A Decision Support System for Optimized Equipment Turnover

Final Report
February 2017

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Iowa Department of Transportation
(InTrans Project 13-483)
Federal Highway Administration

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The preparation of this report was financed in part through funds provided by the Iowa Department of Transportation through its "Second Revised Agreement for the Management of Research Conducted by Iowa State University for the Iowa Department of Transportation" and its amendments.

Front Cover Images: Iowa DOT

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.	
InTrans Project 13-483			

4. Title and Subtitle
A Decision Support System for Optimized Equipment Turnover

5. Report Date
February 2017

6. Performing Organization Code

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8. Performing Organization Report No.
InTrans Project 13-483

9. Performing Organization Name and Address
Institute for Transportation
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10. Work Unit No. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Organization Name and Address
Iowa Department of Transportation
800 Lincoln Way
Ames, IA 50010

U.S. Department of Transportation
Federal Highway Administration
1200 New Jersey Avenue, SE
Washington, DC 20590

13. Type of Report and Period Covered
Final Report

14. Sponsoring Agency Code
SPR RB14-014

15. Supplementary Notes
Visit www.intrans.iastate.edu for color pdfs of this and other research reports.

16. Abstract

The objective of this research was to review current Iowa Department of Transportation (DOT) processes and procedures related to vehicle procurement, maintenance, operations, and sales and develop a tool to optimize equipment lifecycles. The study focused on single-axle A07 and double-axle A12 snowplows, as these represented 31.7% and 45.6%, respectively, of the fiscal year (FY) 2015 equipment replacement budget.

Using data currently collected by the Iowa DOT and the models developed, the researchers developed a decision support system (DSS) that recommends optimized normal replacement cycles for single-axle A07 and double-axle A12 vehicles. The objective of the DSS is to minimize equipment lifecycle cost while meeting the needs of Iowa DOT road service.

Based on the data provided by the Iowa DOT and the estimated resale value curve of the vehicles, this research indicated that the optimal replacement model is eight years for single-axle A07 vehicles and six years for double-axle A12 vehicles. Assuming the resale value curve is accurate, we estimate that the Iowa DOT would save approximately $1.8 million for single-axle A07s and $6.47 million for double-axle A12s per year by moving from a 15-year normal replacement model to eight years for single-axle A07s and six years for double-axle A12s.

17. Key Words
decision support—DOT vehicle fleets—equipment maintenance cost—lifecycle analysis—optimal replacement model—snowplow depreciation—transportation asset management

18. Distribution Statement
No restrictions.

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified.	Unclassified.	52	NA

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

A DECISION SUPPORT SYSTEM FOR OPTIMIZED EQUIPMENT TURNOVER

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Sponsored by
Federal Highway Administration and
Iowa Department of Transportation
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Preparation of this report was financed in part
through funds provided by the Iowa Department of Transportation
through its Research Management Agreement with the
Institute for Transportation

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ACKNOWLEDGMENTS

The authors would like to thank the Iowa Department of Transportation (DOT) for sponsoring this research and the Federal Highway Administration for state planning and research (SPR) funds used for this project.

EXECUTIVE SUMMARY

The Iowa Department of Transportation (DOT) primarily uses two classes of snowplow trucks: single-axle (A07) and double-axle (A12). These two classes of vehicles made up about 77% ($7.88 million) of the heavy equipment budget for fiscal year (FY) 2015.

This research project investigates the predominant factors and analyzes equipment data to determine an optimal normal replacement model for the Iowa DOT's single-axle A07 and double-axle A12 vehicles considering maintenance cost, equipment replacement cost, and residual resale values. Two methods were considered: age of vehicle and cumulative maintenance costs. In FY 2014, the fleet inventory for single-axle A07 and double-axle A12 vehicles was 364 and 456, respectively, with estimated purchase costs of approximately $134,500 and $150,000 per vehicle, respectively. Currently the Iowa DOT uses a 15-year depreciation for these vehicles. Thus, for FY 2015, the Iowa DOT planned on purchasing 24 single-axle A07s and 31 double-axle A12s.

The Iowa DOT provided the researchers with nine years of historical data for these vehicles, including purchase cost, maintenance cost, purchase date, and actual and estimated resale values. The estimated resale values were derived from actual data and through internal expert opinion. The resale value curve assumes 100% purchase price value at year 0 and approximately 12% of purchase price for single-axle A07s and 11% for double-axle A12s at year 17. It's an exponential curve with the greatest decrease in value in the initial years. Additionally, the Iowa DOT provided an estimated inflation adjustment of 4.23% based on historical data, which was used to adjust maintenance event costs for comparative analysis.

Using these data, the researchers were asked to evaluate and recommend a normal replacement model that would minimize total cost. Accordingly, we developed a series of simulations evaluating total cost of ownership for vehicles. We modified the simulations by replacing vehicles every 1, 2, 3, …, 15 years as well as replacing the top 20, 30, 40, …, 160 most expensive vehicles in terms of cumulative maintenance costs. We ran each scenario 30 times for 500 years each to allow for the full effect of modified variables. The total cost of ownership (TCO) equation was the cost of purchasing each truck plus the estimated maintenance cost per truck minus the value of the truck when sold.

The total purchase price of both classes of vehicles included a base cost and modification costs for extra equipment. It was necessary to estimate the total purchase price due to total data not provided by the Iowa DOT. Furthermore, maintenance costs were calculated only for work performed on the vehicle and not for work performed on modification equipment and those data were not provided by the Iowa DOT.

For the analysis performed, the additional costs were 38% above the vehicle purchase price for single-axle A07 vehicles and 41% above the purchase price for double-axle A12s. Furthermore, it was assumed that the resale value of each vehicle included the modification equipment.

Based on the data provided by the Iowa DOT and the estimated resale value curve of the vehicles, our research indicated that the optimal replacement model is eight years for single-axle A07 vehicles and six years for double-axle A12 vehicles. Assuming the resale value curve is accurate, we estimate that the Iowa DOT would save approximately $1.8 million for single-axle A07s and $6.47 million for double-axle A12s per year by moving from a 15-year normal replacement model to eight years for single-axle A07s and six years for double-axle A12s.

1. INTRODUCTION

Problem Statement

Currently, the Iowa Department of Transportation (DOT) collects considerable data on its entire fleet of heavy and light equipment. In this case, the Iowa DOT is data rich and information poor in that the data are not being analyzed with modern tools and models for optimality. The Iowa DOT uses straight-line 15-year depreciation for most heavy equipment vehicles and replaces most vehicles uniformly regardless of varying operational costs and replacement values. Consequently, the equipment lifecycle is sub-optimal and is generating significant cost to the state.

Background Summary

The Iowa DOT spends over $15 million per year on vehicle and equipment purchases covering a fleet of more than 900 plow trucks, 50+ motor graders, 100+ loaders, and a wide array of other heavy equipment. In addition, the Iowa DOT has a sizable fleet of “light” vehicles such as pickup trucks, vans, and sedans. As this equipment ages, it becomes increasingly costly to maintain.

As equipment technologies change, it is necessary to adapt lifecycle analysis accordingly. For example, single-axle plows may not have the capacity of double-axle plows and appear to be less desirable equipment. However, it may be that single-axle plows maintain their value beyond the double-axle plows and command a higher resale value. What is the optimal mix of plows such that roads can be maintained at the lowest cost and equipment can be serviced and replaced efficiently?

Objectives

Iowa DOT staff wanted to analyze and identify alternative methods of equipment turnover to optimize equipment operation costs and to look at a more data-driven approach to understand fleet costs and work toward optimizing fleet turnover.

The objective of this research was to review current Iowa DOT processes and procedures related to equipment procurement, maintenance, operations, and sales and develop a tool to optimize equipment lifecycles. The study focused on single-axle A07 and double-axle A12 snowplows, as these represented 31.7% and 45.6%, respectively, of the fiscal year (FY) 2015 equipment replacement budget.

Using data currently collected by the Iowa DOT and the models developed, the researchers developed a decision support system (DSS) that recommends optimized normal replacement cycles for single-axle A07 and double-axle A12 vehicles. The objective of the DSS is to minimize equipment lifecycle cost while meeting the needs of Iowa DOT road service.

Deliverables

The researchers provided the following deliverables at the completion of the project:

- This research final report describing data preparation, analysis methodology, and output
- A technology transfer summary for the project
- An Excel-based DSS for Iowa DOT use, process steps describing input parameters, and a description of DSS functionality and usage

2. DATA PREPARATION

The Iowa DOT provided three tables in a Microsoft Access database format. The three tables were Equipment Information, Repair Cost Information, and Meter Log. The first two tables contained data regarding specific equipment. The data definitions provided by the Iowa DOT are shown in Table 1 for repair costs and Table 2 for equipment information. (The Meter Log table contained three attributes: equipment number, date, and meter reading for that specific date.)

