (2000) approach.

The replacement procedure of Dietz and Katz (2001) was also selected for inclusion, since the scoring and ranking method used in the model was also well-suited to the interdependence introduced by capital constraints. This model specifically incorporates asset utilization as a function of age into the scoring procedure. Per-mile costs are calculated based on past vehicle performance and these costs, along with a vehicles' per-mile costs to date, are used to score and rank vehicles for replacement.

3.2 COMPARISON METHODOLOGY

An overview of the simulation structure for comparing different replacement methodologies is shown in Figure 3.1

The major components include the core fleet simulation, replacement procedure implementations, and regression cost model. Each of these components will be described. The methodology was applied to two different fleets of equipment: sedans and heavy diesel trucks.

3.2.1 Fleet Simulation Component

The discrete event fleet simulation was programmed in Python as an extension of the fleet simulation in Wagner (2008). Simulation parameters were pulled from a Microsoft Access database. The core functionality of the simulation is based upon maintaining an event list with vehicle-request, year-end, and simulation-end events.

3.2.1.1 Vehicle-Request Events

Vehicle requests arrive in the form of arrival events. Requests have exponentially distributed inter-arrival times with the mean rate of arrival specified as a parameter. There is no request queue; if all vehicles are busy and a new request arrives, the request is rejected. Parameters were selected to maintain rejections at a level of approximately 5 percent. Upon arrival, a request is assigned to the newest available vehicle (ties are broken randomly).

After a request is assigned a vehicle, a corresponding service-completion event is added to the event queue. Vehicles assigned to requests have exponentially distributed service times with the mean service rate specified as a parameter. Upon occurrence of a service-completion event, the relevant vehicle is again made available for use. Service-completion events for vehicles that have since been retired are ignored (any active request is terminated when the vehicle is retired).

3.2.1.2 Year-End Event

For each non-retired vehicle, annual and lifetime usage are recorded at each year-end event. Operating costs are calculated using the regression cost model and are recorded as well. The specified replacement procedure is then run for the fleet as a whole, and another year-end event is added for the following year.

3.2.1.3 Simulation-End Event

A simulation-end event is used to mark the end of the simulation. The occurrence of this type of event clears any events remaining in the queue. Throughout the simulation, vehicle data (age, annual usage and lifetime usage) are tracked. At simulation end, data are recorded back to the Microsoft Access database for further analysis.

3.2.2 Replacement Procedure Component

Nine replacement procedures from the literature were evaluated for the potential to be included in the comparison. Seven of these procedures were ruled out for a variety of reasons described above in more detail (e.g., no multivehicle ability, fixed charge was only source of interdependence, or too computationally intense to be practical).

The three approaches selected for comparison were the age standard model (see section 3.1), the approach developed by Hartman (2000), and the Dietz and Katz (2001) procedure.

3.2.2.1 Hartman (2000) Procedure

The Hartman (2000) procedure is a binary integer programming optimization model where the decision variables at the end of each year are the number of new vehicles to purchase, the specific vehicles to keep in service, and the specific vehicles to store or retire. The linear programming relaxation for the integer programming formulation in equations (1) – (10) was shown to have integer extreme points if the economies of scale binary variables (Z_j) are fixed (Hartman, 2000). The result of this is a more reasonable computation time. Decision variables are summarized in Table 3.2.

Table 3.2: Decision variables in the Hartman (2000) model.

Decision Variable	Value
B_j	Number of new assets purchased at the end of period j
Z_j	1 if a purchase is made in period j, else 0
X_{ij}	Number of i-period old assets in use from the end of period j to j +1
Y_{ij}	Number of i-period old assets in storage from the end of period j to j +1
S_{ij}	Number of i-period old assets salvaged at the end of period j

$$\min_{B,X,Y,S,Z} \sum_{j=0}^{T-1} \delta^j (p_j B_j + k_j Z_j) + \sum_{i=0}^{N-1}\sum_{j=0}^{T-1} \delta^{j+1} c_{ij} X_{ij} + \sum_{i=0}^{N-2}\sum_{j=0}^{T-2} \delta^{j+1} c'_{ij} Y_{ij} - \sum_{i=1}^{N}\sum_{j=0}^{T} \delta^j r_{ij} S_{ij} \quad (1)$$

subject to

$$\sum_{i=0}^{N-1} X_{ij} \geq d_j \quad \forall\, j\ \{0,1,\dots,T-1\} \quad (2)$$

$$B_j - X_{ij} - Y_{ij} = 0 \quad \forall\, j\ \{0,1,\dots,T-1\}, i = 0 \quad (3)$$

$$-X_{ij} - Y_{ij} - S_{ij} = -H_i \quad \forall\, i\ \{1,2,\dots,N\}, j = 0 \quad (4)$$

$$X_{(i-1)(j-1)} + Y_{(i-1)(j-1)} - X_{ij} - Y_{ij} - S_{ij} = 0 \ \ \forall\, i\ \{1,2,\dots,N\}, j \in \{1,2,\dots,T\} \quad (5)$$

$$B_j \leq \left\lfloor \frac{c_j - k_j}{p_j} \right\rfloor Z_j \quad \forall\, j\ \in \{0,1,\dots,T-1\} \quad (6)$$

$$X_{ij} \equiv 0 \quad \forall\, i, j = T \text{ and } \forall\, j, i = N \quad (7)$$

$$Y_{ij} \equiv 0 \quad \forall\, i, j = T-1, T \text{ and } \forall\, j, i = N-1, N \quad (8)$$

$$B_j, X_{ij}, Y_{ij}, S_{ij} \in \{0,1,2,\cdots\} \quad (9)$$

$$Z_j \in \{0,1\} \quad (10)$$

The linear programming relaxation for the integer programming formulation in equations (1) – (10) was shown to have integer extreme points if the economies of scale binary variables (Z_j) are fixed (Hartman, 2000). The result of this is a more reasonable computation time. However, several of the conditions of the simulation allow for further simplification of the Hartman (2000) model, resulting in the modified model of equations (11) – (18). The simulation does not include a fixed charge (k_j), so the fixed charge decision variables (Z_j) were removed. Neither is vehicle storage an option in the simulation, so those variables (Y_{ij}) and parameters (c'_{ij}) were also removed. The simulation assumes salvage values (r_{ij}) of zero, so the salvage component of the objective function was removed. Finally, several of the parameters were simplified. The parameter c_i is used to refer to age-dependent annual O&M cost instead of c_{ij} (which would also be dependent on simulation year). The capital constraint notation was simplified to use parameter b as the maximum number of vehicles that can be replaced in any year, and demand (number of vehicles in the fleet) is assumed to be constant from year to year with a value according to parameter d. The parameters are summarized in Table 3.3.

$$\min_{B,X,Y,S,Z} \sum_{j=0}^{T-1} \delta^j p_j B_j + \sum_{i=0}^{N-1} \sum_{j=0}^{T-1} \delta^{j+1} c_i X_{ij} \tag{11}$$

subject to

$$\sum_{i=0}^{N-1} X_{ij} \geq d \quad \forall\, j\, \{0,1,\dots,T-1\} \tag{12}$$

$$B_j - X_{ij} = 0 \quad \forall\, j\, \{0,1,\dots,T-1\}, i = 0 \tag{13}$$

$$-X_{ij} - S_{ij} = -H_i \quad \forall\, i\, \{1,2,\dots,N\}, j = 0 \tag{14}$$

$$X_{(i-1)(j-1)} - X_{ij} - S_{ij} = 0 \quad \forall\, i\, \{1,2,\dots,N\}, j \in \{1,2,\dots,T\} \tag{15}$$

$$B_j \leq b \quad \forall\, j\, \in \{0,1,\dots,T-1\} \tag{16}$$

$$X_{ij} \equiv 0 \quad \forall\, i, j = T \text{ and } \forall\, j, i = N \tag{17}$$

$$B_j, X_{ij}, S_{ij} \in \{0,1,2,\cdots\} \tag{18}$$

Table 3.3: Parameters for the simplified Hartman (2000) model.

Parameter	Value
p_j	Per-unit cost for a new asset purchased at the end of period *j*
c_i	O&M cost for an *i*-period old asset in use for one period
H_i	Number of *i*-period old assets available at time zero
d	Number of assets demanded in each period
b	Capital budget limit (maximum vehicles purchased per period)
δ^j	Discount factor for period *j*

Before the simulation is run with the Hartman (2000) replacement procedure, the modified model is formulated using PyMathProg/GLPK (a mathematical programming solver routine in Python) using parameters from the database. O&M cost parameters were determined by fitting a simplified regression cost model where age is the only independent variable, since that is all that is allowed by the Hartman (2000) model (see section 3.2.3). A logarithm transformation was applied to ensure equal variance. Table 3.4 gives the formula for the median O&M cost for a vehicle, given its age and class.

Table 3.4. O&M cost models used with the Hartman (2000) model.

Vehicle Class	O&M Median Cost Formula
Sedan	$Median\ Cost = e^{-0.02991101*age+7.534281518}$
Heavy Diesel Truck	$Median\ Cost = e^{-0.046115396*age+9.940155695}$

The model is solved using PyMathProg/GLPK after formulation, and the resulting replacement decisions are stored. The simulation then uses the stored results to change the composition of the fleet of vehicles. The model is solved once every replacement cycle.

3.2.2.2 Dietz and Katz (2001) Procedure

In the Dietz and Katz (2001) model, assets in the fleet are prioritized for replacement according to their replacement score (z_k for asset k). Higher scores indicate greater potential savings from replacement. Values for z_k are calculated according to equation (19). The four key parameters of this equation are described Table 3.5.

$$z_k = \frac{100m * v_k}{R_k} \tag{19}$$

Table 3.5. Definition of parameters in equation 19.

Component	Description	Determination of value in simulation
m	Average annual mileage for a vehicle (sedan or heavy diesel)	Usage demand parameters
v_k	Value of replacing the asset ($/mile)	Discussed below
R_k	Replacement cost of the asset	Replacement cost parameter

To calculate v_k, a cost-per-mile value (r_{ik}) is calculated for each replacement age i according to equation(20) (additional notation is defined in Table 3.6).

$$r_{ik} = \frac{\sum_{j=1}^{i} \mu_j (1-\Delta)^j + R_k}{m_j} \tag{20}$$

Table 3.6. Definition of notation in equation 20.

Component	Description	Determination of value in simulation
Δ	Annual discount rate	Discount rate parameter
μ_j	Average annual maintenance cost for a j-year-old asset in asset k's asset group (sedan or heavy diesel)	Dietz and Katz (2001) fit a quadratic regression model (with age as the independent variable) and impose a non-decreasing requirement. Regression coefficients for the simulation are calculated based on the same ODOT historical data that were used to build the regression model used to assign costs in the simulation.
s_{ik}	Salvage value of asset k at age i	Salvage value parameter
m_j	Average annual mileage for a j-year-old asset in asset k's asset group (sedan or heavy diesel)	Dietz and Katz (2001) fit a quadratic regression model (with age as the independent variable) and impose a non-decreasing requirement. The intercept parameter is also assumed to be zero. Regression coefficients for the simulation are calculated based on the same ODOT historical data that were used to build the regression model used to assign costs in the simulation.

Equation (20) is equivalent to dividing the net present value (NPV) of an asset replaced at age i by the estimated cumulative mileage at that age. The Dietz and Katz (2001) model includes tax effects nd downtime opportunity costs. Neither of these is incorporated into the simulation. Downtime is assumed to be reflected in maintenance costs. Equation (20) represents a simplification after removing tax effects and downtime costs, which were modeled by Dietz and Katz (2001).