Table 1. Iowa DOT Repair Cost Information table attributes

Attribute Name	Definition
A #	A unique number assigned to each piece of equipment. (A32145 for example.). All powered equipment has an A Number.
Repair Order Number	Six-digit number that is unique to a repair event. Each repair order may have multiple lines.
Repair Order Line	Four-digit number indicating the line number of the repair order.
Object Code	An accounting designation that groups types of expenses. A reference table is provided.
Class Key	Describes a grouping of equipment by size or function. (A01b for example, where A relates to the fact that it is A equipment, 01 means sedans, and the letter b at the end designates that it is a midsized.) Class Name does a fair job of explaining what each class Key means.
Class Name	This is the English translation of the Class Key using descriptive terms.
Estim Repl Yr	This is the year that we GUESS we might replace this piece of equipment. It is a calculated value and changes annually based on the actual replacement of equipment with a higher priority.
Warranty Year	Year in which the warranty started.
Cost Year	Year in which a cost was incurred.
Years Old	A calculated age based on the date at the time the observation was recorded and the warranty start date.
Hrs	Hours worked on the maintenance event.
Repair Date	Date that a repair was indicated as complete.
Transaction Type	This is a generalization of the type of expense experienced in an event.
Transaction Type Description	Does a fair job of describing the Transaction Type.
Event Cost	This is the cost for this event.
Miles or Hours	This is a reading of how many miles or hours were recorded at the time of the event.
SAC Code	System, Assembly, Component: a standardized industry nomenclature for items repaired on vehicles.
SAC Description	This is the English translation of the SAC Code.

Table 2. Iowa DOT Equipment Information table attributes

Attribute Name	Definition
Fiscal Year	Begins July 1 and ends June 30th. (The state fiscal year runs from July 1 to the following June 30 and is numbered for the calendar year in which it ends.)
History Run Date	Date on which the observation about the equipment was recorded.
A Number	A unique number assigned to each piece of equipment. (A32145 for example.)
CC Location	CC is the cost center. This is an accounting designation relating to an office or garage.
Equip Class	Describes a grouping of equipment by size or function. (A01b for example, where A relates to the fact that it is A equipment, 01 means sedans, and the letter b at the end designates that it is a midsized.)
LD – HD	Designates Light Duty or Heavy Duty (Class 1–6 or 7+).
Equip Status Description	Does a fair job of describing the equipment status.
Equip Year	Relates to the model year of the equipment.
Make Description	Manufacturer Name. (Ford for example.)
Model	(Focus or Civic for example.)
Fuel Type	Self-explanatory.
Warranty Start Date	This is the date that the equipment was transferred to the CC of assignment. It is also the date that the manufacturer’s warranty begins to expire. (We ask for a delay to compensate or account for the time it takes to prep vehicles and get them into service.)
Est Replace Year	A calculated value that approximates year in which we expect (or expected) to replace the equipment.
Estim Life Miles	This is a figure that represents how many miles we expect to use a piece of equipment prior to disposal.
Estim Life Hours	This is a figure that represents how many hours we expect to use a piece of equipment prior to disposal.
Meter Reading	A reported reading of an odometer or hour meter, depending on whether it is a light or heavy vehicle.
Life Hours/Life Miles	A total cumulative value of hours or miles. (Sometimes hour meters and odometers must be replaced and this accumulates usage prior to the change of the meter.)
Total Cost	The sum of the purchase price, costs to prep the vehicle for use, and improvements to the vehicle.
PO Number	The purchase order number.
Salvage Value	A dollar figure established at the time we receive the equipment. (It is a prediction of sale price.)
Equipment End Date	An approximation to within a few weeks of when the item was sold.

The Repair Cost Information table contained 1,065,002 records while the Equipment Information table contained 35,744 records. The Iowa DOT provided 9 years of maintenance data, for the calendar years of 2005 through the end of 2013.

The Iowa DOT datasets included anomalous and missing data. Additionally, the two tables were not properly normalized. It was necessary to create a third table with A_Num as a primary key to link the two tables provided by the Iowa DOT.

Anomalous Data

Given the large number of records provided by the Iowa DOT, it is expected that some data are anomalous. One example of anomalous data was for vehicle A28428. In the Repair Information table, that specific vehicle had a repair order with an object code of 610, 37,680 hours of labor, and an event cost of $1,039,981.23. After bringing this to the attention of Iowa DOT staff, we were told it was a data input error, and that the hour meter was most likely erroneously entered as the labor hours. We were able to adjust for this specific error, but it is an indicator of other potential errors that we did not catch. Therefore, our results are largely dependent on the accuracy of the data provided by the Iowa DOT.

Missing Data

Missing Event Cost

In the Repair Cost Information table, many instances of the attribute [Event Cost] had zero amounts, even though there were hours assigned for the [Hrs] attribute. Of the 1,065,002 records in the Repair Cost Information table, 84,306 records had a zero amount for the Event Cost, an Object Code of 610, and Hrs assigned to work greater than zero. After discussing this with Iowa DOT staff, it was determined that those values should be set as a function of an hourly rate times the number of hours worked on that vehicle for the specific event (Object Code 610). The Iowa DOT provided the past hourly rates shown in Table 3.

Table 3. Historical hourly rates

Fiscal Year	Date Range	Hourly Rate
2014	July 1, 2013-June 30, 2014	$42.37
2013	July 1, 2012-June 30, 2013	$40.37
2012	July 1, 2011-June 30, 2012	$37.36
2011	July 1, 2010-June 30, 2011	$37.36
2010	July 1, 2009-June 30, 2010	$37.36
2009	July 1, 2008-June 30, 2009	$37.36
2008	July 1, 2007-June 30, 2008	$35.74
2007	July 1, 2006-June 30, 2007	$32.02
2006	July 1, 2005-June 30, 2006	$32.02
2005	July 1, 2004-June 30, 2005	$28.27

It was then determined, based on discussions with Iowa DOT staff and analysis of the data, that a 4.6% yearly adjustment would be made for all hourly rates to normalize any data beyond this time window. The Iowa DOT provided some vehicle data as far back as 1992. An example of the SQL statement to set the hourly rate (for the 2013 calendar year) is shown below.

```
UPDATE    [Repair Cost Information] SET [Event Cost] = Hrs * 40.37
WHERE     [Repair Cost Information].[Repair Date] Between #1/1/2013# And #12/31/2013#
AND       [Repair Cost Information].[Object] = "610"
AND       [Repair Cost Information].[Event Cost])=0;
```

This UPDATE query was repeated for each year.

Missing B on A Equipment Costs

Another missing piece of information that became important in our analysis is the B on A costs. The Total Cost of a vehicle in the Equipment Information table is the purchase price plus any improvements made to the vehicle. What is not included in that amount is the B equipment that is installed. For example, a snow blade is B equipment that is installed on a snowplow truck. It is not included in the A costs of the vehicle, and it was not provided by the Iowa DOT. Furthermore, the maintenance costs in the Repair Cost Information table is only for A equipment maintenance events and not for the B on A equipment. However, the Iowa DOT asked that we include the “total” cost (B on A included) in our simulation to better reflect the true costs of equipment. Consequently, we were given the data shown in Table 4.

Table 4. B on A equipment costs

Year	# Purchased	Average A Cost	Average B Cost	Average Total
FY 2014	23 Single-Axle A07	$109,655	$38,404	$148,058
FY 2014	28 Double-Axle A12	$97,796	$45,593	$168,965
FY 2015	20 Single-Axle A07	$108,508	$41,236	$149,743
FY 2015	33 Double-Axle A12	$123,114	$50,923	$174,037

Thus, for FY 2015, the B equipment costs for single-axle A07 vehicles was about 38% of A equipment cost and about 41.3% of A equipment cost for double-axle A12 vehicles.

Event Cost Adjustment

The data used in our analysis was based on the age of the vehicles in the Iowa DOT inventory. We parsed the vehicles into age groups. Figures 1 and 2 show the number of vehicles in the dataset parsed by age for each type of vehicle.