Once r_{ik} has been calculated for each replacement age i, the minimum per-mile cost for asset k (r_k^*) is assumed to indicate asset k's optimal replacement age (i_k^*). The value of replacing the asset is then calculated according to equation (21), where j is the current age of asset k.

$$v_k = \begin{cases} r_{jk} - r_k^* & j > i_k^* \\ 0 & \text{otherwise} \end{cases} \tag{21}$$

In the simulation, the fleet operates under capital constraints. Replacements are selected one at a time, from highest replacement score (z_k) to lowest, until the capital budget has been exhausted. At that point, no further replacements are made until the next replacement cycle. An asset's replacement score must be positive for the asset to be replaced. There is an exception for assets that have reached the maximum replacement age limit – these assets will be replaced regardless of replacement score and whether the budget constraint is violated.

Two vehicle classes are considered (one at a time) in the simulation: sedans and heavy diesel trucks. A maximum replacement age of 30 years is assumed for both vehicle classes.

Dietz and Katz (2001) find m_j according to equation (22) and μ_j according to equation (23).

$$m_j = \begin{cases} \beta_2^m + \beta_1^m & j = 1 \\ \max(\beta_2^m j^2 + \beta_1^m j, m_{j-1}) & j > 1 \end{cases} \tag{22}$$

$$\mu_j = \begin{cases} \beta_2^\mu + \beta_1^\mu + \beta_0^\mu & j = 1 \\ \max(\beta_2^\mu j^2 + \beta_1^\mu j + \beta_0^\mu, \mu_j) & j > 1 \end{cases} \tag{23}$$

Values for these parameters were found by fitting least-squares quadratic coefficients to ODOT historical data. Results are shown in Table 3.7

Table 3.7. Parameters for the Dietz and Katz (2001) model estimated from ODOT data.

Parameter	Sedans	Heavy Diesel Trucks
β_1^m	17009	17209
β_2^m	-747.28	-119.01
β_0^μ	1729.3	23240
β_1^μ	108.95	875.11
β_2^μ	-14.519	10.986

Note that the positive value β_2^μ for heavy diesel trucks results in a μ_j value of $22,375.88 at all ages.

3.2.3 Regression Model Component for Operating and Maintenance Costs

The fleet simulation component generates realizations of vehicle usage over time (years) as a function of demand and the priority that a vehicle is assigned to incoming requests (newer vehicles having higher priority). The regression model component is a model that generates operating and maintenance cost realizations for a vehicle as a function of its age and usage. In the simulation, a random term is added to the expected cost calculated from the regression models that reflects the variability observed in the data.

Two types of O&M costs were separately analyzed: operating costs and repair costs. Operating costs exclude repairs but include fuel, motor oil, etc. Fixed costs, such as insurance, are not included in the regression model. Both operating and repair costs are added together to give a total O&M cost for a vehicle for each year of operation. All costs were adjusted to 2008 dollars using appropriate price indices.

Data were obtained from reports generated by internal ODOT database systems. Regression models were fit to cost data for two of ODOT's largest vehicle classes: sedans and heavy diesel trucks. Table 3.8 defines the independent variables in the regression models.

Table 3.8. Independent variables in the regression models for operating and repair costs.

Variable	Units	Description
Vehicle class	n/a	Sedan or heavy diesel truck (indicator variable)
Life usage	miles	Odometer reading at end of year
Annual usage	miles	Difference between odometer reading at end of year and odometer reading at end of previous year
Age	years	Age of the vehicle

3.2.3.1 Operating Costs

Plotting the residuals (Figure 3.2) or a regression model including all explanatory variables demonstrated that the data violated the assumption of equal variance. All variables except for the vehicle-class indicator variable were then logarithm-transformed (log-transformed), and the residual plot for the transformed reduced model is shown in Figure 3.3.
The life-usage explanatory variable and vehicle-class indicator variable interactions were removed, resulting in a model with slightly less predictive value (p-value = 0.04146 for an extra sum of squares F-test) but also a more useful model.
The model from the 2006 data was then taken and applied to similar data from 2005 for validation. A plot of the residuals for the original model, as well as for the validation data, does not reveal any significant differences (Figure 3.4). Residuals for the validation data set were also plotted against the other explanatory variables included in the model (Figure 5). This did not reveal any unusual trends.

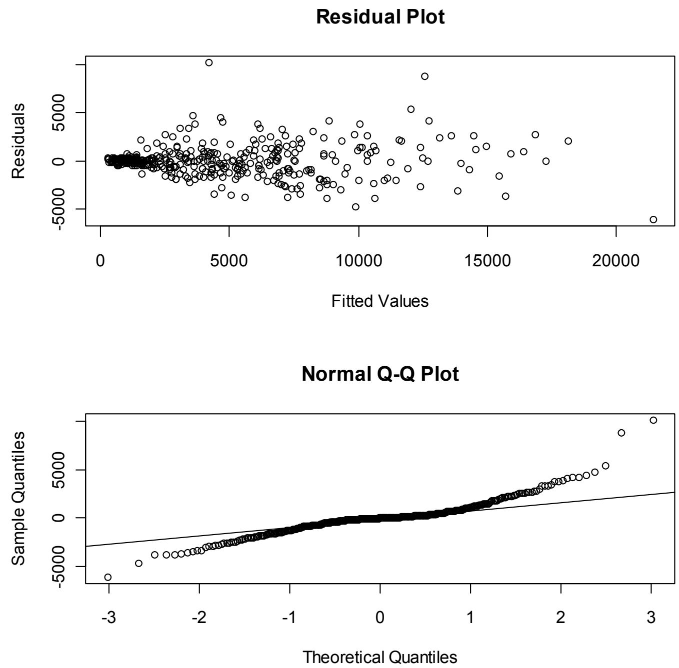

Figure 3.2 Residual and Q-Q plots of the operating cost model with all independent variables before data transformation.