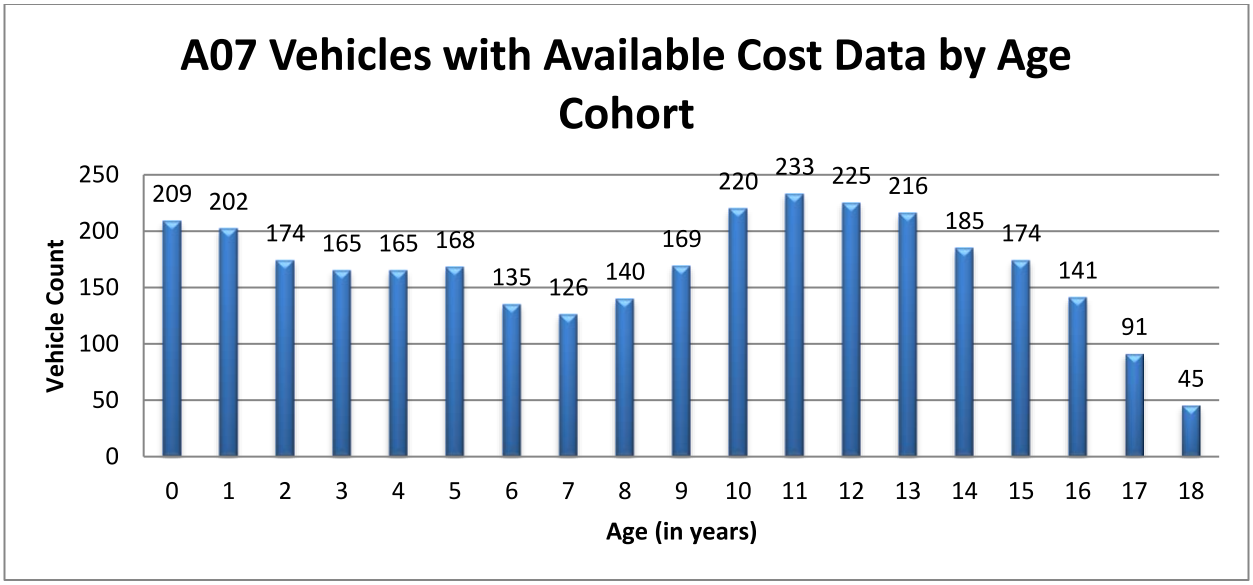


Figure 1. Count of single-axle A07 vehicles by age

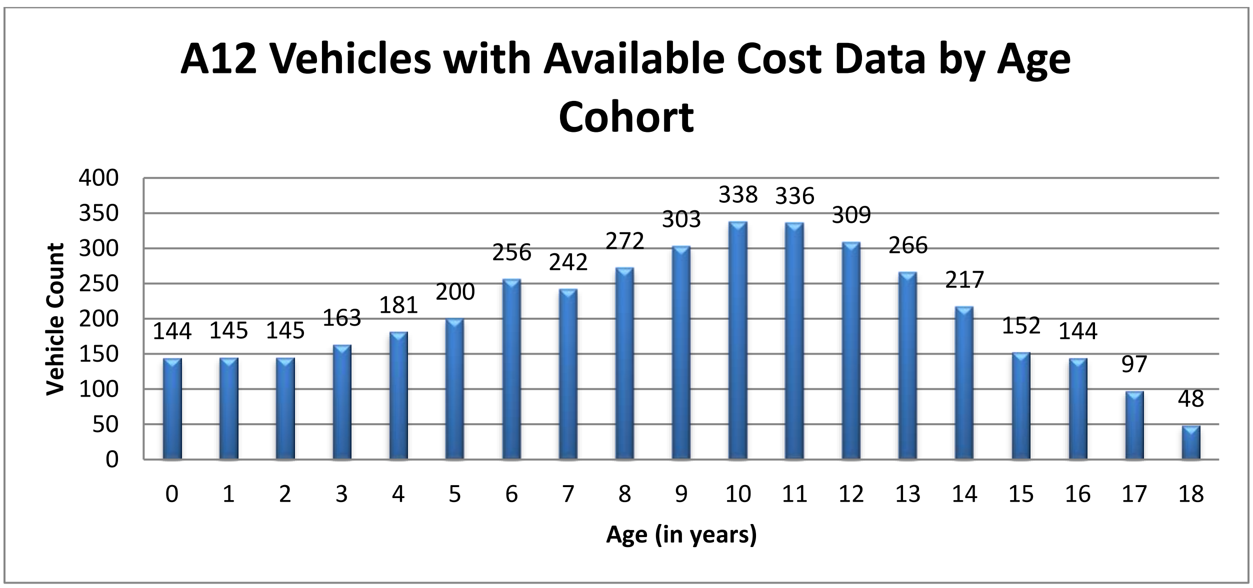


Figure 2. Count of double-axle A12 vehicles by age

We calculated the event costs for vehicles at specific ages, and these were the counts of those vehicles for the event cost calculation. It is important to note that vehicles were specific ages at different dates, so events for vehicles one year old may have occurred in 2005, 2006, 2007, …, 2013. Therefore, it was necessary to normalize the event costs to adjust for inflation. The reason for the normalization was to generate a distribution of expected maintenance costs for vehicles of specific ages, and the dollar cost of events in earlier years was less than it was in latter years. After discussing this with Iowa DOT staff, we agreed to adjust the maintenance event cost by 4.23% per year. This adjustment value was determined based on the expert opinion of Iowa DOT staff.

The query for the maintenance adjustment is shown here:

```
SELECT DISTINCT    [Repair Cost Information].[A#],
                   [Repair Cost Information].[Class Key],
                   [Repair Cost Information].[Repair Date],
                   [Repair Cost Information].[Cost Year],
                   [Equip Info].[Fiscal Year],
                   [Equip Info].[Life Usage],
                   [Repair Cost Information].[Years Old],
                   [Repair Cost Information].Object, 2013-Year([Repair Cost
                   Information].[Repair Date]) AS YRS,
                   [Repair Cost Information].[Event Cost],
                   [Repair Cost Information].[Event Cost]*(1.0423)^YRS AS ADJCost,
                   [Equip Info].[Total Cost],
                   [Equip Info].[Equip Status Desc],
                   [Equip Info].[Salvage Value]
FROM               (ANums INNER JOIN [Repair Cost Information]
ON                 ANums.A_Num = [Repair Cost Information].[A#])
INNER JOIN         [Equip Info]
ON                 ANums.A_Num = [Equip Info].[A Number]
WHERE              [Repair Cost Information].[Cost Year]=[Equip Info].[Fiscal Year];
```

Note that the line [Repair Cost Information].[Event Cost]*(1.0423)^YRS AS ADJCost creates an adjusted cost as a function of 4.23% to the power of the number of years old the vehicle is. This query is used to create the data necessary for a PivotTable used in Excel to create the maintenance distribution. Because the A number is a unique identifier for each vehicle, but the structure of the database was not normal, it was necessary to create a separate table called ANums, which had the A Number as the primary key. We then used the ANums table to join the Equipment Information table with the Repair Cost Information table.

PivotTable for Maintenance Cost Distribution

It is necessary to use the INNER JOIN in the previous query because the data provided by the Iowa DOT are not historically synchronized. Thus, the INNER JOIN causes the query to return only maintenance data for which the years coincided with equipment information data. While the data provided by the DOT contained vehicle records predating 2005, maintenance data given began at 2005; thus, anything prior to that year was excluded from analysis.

The PivotTable should have Class Key as the Filter so we can distinguish between A07 and A12 vehicles. The Columns should contain the A Numbers. The Rows should contain Years Old and the summary (∑) Values should contain the Sum of the adjusted maintenance costs (see Figure 3). Additionally, we select the filter on row labels to show only those vehicles with years 0 through 18.

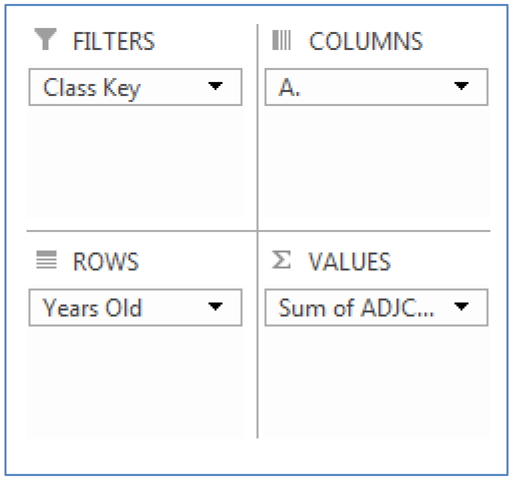


Figure 3. PivotTable fields

Once this table is created, the output will look like this:

Class Key	(Multiple Items)			
Sum of ADJCost	**Column Labels**			
Row Labels	**A27169**	**A27569**	**A27573**	**A27**
0				
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13		4893.560894	9951.868402	334
14	5232.818846	4417.225152	3544.637352	242
15	1289.463239	5768.382869	2488.51033	363
16	1118.875049	15088.44008	2295.797135	756
17	662.628869	4271.412698		237
18	1055.549155	5480.973106	486.8964061	255

Figure 4. PivotTable results

The next step is to calculate a running total of maintenance costs per vehicle per age. For example, take vehicle A27169 shown in Table 5.

Table 5. Cumulative maintenance cost (rounded)

Age	A27169
0	
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	$5,233
15	$6,522
16	$7,641
17	$8,304
18	$9,359

Notice that for Age 14 through 18, there are reported maintenance values. We do not, however, have data for earlier years due to the specific data provided by the Iowa DOT as discussed earlier. The data shown in the PivotTable shows that, when A27169 was 14 years old, $5,232.82 was spent on maintenance, and $1,289.46 when it was 15 years old and so on. However, for our analysis, we need a cumulative total of maintenance for vehicles at each age. Thus, we need a table to be in the following form:

For each year, it is necessary to add the preceding cost to the running total. Once this is done for all vehicles, it is possible to calculate the cumulative amount spent for vehicles at any given age. One point we must mention in creating this table, there are some years for specific vehicles where no work was recorded, but there were in the previous and later years. Therefore, for the few vehicles that we encountered with that situation, it was necessary to manually enter a zero into the blank year. We did this to keep our cumulative formula functional. The researchers provided the Iowa DOT with an Excel workbook that includes the specifics of the formulas created for this calculation. For a point of reference, here is an example of the formula used =IF(B16="","",B16+IF(B37="",0,B37)).

Due to the nature of the data copied from the PivotTable, zeros were not entered in years with no values. Those cells were blank or null. Therefore, the formula checked if any value was in the cell, and if it was, it would add the previous value. Thus, when a blank year is sandwiched between two non-blank years the formula would begin again, and this is not what we required for our distribution table (see Table 6).

Table 6. Maintenance cost distribution for single-axle A07 vehicles based on age

Age	Min	25th	50th	75th	Max
0	$2.18	$163.97	$364.98	$997.27	$10,522.97
1	$563.52	$1,576.28	$2,354.96	$3,481.30	$13,395.10
2	$1,589.38	$3,727.00	$5,029.16	$6,949.57	$18,609.99
3	$2,563.37	$6,030.30	$8,238.61	$11,327.08	$27,290.10
4	$2,228.93	$7,817.44	$11,007.06	$15,364.44	$33,424.40
5	$3,579.13	$9,519.10	$14,217.20	$19,504.63	$42,668.64
6	$4,078.69	$12,351.32	$18,469.37	$24,296.14	$58,107.19
7	$2,460.74	$13,167.23	$19,436.40	$27,260.23	$57,779.93
8	$2,286.87	$9,861.79	$19,574.96	$30,043.80	$68,722.69
9	$1,902.53	$10,819.10	$19,103.06	$31,340.61	$89,728.22
10	$2,025.77	$10,509.67	$18,242.12	$35,714.14	$94,581.61
11	$3,296.54	$14,387.76	$24,488.21	$44,350.66	$103,379.65
12	$3,258.98	$18,959.34	$27,976.74	$48,299.93	$114,872.45
13	$393.79	$21,783.94	$32,467.06	$49,692.88	$95,430.81
14	$423.78	$23,935.59	$35,062.72	$49,076.17	$97,586.09
15	$423.78	$28,684.92	$39,279.86	$53,679.38	$116,222.98
16	$511.37	$30,528.74	$43,314.55	$55,700.49	$109,806.36
17	$786.46	$29,283.70	$40,928.34	$53,910.76	$113,851.45
18	$828.56	$27,144.42	$38,417.42	$54,296.50	$91,674.97

The distribution table contains the minimum maintenance cost for the single-axle A07 vehicles of a specific age as well as the 25th, 50th, and 75th percentile values, and the maximum maintenance cost. The same distribution table was generated based on double-axle A12 maintenance records.