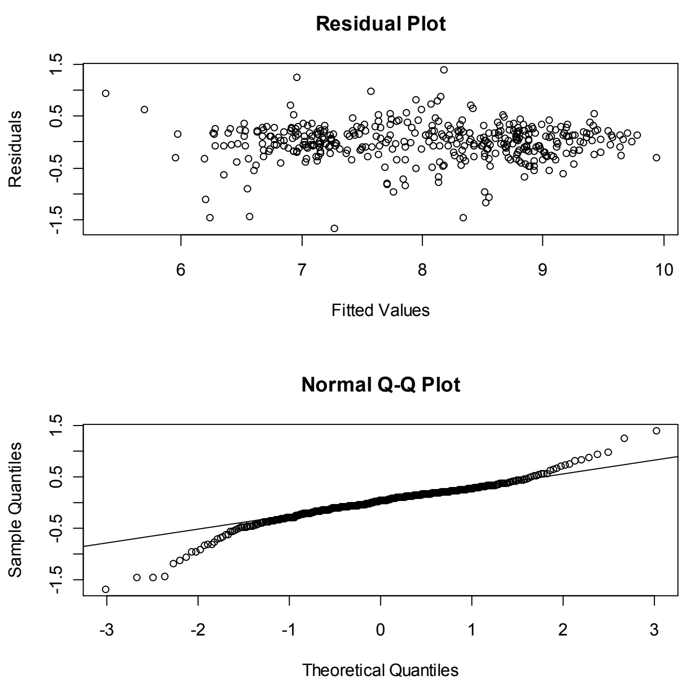

Figure 3.3 Residual and Q-Q plots of the operating cost model with all independent variables after the logarithmic transformation.

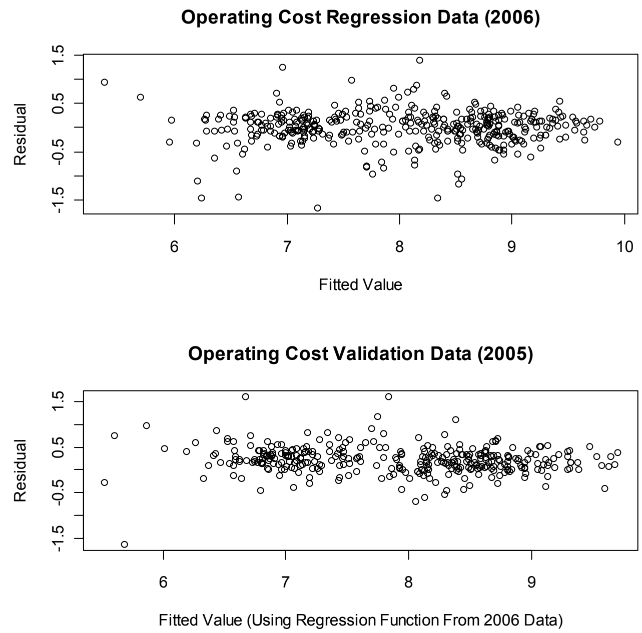

Figure 3.4 Operating cost residual plots for 2006 data (from the regression) and from 2005 data (after using the regression to predict costs).

Vehicle class (sedanind), age, and annual usage (annuse) explain 87.3 percent of the variation in the annual operating cost for an ODOT sedan or heavy diesel truck. Given values for these variables, the median operating cost for a vehicle in a particular year can be predicted using regression equation (24). Appendix C shows the statistical software output for the regression.

$$Expected\ Operating\ Cost = 2.77 \cdot 0.185^{sedanind} \cdot age^{-0.0893} \cdot annuse^{0.833} \tag{24}$$

3.2.3.2 Repair Costs

Analysis of the repair cost data also revealed the need for a log-transformation of the data. Inspection of the residual and Q-Q plots after transformation did not reveal any further issues. Age and vehicle-class annual usage interaction terms were removed from the model to improve usefulness (p-value = 0.04474 for an extra sum of squares F-test). The same residual comparisons as for operating costs were made using the 2006 regression data set and 2005 validation data set (Figure 5).

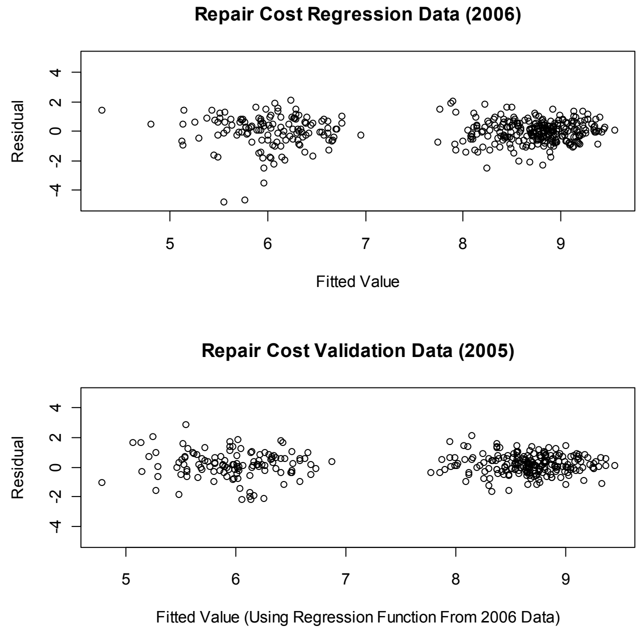

Figure 3.5 Repair cost residual plots for 2006 data (from the regression) and from 2005 data (after using the regression to predict costs).

Vehicle class (sedanind), annual usage (annuse), and lifetime usage (lifeuse) explain 70.3 percent of the variation in the annual repair cost for an ODOT sedan or heavy diesel truck. The median repair cost for a vehicle in a particular year can be predicted using equation (25). Appendix C shows the statistical software output for the regression.

$$Expected\ Repair\ Cost = 17.4 \cdot 0.000446^{\,sedanind} \cdot annuse^{0.497} \cdot lifeuse^{0.107+0.467 \cdot sedanind} \tag{25}$$

3.3 EXPERIMENTAL DESIGN

An experiment was designed to compare replacement methodologies. The experiment is a full factorial experiment with three fixed factors: replacement method, replacement budget and fleet composition (sedans or heavy diesel).