The DSS uses these values in generating maintenance costs in the simulation. Based on these values, we can generate a box-and-whisker plot showing the range of maintenance costs per age of vehicle (see Figures 5 and 6).

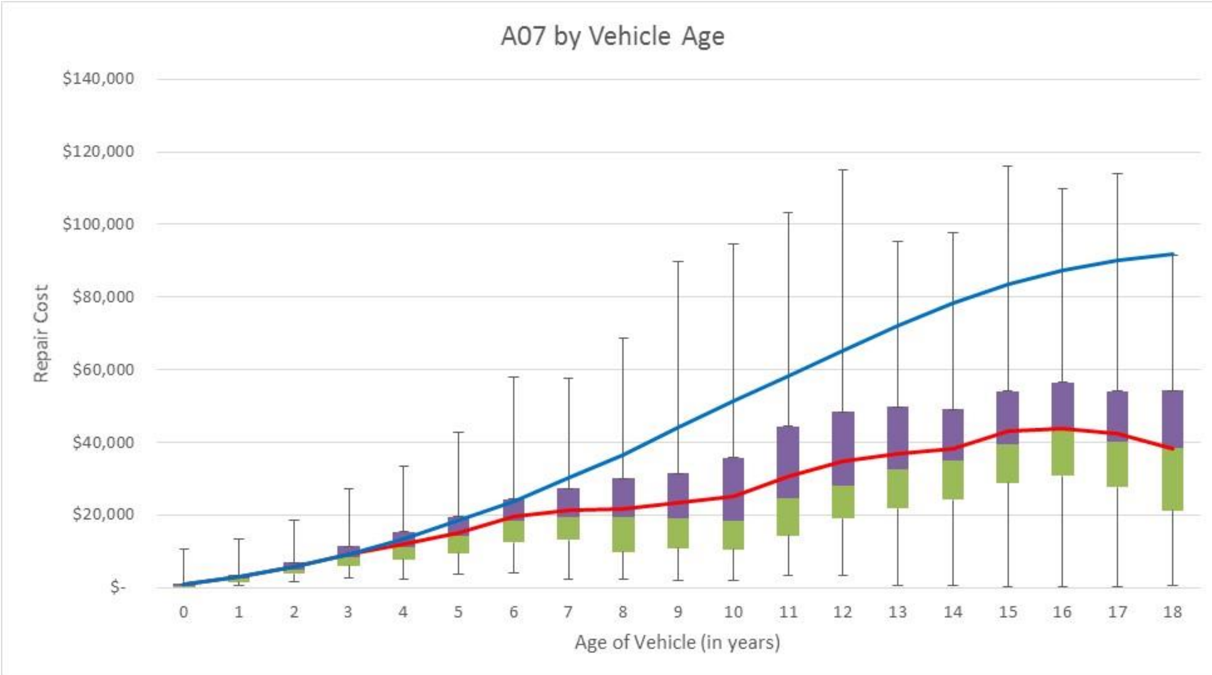


Figure 5. Single-axle A07 box-and-whisker plot

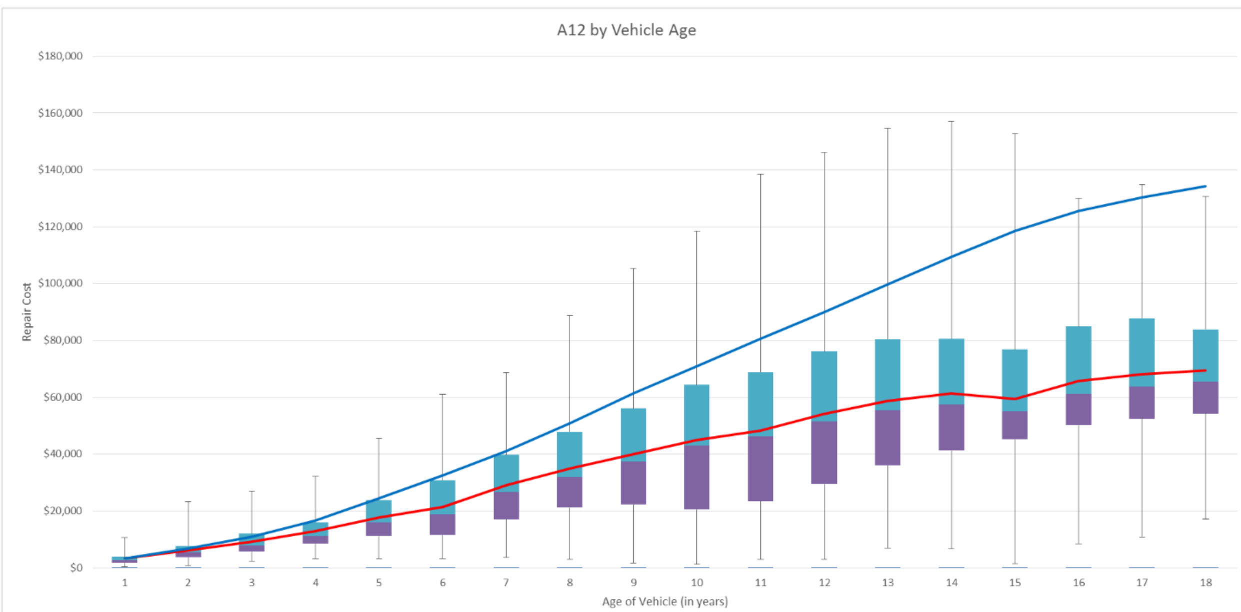


Figure 6. Double-axle A12 box-and-whisker plot

The red line in each plot represents the cumulative mean of the maintenance costs for that specific age cohort. The blue line represents the total cumulative mean for the maintenance costs. The division in the boxes between the purple and the green for single-axle A07s and between the blue and the purple for double-axle A12s is the median of the cumulative maintenance costs.

Estimated Sales Curve

The current Iowa DOT practice is to keep vehicles until after their depreciation time expires (15 years) and then to sell them at auction. Therefore, the Iowa DOT does not have valid data on the resale value of vehicles sold before final depreciation. It was necessary to estimate a percentage of original truck value for resale at years 1, 2, 3, …, 17 to simulate various scenarios. We analyzed final sales values from data provided by the Iowa DOT and discussed an acceptable sales curve with Iowa DOT representatives. Based on our conversations, we derived the sales values shown in Table 7 for vehicles sold in each year.

Table 7. Estimated resale values for A07 and A12 vehicles by year sold

Resale at Year	Min	Most Likely	Max
1	60%	70%	80%
2	40%	50%	60%
3	31%	40%	49%
4	25%	34%	43%
5	23%	31%	39%
6	20%	28%	36%
7	19%	26%	33%
8	17%	24%	31%
9	16%	22%	28%
10	15%	21%	27%
11	14%	19%	24%
12	13%	18%	23%
13	13%	17%	21%
14	11%	15%	19%
15	11%	14%	17%
16	10%	13%	16%
17	10%	12%	14%

As Figure 7 shows, the curve follows an exponential decay with the greatest decrease in value occurring in the first four years and the remaining decrease steadily declining in the years that follow.

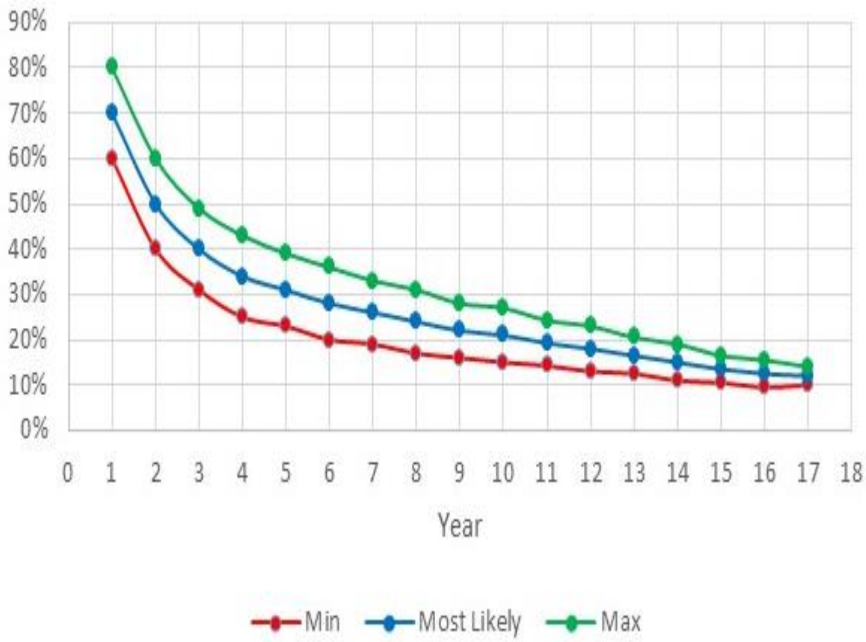


Figure 7. Estimated resale values for A07 and A12 vehicles by year sold

For additional robustness, we use a triangular distribution for the resale value for each year. We decrease the fluctuation as the vehicles age; so in year one, the potential variation is 20 percentage points, while in year 17, the variation is only four percentage points.