Simulation replications were run using either a fleet of sedans or a fleet of heavy diesel trucks. Four capital budget constraint levels were evaluated for each fleet. These budget constraint levels were equivalent to replacing a maximum of four, two, three and one vehicles per year, respectively. At each budget level, the Dietz and Katz (2001) replacement procedure, Hartman (2000) replacement procedure, and all feasible age standards were evaluated.

Details of the initial makeup of the sedan fleets are included in Table 3.9 details for the heavy diesel fleets are included in Table 3.10. Initial mileage was generated from simulations using a 30-year vehicle replacement age, but the impact of initial mileage was minimal since each simulation replication was run for 100 years. All fleets consisted of 20 vehicles. An interest rate of 10 percent was used for time-value-of-money calculations.

Table 3.9. Initial composition of sedan fleets.

	Capital Budget Level							
	4		3		2		1	
Vehicle	Age	Mileage	Age	Mileage	Age	Mileage	Age	Mileage
1	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	1	15,396
3	0	0	0	0	1	15,236	2	30,623
4	0	0	1	15,160	1	15,236	3	45,806
5	1	15,102	1	15,160	2	30,286	4	60,830
6	1	15,102	1	15,160	2	30,286	5	75,640
7	1	15,102	2	29,996	3	45,119	6	90,388
8	1	15,102	2	29,996	3	45,119	7	105,018
9	2	29,593	2	29,996	4	59,566	8	119,316
10	2	29,593	3	44,385	4	59,566	9	133,569
11	2	29,593	3	44,385	5	73,684	10	147,509
12	2	29,593	3	44,385	5	73,684	11	161,239
13	3	43,104	4	58,081	6	87,093	12	174,571
14	3	43,104	4	58,081	6	87,093	13	187,546
15	3	43,104	4	58,081	7	99,979	14	200,259
16	3	43,104	5	70,864	7	99,979	15	212,602
17	4	55,601	5	70,864	8	112,200	16	224,779
18	4	55,601	5	70,864	8	112,200	17	236,589
19	4	55,601	6	82,950	9	124,105	18	248,197
20	4	55,601	6	82,950	9	124,105	19	259,454

Table 3.10. Initial composition of heavy diesel fleets.

	Capital Budget Level							
	4		3		2		1	
Vehicle	**Age**	**Mileage**	**Age**	**Mileage**	**Age**	**Mileage**	**Age**	**Mileage**
1	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	1	21,455
3	0	0	0	0	1	21,374	2	43,030
4	0	0	1	21,291	1	21,374	3	64,348
5	1	21,098	1	21,291	2	42,514	4	85,561
6	1	21,098	1	21,291	2	42,514	5	106,381
7	1	21,098	2	42,194	3	63,144	6	127,088
8	1	21,098	2	42,194	3	63,144	7	147,547
9	2	41,630	2	42,194	4	83,277	8	167,574
10	2	41,630	3	62,205	4	83,277	9	187,447
11	2	41,630	3	62,205	5	102,880	10	207,225
12	2	41,630	3	62,205	5	102,880	11	226,171
13	3	61,223	4	81,356	6	121,678	12	245,020
14	3	61,223	4	81,356	6	121,678	13	263,511
15	3	61,223	4	81,356	7	139,983	14	281,841
16	3	61,223	5	99,352	7	139,983	15	299,192
17	4	79,342	5	99,352	8	157,693	16	316,499
18	4	79,342	5	99,352	8	157,693	17	333,292
19	4	79,342	6	116,109	9	174,249	18	349,713
20	4	79,342	6	116,109	9	174,249	19	365,984

3.3.1 Method of Comparison

In order to find the best replacement procedure, numerous comparisons must be made for each fleet and budget level due to the number of feasible age standards. The two-stage Bonferroni procedure (Banks, Carson, Nelson and Nichol, 2001, pp. 473-475) was used to select the best replacement procedures and all others that are statistically indistinguishable from it.

For sedans, a practically significant difference (ε) of \$2,500 in the AEC for total fleet costs was selected. An ε of \$25,000 was selected for the more expensive heavy diesel trucks. A value of 5 percent was used for α (Type I error level), and a value of 10 was used for the first-stage sample size (R_0). The second-stage sample size for each capital constraint and vehicle class was calculated based on the maximum sample variance of the difference within that set of replications and is discussed in more detail in the following section.

3.4 RESULTS

R_0 replications were run for each vehicle class, capital constraint, and replacement procedure combination. Sample means were calculated for each replacement procedure within a capital constraint within a vehicle class. The sample variance of the difference in results between replacement procedures was then calculated for all of the replications within each capital constraint and vehicle class according to equation (26). Y_{ri} is the AEC for the fleet using replacement procedure *i* for simulation replication *r*. $\bar{Y}_{\cdot i}$ is the average of these values for the R_0 simulation replications.

The largest sample variance was used as $\hat{S}^2$ ($\hat{S}^2 = \max_{i \neq j} S_{ij}^2$) in equation (27) (see Kelton et al., 2010) to calculate *R*, the second-stage sample size (Table 3.11). $z_{\alpha/2}^2$ is the critical value from a standard normal distribution.

$$S_{ij}^2 = \frac{1}{R_0 - 1} \sum_{r=1}^{R_0} \left(Y_{ri} - Y_{rj} - \left(\bar{Y}_{\cdot i} - \bar{Y}_{\cdot j} \right) \right)^2 \quad \forall\, i \neq j \tag{26}$$

$$R = \max \left\{ R_0, \left\lceil \frac{z_{\alpha/2}^2 \hat{S}^2}{\varepsilon^2} \right\rceil \right\} \tag{27}$$

Table 3.11. Second-stage sample sizes (number of simulation replications).