3. ANALYSIS

We developed the DSS to run two different scenarios: one based on resale year (age of vehicles when sold) and the other based on maintenance cost.

Decision Support System Interface

Home Page Tab

Figure 8 shows the main interface for the DSS.

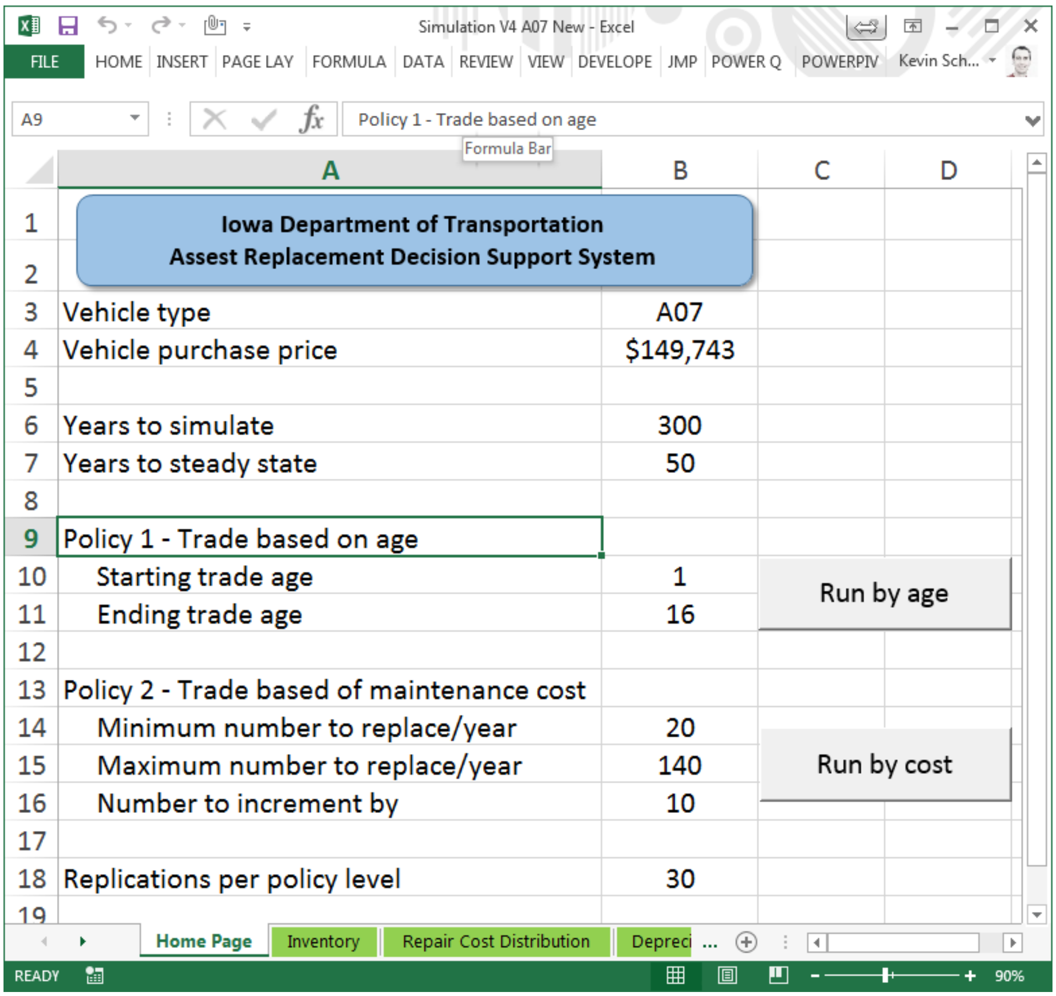


Figure 8. DSS home page

The user enters the vehicle type and the total vehicle purchase price (this value, which is calculated to include B on A equipment costs, can be found on the Inventory tab). The user also has the option to vary the number of years to simulate as well as the number of years to reach steady state.

Years to Simulate

The DSS will run multiple analyses varying the replacement model. By simulating over a long period of time, we are able to view trends from the perspective of a normal distribution. By increasing our simulation years and by replicating the simulations, we are able to calculate an average cost and avoid short-term variations in the data. Thus, we can observe the average cost of selling vehicles every one year, two years, three years, and so on, or we can observe selling the 10 most expensive vehicles, 20 most expensive vehicles, and so on. By most expensive, we mean in terms of maintenance costs.

Years to Steady State

When running simulations, it is necessary to establish a steady state. That is to say, when simulations begin, they are often affected by initial inputs with greater degrees of variation. It is common practice to allow a simulation to reach a steady state before observing the results. The length of the steady state run can vary, and we allow the users to adjust this, with a minimum of 20 years.

Replications per Policy Level

We repeat each sale policy to observe results that are normally distributed. In general statistical terms, a minimum of 30 observations are required to estimate a population. Thus, by repeating each policy (30 times) we can say the results will be contained in a normal distribution. We set the maximum replication to 30 for statistical power, but allow the simulation to have fewer replications for testing and observation. (It takes less time to run fewer replications.)

Inventory Tab

The Inventory Tab contains four attributes. The first is the Asset ID. This attribute is the A Number (A_Num) for each specific vehicle. The Asset ID number should be unique with each vehicle listed once. The second attribute is the Cumulative Maintenance for each vehicle. This value has been adjusted for inflation. The third attribute is the purchase price of the vehicle. Given that the B on A equipment costs (such as a snowplow) were not given in the original data, it was necessary to calculate the total purchase price as the A costs with a percentage of A added on as the B costs. The fourth attribute is the age of the vehicle at the time of analysis. Since we were analyzing the data at FY 2013, we only wanted vehicles that were active in FY 2013. (The data from the Iowa DOT showed 450 A07 class vehicles were active.)

These inventory data are used to seed the simulation as it runs multiple years. The data are also used by the simulation to determine the initial set of costliest vehicles in terms of cumulative maintenance.

There is no simple query used to generate the data used in the Inventory Tab table. It was necessary to migrate the data to a PivotTable as shown in the last chapter.

Repair Cost Distribution Tab

The maintenance cost data (like those shown earlier in Table 6) are placed in the Repair Cost Distribution Tab. The DSS uses these data to simulate probable costs for vehicles as they age. These data are generated from actual maintenance records for the vehicle under simulation.

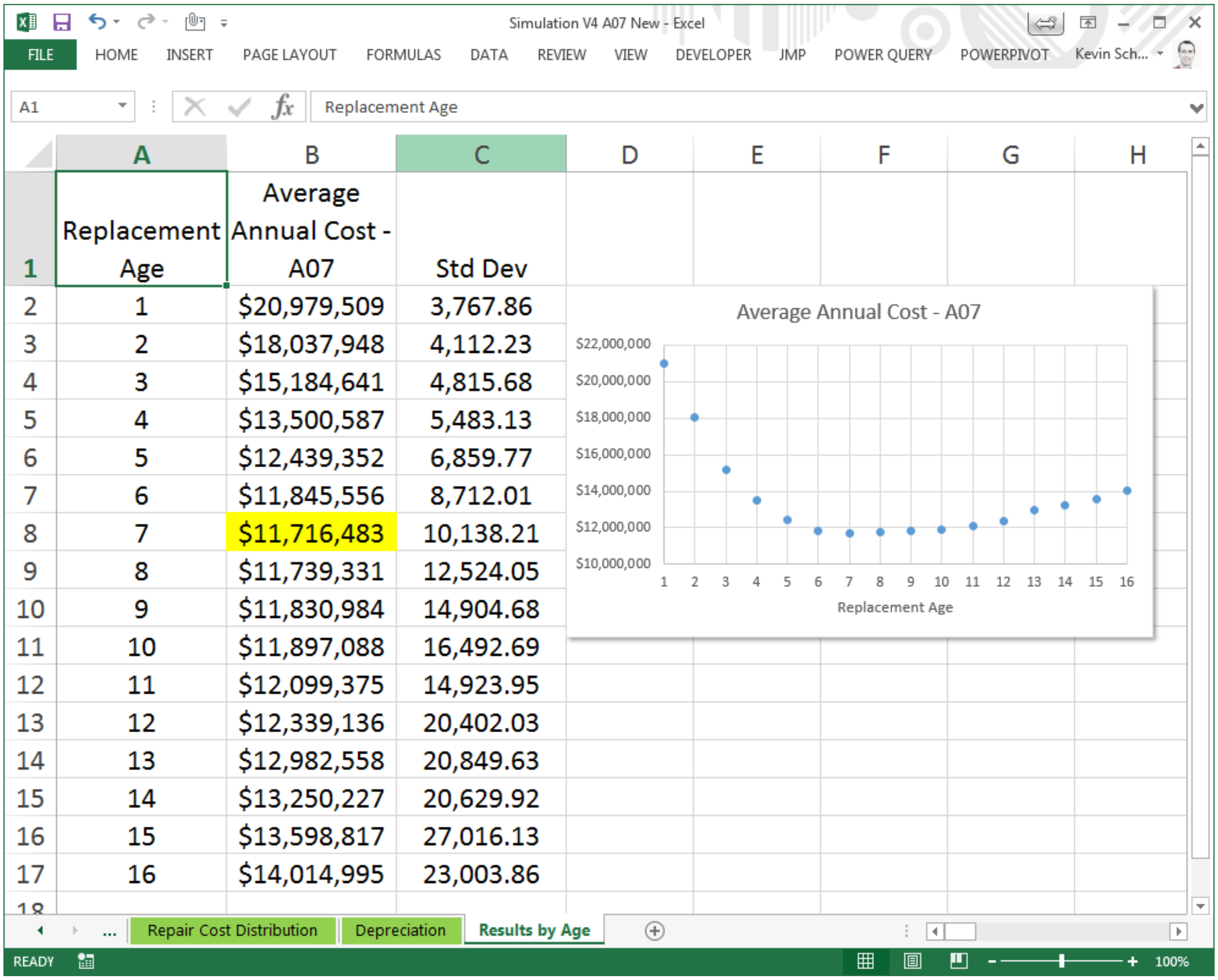
Depreciation Tab

The estimated resale data (like those shown earlier in Table 7) are placed in the Depreciation Tab. These data determine the percentage of the original value of a vehicle that will be recouped when sold in a given year.

DSS Results

Single-Axle A07 Results by Age

In this example, simulating the sale of A07 vehicles for 1 to 16 years reveals the results shown in Figure 9.



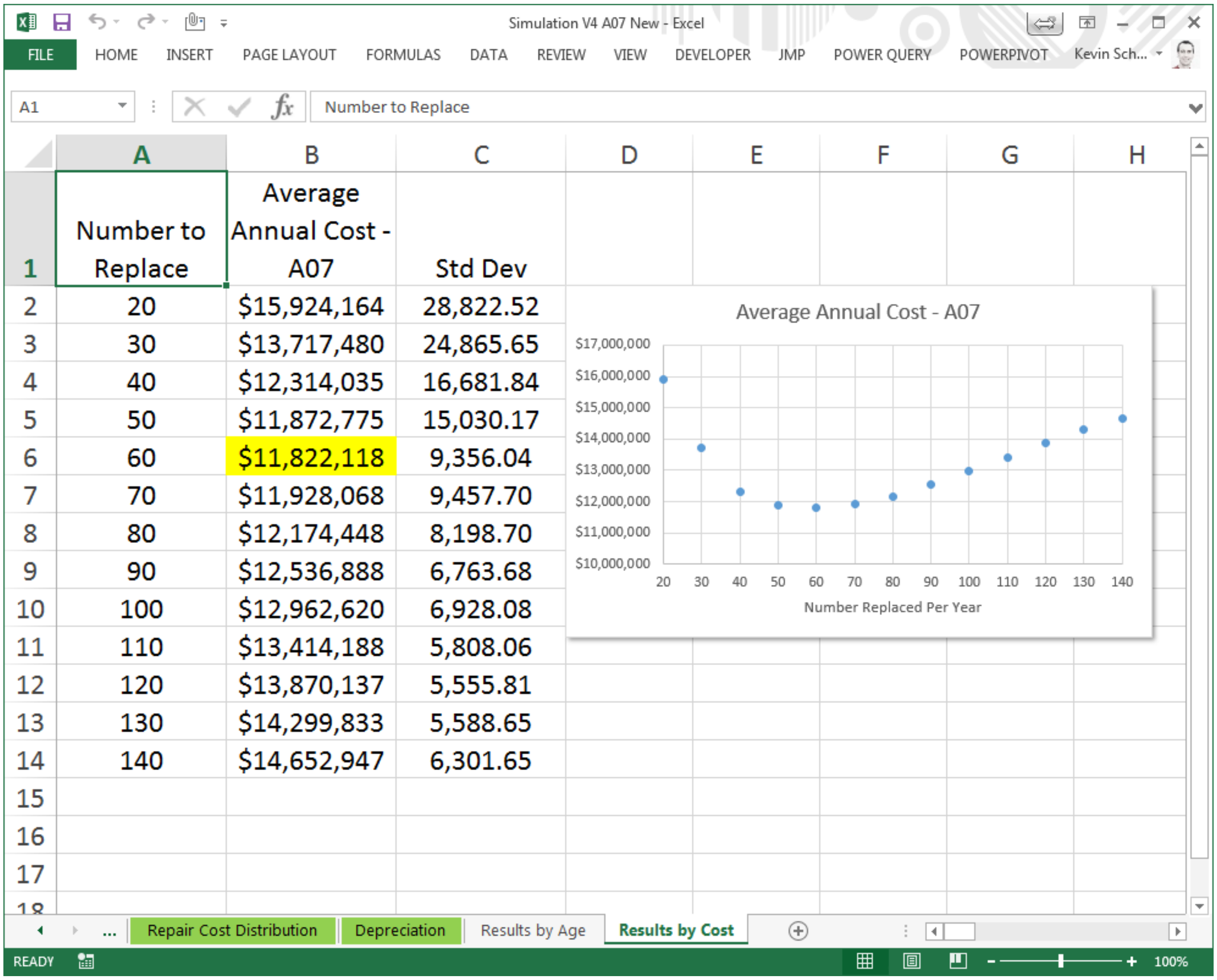
Replacement Age	Average Annual Cost - A07	Std Dev
1	$20,979,509	3,767.86
2	$18,037,948	4,112.23
3	$15,184,641	4,815.68
4	$13,500,587	5,483.13
5	$12,439,352	6,859.77
6	$11,845,556	8,712.01
7	$11,716,483	10,138.21
8	$11,739,331	12,524.05
9	$11,830,984	14,904.68
10	$11,897,088	16,492.69
11	$12,099,375	14,923.95
12	$12,339,136	20,402.03
13	$12,982,558	20,849.63
14	$13,250,227	20,629.92
15	$13,598,817	27,016.13
16	$14,014,995	23,003.86

Figure 9. A07 Results by Age

Given the current purchase price of $149,743 and the maintenance costs derived from the Iowa DOT data, the optimal sale point in terms of years is seven. The average annual cost for A07 vehicles if sold every seven years (assuming demand) would be $11,716,483 versus $13,598,817 if sold at year 15. Thus, by replacing A07 vehicles every seven years instead of 15, the Iowa DOT could save $1,882,334 on average per year.

Single-Axle A07 Results by Cost

Simulating the sale of A07 vehicles for 20 to 140 in increments of 10 reveals the results shown in Figure 10.



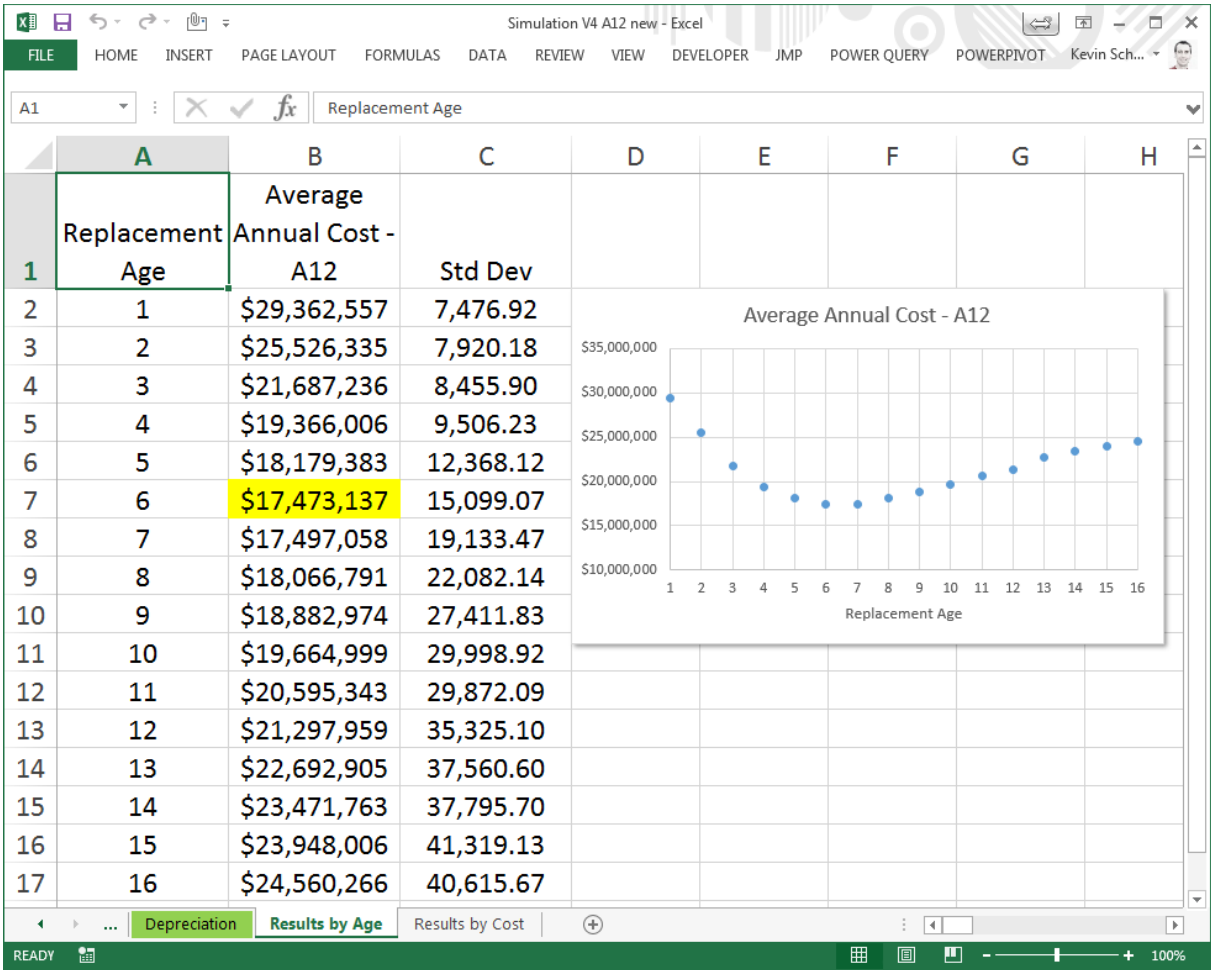
Number to Replace	Average Annual Cost - A07	Std Dev
20	$15,924,164	28,822.52
30	$13,717,480	24,865.65
40	$12,314,035	16,681.84
50	$11,872,775	15,030.17
60	$11,822,118	9,356.04
70	$11,928,068	9,457.70
80	$12,174,448	8,198.70
90	$12,536,888	6,763.68
100	$12,962,620	6,928.08
110	$13,414,188	5,808.06
120	$13,870,137	5,555.81
130	$14,299,833	5,588.65
140	$14,652,947	6,301.65