Vehicle Class	Practically Significant Difference (ε)	Annual Capital Budget in Vehicles	Largest Sample Variance	Second-Stage Sample Size (*R*)
Sedans	2,500	4	6,375,859	18
		3	6,653,991	18
		2	8,700,902	22
		1	9,255,974	18
Heavy Diesel Trucks	25,000	4	824,494,060	24
		3	793,498,451	21
		2	850,453,435	22
		1	615,271,738	12

Additional replications were run as required to reach the second-stage sample size, and overall sample means were calculated. The replacement procedure with the minimum sample mean was selected as the best. All replacement procedures within ε of the best were considered to be statistically indistinguishable from the best, while those replacement procedures where the AEC was more than ε greater than the best AEC were considered to be inferior to the best. In Table 3.12 the smallest AEC for each vehicle class and capital budget level is indicated in bold text with the darkest background; replacement procedures that were statistically indistinguishable from the best are indicated with a medium dark background.

Table 3.12. Summary of the experimental results.

Replacement Procedure	Average AEC: Sedans by Capital Budget 4	3	2	1	Heavy Diesel Trucks by Capital Budget 4	3	2	1
Age standard: 5 years	109,049	-	-	-	811,072	-	-	-
Age standard: 6 years	94,157	-	-	-	724,656	-	-	-
Age standard: 7 years	83,818	88,616	-	-	661,732	690,263	-	-
Age standard: 8 years	76,275	80,218	-	-	610,223	635,062	-	-
Age standard: 9 years	70,630	73,769	-	-	579,022	595,462	-	-
Age standard: 10 years	66,325	69,091	75,185	-	550,988	566,950	603,184	-
Age standard: 11 years	62,465	64,997	70,136	-	525,739	540,271	569,509	-
Age standard: 12 years	59,596	61,968	66,841	-	510,562	522,152	548,382	-
Age standard: 13 years	57,189	59,063	63,379	-	491,719	501,147	523,660	-
Age standard: 14 years	55,238	57,132	61,106	-	479,802	487,446	509,316	-
Age standard: 15 years	53,516	55,334	58,958	-	467,112	475,639	495,694	-
Age standard: 16 years	52,377	54,011	57,130	-	459,242	466,351	481,000	-
Age standard: 17 years	50,530	52,024	55,263	-	445,449	450,658	467,417	-
Age standard: 18 years	50,386	51,917	54,553	-	445,184	451,317	464,749	-
Age standard: 19 years	49,843	51,208	53,934	-	443,574	449,382	461,011	-
Age standard: 20 years	48,591	49,907	52,647	61,129	432,949	438,888	450,737	496,984
Age standard: 21 years	48,528	49,798	52,185	60,381	431,222	436,767	446,817	487,667
Age standard: 22 years	47,494	48,709	51,009	58,509	424,868	428,841	437,216	475,685
Age standard: 23 years	46,758	47,990	50,277	57,624	417,831	423,343	430,385	464,101
Age standard: 24 years	46,586	47,714	49,687	56,863	416,009	418,790	426,737	460,016
Age standard: 25 years	46,341	47,436	49,498	56,297	413,242	418,231	426,002	456,757
Age standard: 26 years	46,570	47,654	49,703	56,080	417,361	421,359	427,465	454,203
Age standard: 27 years	46,163	47,329	49,394	55,450	416,299	419,586	425,381	446,851
Age standard: 28 years	45,931	46,964	48,777	54,379	410,317	411,940	418,548	443,486
Age standard: 29 years	**44,929**	**45,898**	**47,850**	53,809	**403,309**	**404,027**	**410,828**	439,505
Age standard: 30 years	45,395	46,423	48,225	53,650	407,127	407,959	413,402	**430,297**
Dietz & Katz (2001)	62,573	65,124	70,620	62,906	407,297	410,091	414,588	432,297
Hartman (2000)	45,340	46,348	48,279	**53,445**	405,797	408,281	413,105	431,699

As can be observed from Table 3.12 no single replacement procedure was a clear exclusive winner. For sedans, age standards near the 30-year maximum and the Hartman (2000) procedure were the best at all budget levels. The Dietz and Katz (2001) procedure was found to be inferior for the sedan fleet at all budget levels. For the heavy diesel fleet, all three procedures – age standards near the 30-year maximum, Hartman (2000), and Dietz and Katz (2001) – were determined to be statistically similar.

3.5 SUMMARY AND CONCLUSIONS FROM THE EVALUATION OF REPLACEMENT PROCEDURES

A simulation was developed to evaluate vehicle replacement procedures for use by an organization such as a state DOT. The simulation has three major components: a fleet portion to simulate vehicle requests and track vehicle age and usage; several replacement procedure components; and a regression cost model based on actual ODOT cost data to transform the fleet component variables into meaningful costs for comparison.

Nine replacement procedures were evaluated for inclusion in the comparison, but seven were ruled out for reasons such as no multivehicle ability, no interdependence due to replacement or vehicle utilization, or they were too computationally intense to be practical. Replacement procedures described by Dietz and Katz (2001) and Hartman (2000) were selected from the literature and were compared against a commonly used age standard approach.

The Hartman (2000) integer programming model was modified to remove unused features and was solved from within the simulation using PyMathProg/GLPK (a mathematical programming solver). The Dietz and Katz (2001) scoring system was also modified to remove unused features. Scores are calculated by the simulation and used to rank vehicles for replacement. Under the age standard, vehicles are replaced as they reach a threshold age.

Regression models were fit to price index-adjusted ODOT data on operating costs and repair costs. Data were logarithm-transformed and the regression model was validated against data from a different year. The simulation includes a random component corresponding to variability in the ODOT data, and adds the two types of costs together to get annual operating and maintenance costs for each vehicle.