Figure 10. A07 Results by Cost

Given the current purchase price of $149,743 and the maintenance costs derived from the Iowa DOT data, the optimal sale point in terms of number to replace is 60 per year. The average annual cost for A07 vehicles if 60 are replaced per year (assuming demand) would be $11,822,118 versus $13,598,817 if sold at year 15. Thus, by replacing A07 vehicles every seven years instead of 15, the Iowa DOT could save $1,776,699 on average per year. Note, we are comparing replacing vehicles based on quantity with replacing them based on years, but there should be a fairly consistent number of vehicles replaced per year through a time-based normal replacement model.

Double-Axle A12 Results by Age

Simulating the sale of A12 vehicles for 1 to 16 years reveals the results shown in Figure 11.



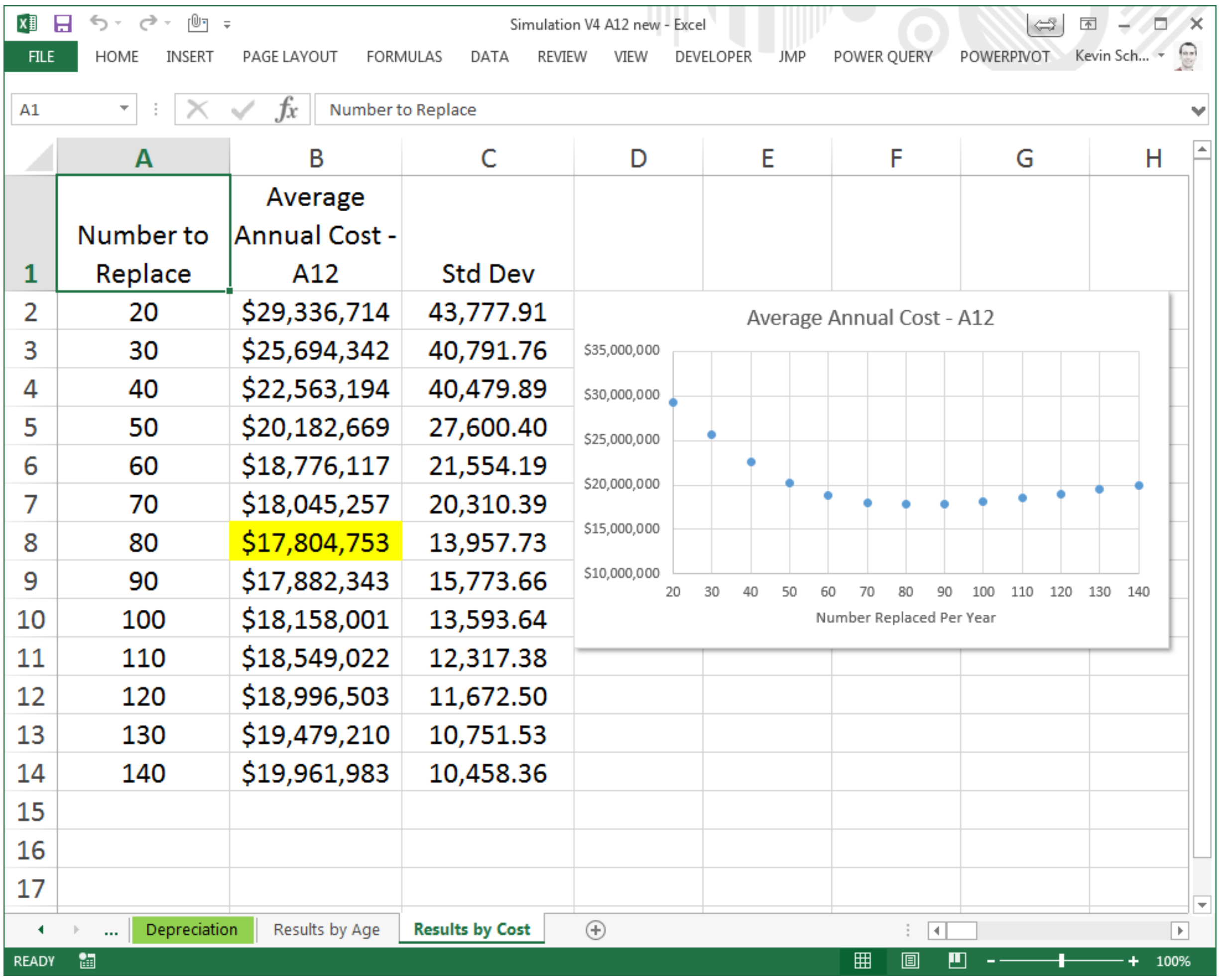
Replacement Age	Average Annual Cost - A12	Std Dev
1	$29,362,557	7,476.92
2	$25,526,335	7,920.18
3	$21,687,236	8,455.90
4	$19,366,006	9,506.23
5	$18,179,383	12,368.12
6	$17,473,137	15,099.07
7	$17,497,058	19,133.47
8	$18,066,791	22,082.14
9	$18,882,974	27,411.83
10	$19,664,999	29,998.92
11	$20,595,343	29,872.09
12	$21,297,959	35,325.10
13	$22,692,905	37,560.60
14	$23,471,763	37,795.70
15	$23,948,006	41,319.13
16	$24,560,266	40,615.67

Figure 11. A12 Results by Age

Given the current purchase price of $149,743 and the maintenance costs derived from the Iowa DOT data, the optimal sale point in terms of years is six. The average annual cost for A12 vehicles if sold every seven years (assuming demand) would be $17,473,137 versus $23,948,006 if sold at year 15. Thus, by replacing A12 vehicles every seven years instead of 15, the Iowa DOT could save $6,474,869on average per year.

Double-Axle A12 Results by Cost

Simulating the sale of A12 vehicles for 20 to 140 in increments of 10 reveals the results shown in Figure 12.



Number to Replace	Average Annual Cost - A12	Std Dev
20	$29,336,714	43,777.91
30	$25,694,342	40,791.76
40	$22,563,194	40,479.89
50	$20,182,669	27,600.40
60	$18,776,117	21,554.19
70	$18,045,257	20,310.39
80	$17,804,753	13,957.73
90	$17,882,343	15,773.66
100	$18,158,001	13,593.64
110	$18,549,022	12,317.38
120	$18,996,503	11,672.50
130	$19,479,210	10,751.53
140	$19,961,983	10,458.36

Figure 12. A12 Results by Cost

Given the current purchase price of $149,743 and the maintenance costs derived from the Iowa DOT data, the optimal sale point in terms of number to replace is 80 per year. The average annual cost for A12 vehicles if 80 are replaced per year (assuming demand) would be $17,804,753 versus $23,948,006 if sold at year 15. Thus, by replacing A12 vehicles every seven years instead of 15, the Iowa DOT could save $6,143,253 on average per year. Note, we are comparing replacing vehicles based on quantity with replacing them based on years, but there should be a fairly consistent number of vehicles replaced per year through a time-based normal replacement model.

Replication of Results

The results presented, like all of the results produced by the DSS, are a function of simulation runs. Some of the input parameters are distributions. The DSS will take those distributions and create a sample value for each simulation run. Thus, results will not always be the same, even when run on the exact same data. However, the results will generally be similar within a confidence interval.

As an analogy, if a vehicle gets a certain fuel economy, say eight miles per gallon, after making multiple observations of the same vehicle, the fuel economy will be close to that estimate, but not exact. There are variations in driving style, road conditions, fuel quality, etc. that will affect the actual numbers, but it should be expected to be near the estimated eight miles per gallon. The same idea applies to simulation runs, and it is that "robustness" that increases our confidence in the final results.

4. CONCLUSIONS

This research project investigates the predominant factors and analyzes equipment data to determine an optimal normal replacement model for the Iowa DOT's single-axle A07 and double-axle A12 vehicles considering maintenance cost, equipment replacement cost, and residual resale values. Two methods were considered: age of vehicle and cumulative maintenance costs.

In FY 2014, the fleet inventory for single-axle A07 and double-axle A12 vehicles was 364 and 456, respectively, with estimated purchase costs of approximately $134,500 and $150,000 per vehicle, respectively. Currently the Iowa DOT uses a 15-year depreciation for these vehicles. Thus, for FY 2015, the Iowa DOT planned on purchasing 24 single-axle A07s and 31 double-axle A12s.