Replacement procedures were compared for 20-vehicle fleets of two different vehicle types (sedans and heavy diesel trucks) at different capital budget levels. These levels included replacement of a maximum of four, three, two or one vehicles annually. For each vehicle class and budget level, a two-stage Bonferroni procedure (Banks, Carson, Nelson, & Nichol, 2001) was used to compare replacement procedures on the basis of AEC. A practically significant difference level (ε) of $2,500 was used for the sedan fleets and an ε of $25,000 was used for the heavy diesel truck fleets, with $\alpha = 0.05$. Results are summarized in Table 3.12.

For the sedan fleet, an age standard of 29 years was the best replacement procedure for annual capital budget levels of four, three and two vehicles, and the Hartman (2000) procedure was best for the capital budget of one vehicle. For capital budget levels of four, three and two vehicles, age standards of 23 years through 30 years were statistically indistinguishable from the best procedure, as was the Hartman (2000) model. For the capital budget of one vehicle, age standards of 27 years through 30 years and the Hartman (2000) model were statistically indistinguishable from the best procedure. The Dietz and Katz (2001) model was significantly worse for the sedan fleet at all budget levels.

An age standard of 29 years was also the best procedure for heavy diesel truck fleets with budget levels of four, three and two vehicles. An age standard of 30 years was best for a budget level of one vehicle. Age standards from 22 years through 30 years, the Dietz and Katz (2001) model, and the Hartman (2000) model were all statistically indistinguishable from the best procedure for capital budgets of four and three vehicles. Age standards from 23 years through 30 years, the Dietz and Katz (2001) model, and the Hartman (2000) model were all statistically indistinguishable from the best procedure for a capital budget of two vehicles. Age standards from 26 years through 30 years, the Dietz and Katz (2001) model, and the Hartman (2000) model were all statistically indistinguishable from the best procedure for a capital budget of one vehicle.

The inclusion of age standards near the maximum of 30 years among the best replacement strategies suggests that the simulation may be running into the maximum replacement age before the otherwise optimal replacement time is reached. A maximum replacement age of 30 years was imposed because data to predict costs for older vehicles were unavailable. However, it is possible that keeping vehicles beyond 30 years could result in even lower AEC values.

One advantage of the Hartman (2000) procedure that is not reflected in the Table 3.12 results is the procedure's greater flexibility in adjusting to a smaller capital budget. The age standard procedure does not adjust to an initially less balanced fleet without extra human intervention. For example, if the initial fleet for an annual capital budget of four vehicles Table 3.9 or Table 3.10 were to be used instead with an annual capital budget of one vehicle, the age standard procedure by itself is not intelligent enough to start replacing vehicles early to spread out capital expenses. On the other hand, the Hartman (2000) procedure is not only flexible enough to spread out replacements, but will also figure out the optimal way to do this.

Based on the simulation results, the Hartman (2000) or the age standard approaches are recommended. The Hartman (2000) approach is more flexible, but requires more technical knowledge to implement and support. Another benefit to the Hartman (2000) approach is that it removes the need to determine what the optimal age standard may be, which is challenging to do without simulation due to interdependence of vehicle utilization. However, these benefits are minor and there is not strong evidence to show that the use of a more complex model will result in significant benefits compared to the simple models currently in use. The Dietz and Katz (2001) procedure is not recommended due to its poor performance for the sedan fleets.

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APPENDIX A

STATE DOT EQUIPMENT REPLACEMENT PERSONNEL CONTACTED

The following table shows the personnel at the state DOTs that provided information regarding their replacement practices.

Organization	Contact Name	Position	Phone Number	E-Mail
Alaska DOT	Diana Rotkis	Fleet Manager	(907) 269-0787	diana.rotkis@alaska.gov
Arizona DOT	Dennis Halachoff	Fleet Management Manager	(602) 712-7284	dhalachoff@azdot.gov
California DOT	Kris Teague	Engineering and Production	(916)-227-9608	kris.teague@dot.ca.gov
Colorado DOT	Ralph Bell	Equipment Engineer	(303) 512-5513	ralph.bell@dot.state.co.us
Florida DOT	Angel Birriel	C.P.M., State Maintenance Office	(850) 410-5517	angel.birriel@dot.state.fl.us
Georgia DOT	Ed Yawn	Assistant State Equipment Management Administrator	(770) 785-6947	edward.yawn@dot.state.ga.us
Hawaii DOT	Llewellyn Honda	Equipment Superintendent/Safety	(808) 587-2628	llewellyn.honda@hawaii.gov
Idaho DOT	Steve Spoor	Maintenance Services and Equipment Fleet Manager	(208) 334-8413	steve.spoor@itd.idaho.gov
Indiana DOT	Bob Timm	Equipment Management Supervisor	(317) 232-5487	btimm@indot.in.gov
Kansas DOT	Michael Stewart	Equipment Engineer	(785) 296-5941	MiStewart@ksdot.org
Maine DOT	Donal Hutchins	Fleet Manager	(207) 282-2677	Donald.Hutchins.III@maine.gov
Minnesota DOT	Bob Ellingsworth	Assistant Fleet Manager	(651) 366-5704	robert.ellingsworth@dot.state.mn.us
Nebraska DOT	Janie Vrtiska	Fleet Manager	(402) 479-4589	janie.vrtiska@ nebraska.gov

Organization	Contact Name	Position	Phone Number	E-Mail
New Mexico DOT	Tom Trujillo	Highway Equipment Manager	(505) 827-5587	tom.trujillo@state.nm.us
New York DOT	Bob Near	Assistant Director	(518) 457-2875	bnear@dot.state.ny.us
North Carolina DOT	Bruce Thompson	Fleet Procurement & Specification Section	(919) 733-2220	roybrucethompson@dot.state.nc.us
Ohio DOT	Alisa C. Di Salvo	Central Office - Equipment	(614) 351-2814	Alisa.DiSalvo@dot.state.oh.us
Oklahoma DOT	Chuck Howard	Equipment Manager	(405) 521-2550	choward@odot.org
Oregon DOT	Bill Ward	Operations & Policy Analyst	(503) 986 2724	william.WARD@odot.state.or.us
Pennsylvania DOT	Mike Connor	Fleet Manager	(717) 787-2790	miconnor@state.pa.us
Rhode Island DOT	Richard Dowding	Fleet Manager Officer	(401) 734-4873	rdowding@dot.ri.gov
Tennessee DOT	Barry Rawls	Motor Vehicle Management Director	615-741-7909	Barry.Rawls@tn.gov
Vermont DOT	Ken Valentine	Superintendent, Central Garage	(802) 828-2564	ken.valentine@state.vt.us
Virginia DOT	Erle Potter	State Equipment Manager	(804) 662-7204	erle.potter@vdot.virginia.gov
Wisconsin DOT	Mark Woltmann	Chief of Program Management	(608) 266-1744	mark.woltmann@dot.state.wi.us
Wyoming DOT	Bernie Kushnir	Equipment Engineer	(307) 777-4392	bernie.kushnir@dot.state.wy.us

APPENDIX B

MINNESOTA DOT EQUIPMENT REPLACEMENT THRESHOLD VALUES

The following table shows a sample of MNDOT equipment life and equipment usage threshold values for different equipment classes.

			MnDOT	
CLASS2	DESCRIPTION	MCC	LIFECYCLE (months)	Utilization Standard
070	CAR SUB COMPACT	SM VEH	60	8,000 Miles
080	CAR MEDIUM	SM VEH	60	8,000 Miles
090	CAR FULL SIZE	SM VEH	72	8,000 Miles
130	CAR STATION WAGON	SM VEH	72	8,000 Miles
131	CAR STA WAGON (FHWA)	SM VEH	72	8,000 Miles
132	CAR STA WAGON COMPACT	SM VEH	72	8,000 Miles
140	VAN STEP/PARCEL	SM VEH	72	8,000 Miles
150	VAN DELIVERY 1/2 TON	SM VEH	72	8,000 Miles
151	VAN PASSENGER	SM VEH	72	8,000 Miles
152	VAN MINI	SM VEH	72	8,000 Miles
153	VAN DELIVERY 3/4 TON	SM VEH	72	8,000 Miles
154	VAN DELIVERY 1 TON	MD VEH (D or G)	72	8,000 Miles
160	TRUCK SUBURBAN 2X4	SM VEH	84	8,000 Miles
161	TRUCK SUBURBAN 4X4	SM VEH	84	8,000 Miles
170	TRUCK S.U.V. TYPE 2X4	SM VEH	72	8,000 Miles
171	TRUCK S.U.V. TYPE 4X4	SM VEH	96	8,000 Miles
180	PICKUP 1/2 TON	SM VEH	84	8,000 Miles
181	PICKUP 1/2 TON UTILITY BO	SM VEH	84	8,000 Miles
182	PICKUP 1/2 TON 4X4	SM VEH	84	8,000 Miles
183	PICKUP 1/2 TON EXT CAB	SM VEH	84	8,000 Miles
184	PICKUP 1/2 TON EXT4X4	SM VEH	84	8,000 Miles
190	PICKUP 3/4 TON	SM VEH	96	8,000 Miles
191	PICKUP 3/4 TON 4X4	SM VEH	96	8,000 Miles
192	PICKUP 3/4 TON UTILITY	SM VEH	96	8,000 Miles
193	PICKUP 3/4 UTILITY 4X4	SM VEH	96	8,000 Miles
194	PICKUP 3/4 TON CREW CAB	SM VEH	96	8,000 Miles
195	PICKUP 3/4 TON CREW 4X4	SM VEH	96	8,000 Miles
196	PICKUP 3/4 CREW UTILITY	SM VEH	96	8,000 Miles
197	PICKUP 3/4 CREW UTIL 4X4	SM VEH	96	8,000 Miles
198	PICKUP 3/4 TON EXT CAB	SM VEH	96	8,000 Miles
199	PICKUP 3/4 TON EXTCAB 4X4	SM VEH	96	8,000 Miles

APPENDIX C

STATISTICAL SOFTWARE OUTPUT FOR REGRESSION MODELS

The following is the raw output from the statistical program R for the reduced operating cost regression model:

```
Call:
lm(formula = log(operadj) ~ sedanind + log(age) + log(annuse))
Residuals:
     Min       1Q   Median       3Q      Max
-1.67518 -0.16106  0.03461  0.20171  1.39551
Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  1.01950    0.34189   2.982  0.00304 **
sedanind    -1.68489    0.05163 -32.632  < 2e-16 ***
log(age)    -0.08925    0.04086  -2.184  0.02953 *
log(annuse)  0.83343    0.03133  26.604  < 2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.3622 on 390 degrees of freedom
Multiple R-squared: 0.8726,     Adjusted R-squared: 0.8716
F-statistic: 890.1 on 3 and 390 DF,  p-value: < 2.2e-16
```

The following is the raw output from R for the reduced repair cost regression model:

```
Call:
lm(formula = log(repadj) ~ sedanind + log(annuse) + sedanind *
    log(lifeuse))
Residuals:
    Min      1Q  Median      3Q     Max
-4.7793 -0.4357  0.0772  0.5484  2.1017
Coefficients:
                      Estimate Std. Error t value Pr(>|t|)
(Intercept)            2.85557    1.08605   2.629  0.00889 **
sedanind              -7.71630    1.92181  -4.015 7.13e-05 ***
log(annuse)            0.49714    0.07131   6.972 1.35e-11 ***
log(lifeuse)           0.10735    0.08260   1.300  0.19448
sedanind:log(lifeuse)  0.46742    0.17245   2.710  0.00702 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.883 on 389 degrees of freedom
Multiple R-squared: 0.7031,     Adjusted R-squared: 0.7001
F-statistic: 230.3 on 4 and 389 DF,  p-value: < 2.2e-16
```

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