The Iowa DOT provided the researchers with nine years of historical data for these vehicles, including purchase cost, maintenance cost, purchase date, and actual and estimated resale values. The estimated resale values were derived from actual data and through internal expert opinion. The resale value curve assumes 100% purchase price value at year 0 and approximately 12% of purchase price for single-axle A07s and 11% for double-axle A12s at year 17. It's an exponential curve with the greatest decrease in value in the initial years. Additionally, the Iowa DOT provided an estimated inflation adjustment of 4.23% based on historical data, which was used to adjust maintenance event costs for comparative analysis.

Using these data, the researchers were asked to evaluate and recommend a normal replacement model that would minimize total cost. Accordingly, we developed a series of simulations evaluating total cost of ownership for vehicles. We modified the simulations by replacing vehicles every 1, 2, 3, …, 15 years as well as replacing the top 20, 30, 40, …, 160 most expensive vehicles in terms of cumulative maintenance costs. We ran each scenario 30 times for 500 years each to allow for the full effect of modified variables. The total cost of ownership (TCO) equation was the cost of purchasing each truck plus the estimated maintenance cost per truck minus the value of the truck when sold.

The total purchase price of both classes of vehicles included a base cost and modification costs for extra equipment. It was necessary to estimate the total purchase price due to total data not provided by the Iowa DOT. Furthermore, maintenance costs were calculated only for work performed on the vehicle and not for work performed on modification equipment and those data were not provided by the Iowa DOT.

For the analysis performed, the additional costs were 38% above the vehicle purchase price for single-axle A07 vehicles and 41% above the purchase price for double-axle A12s. Furthermore, it was assumed that the resale value of each vehicle included the modification equipment.

Based on the data provided by the Iowa DOT and the estimated resale value curve of the vehicles, our research indicated that the optimal replacement model is eight years for single-axle

A07 vehicles and six years for double-axle A12 vehicles. Assuming the resale value curve is accurate, we estimate that the Iowa DOT would save approximately $1.8 million for single-axle A07s and $6.47 million for double-axle A12s per year by moving from a 15-year normal replacement model to eight years for single-axle A07s and six years for double-axle A12s.

APPENDIX. DETAILED STEPS FOR PREPARING DATA FOR THE IOWA DOT DSS

This research project investigates the predominant factors and analyzes equipment data to determine an optimal normal replacement model for the Iowa DOT's single-axle A07 and double-axle A12 vehicles considering maintenance cost, equipment replacement cost, and residual resale values.

The dataset provided by the Iowa DOT consists of equipment maintenance history for 6,187 vehicles for calendar years 2005 through 2013. It not only includes transactional (financial) data relating to maintenance of vehicles like purchase cost, maintenance cost, purchase date, and actual and estimated resale values of the vehicles, but also, usage parameters of vehicles in terms of hours, miles, meter readings, etc. The estimated resale values were derived partially from actual data and also from internal expert opinion.

For this research project, we focused on estimating equipment turnover to optimize equipment operation costs of A07 (single-axle snowplows) and A12 (double-axle snowplows), as these represented 31.7% and 45.6%, respectively, of the FY 2015 equipment replacement budget.

The Iowa DOT provided three data tables in a Microsoft Access database format:

1. **Equipment Information** consisted of maintenance information for vehicles belonging to seven different classes, out of which 1,483 vehicles were A07s or A12s. This table includes the cost year (year when the cost was incurred), warranty date, vehicle make and model, event cost, life usage in terms of miles, vehicle age up to corresponding fiscal year, total cost, purchase order number, estimated salvage value, estimated equipment end date and, other related information.

2. **Repair Cost Information** consisted of 1,065,002 instances of repairs of all vehicles recorded during the period 2005–2013 along with related transactional data on repairs like repair event cost, date, transaction type, object code, and other related information.

3. **Meter Log** consists of meter reading at every repair instance of each vehicle, which runs until 1,230,324 repair instances of all vehicles.

Data Extraction

The data extraction is done by querying and inspecting the access database for the necessary fields of vehicle data.

The A Number is a unique identifier for each vehicle, which was a key field of all three tables presenting different information of the vehicles. However, the structure of the database was not normalized to third normal form. It was necessary to create a separate table called ANums, which had the A Number as the primary key. In order to acquire normalized data of vehicles from required tables, we used the ANums table to join the Equipment Information table with the Repair Cost Information table. The reason we needed to join the tables was to bring together data from each table related to the associated A#.

Data Cleaning

This step helps to ensure the quality of data by detecting and removing anomalies or inaccurate records. Given the volume of data, errors in the data are expected. One example of anomalous data was for vehicle A28428. In the Repair Information table, that specific vehicle had a repair order with an object code of 610, 37,680 hours of labor and an event cost of $1,039,981.23. After bringing this to the attention of Iowa DOT staff, we were told it was a data input error, and that the hour meter was most likely erroneously entered as the labor hours. `

Such anomalies can be checked and found from manual inspection, calculating descriptive statistics of each field (average, mean, mode, IQR ranges, and variance), and identifying the outliers. This stage also included data exploration. Data visualization tools are also available to aid in identifying anomalies, but that is beyond the scope of this project.

Data Transformation

The transform step applies a set of rules to transform the data from the source to the target.

Missing Event Cost

While cleaning the data, another issue was found in the Repair Cost Information table, where many instances of the attribute [Event Cost] had zero amounts even though there were hours assigned in the [Hrs – Labor Hours] attribute. Thus, we were able to detect this missing data. Of the 1,065,002 records in the Repair Cost Information table, 84,306 records had a zero amount for the Event Cost, an Object Code of 610, and Hrs assigned to work greater than zero. After discussing this with Iowa DOT staff, it was determined that those values should be set as a function of an hourly rate times the number of hours worked on that vehicle for the specific event (Object Code 610). The Iowa DOT provided the past hourly rates shown in Table A-1.

Table A-1. Historical hourly rates

Fiscal Year	Date Range	Hourly Rate
2014	July 1, 2013-June 30, 2014	$42.37
2013	July 1, 2012-June 30, 2013	$40.37
2012	July 1, 2011-June 30, 2012	$37.36
2011	July 1, 2010-June 30, 2011	$37.36
2010	July 1, 2009-June 30, 2010	$37.36
2009	July 1, 2008-June 30, 2009	$37.36
2008	July 1, 2007-June 30, 2008	$35.74
2007	July 1, 2006-June 30, 2007	$32.02
2006	July 1, 2005-June 30, 2006	$32.02
2005	July 1, 2004-June 30, 2005	$28.27

In order to populate this data, an UPDATE query was written for each year to update the event cost. The one below is for FY 2013.

```
UPDATE    [Repair Cost Information] SET [Event Cost] = Hrs * 40.37
WHERE     [Repair Cost Information].[Repair Date] Between #1/1/2013# And #12/31/2013#
AND       [Repair Cost Information].[Object] = = "610"
AND       [Repair Cost Information].[Event Cost])=0;
```

This UPDATE query was repeated for each year with data parameters. The query looks for every record with an [Object] value of 610 and [Event Cost] of 0. It would then modify the [Event Cost] to be the number of hours found in [Hrs] times the hourly rate set for that time period.

Missing B on A Equipment Costs

Another missing piece of information that became important in our analysis is the B on A costs. The Total Cost of a vehicle in the Equipment Information table is the purchase price plus any improvements made to the vehicle. What is not included in that amount is the B equipment that is installed. For example, a snow blade is B equipment that is installed on a snowplow truck. It is not included in the A costs of the vehicle, and it was not provided by the Iowa DOT. Furthermore, the maintenance costs in the Repair Cost Information table is only for A equipment maintenance events and not for the B on A equipment. However, the Iowa DOT asked that we include the “total” cost (B on A included) in our simulation to better reflect the true costs of equipment. Consequently, we were given the data shown in Table A-2.

Table A-2. B on A equipment costs

Year	# Purchased	Average A Cost	Average B Cost	Average Total
FY 2014	23 Single-Axle A07	$109,655	$38,404	$148,058
FY 2014	28 Double-Axle A12	$97,796	$45,593	$168,965
FY 2015	20 Single-Axle A07	$108,508	$41,236	$149,743
FY 2015	33 Double-Axle A12	$123,114	$50,923	$174,037

Thus, for FY 2015, the B equipment costs for single-axle A07 vehicles was about 38% of A equipment cost and about 41.3% of A equipment cost for double-axle A12 vehicles.

Event Cost Adjustment

Another important step in transformation was to normalize the costs of all vehicles based on their age with respect to each fiscal year (adjusted for inflation). Hence, adjustment was required to the event cost of vehicles, which were specific ages at different dates. Events for vehicles one year old may have occurred in 2005, 2006, 2007, …, 2013. Therefore, after discussing this with the Iowa DOT, we agreed to adjust the maintenance event cost by 4.23% per year. This adjustment value was determined based on the expert opinion of Iowa DOT staff. By adjusting the event cost we were able to compare repair costs of each vehicle or class based on the age of the vehicles irrespective of the fiscal year of the repairs.

The query for the maintenance adjustment is shown here:

```
SELECT DISTINCT    [Repair Cost Information].[A#],
                   [Repair Cost Information].[Class Key],
                   [Repair Cost Information].[Repair Date],
                   [Repair Cost Information].[Cost Year],
                   [Equip Info].[Fiscal Year],
                   [Equip Info].[Life Usage],
                   [Repair Cost Information].[Years Old],
                   [Repair Cost Information].Object,
                   2013-Year([Repair Cost Information].[Repair Date]) AS YRS,
                   [Repair Cost Information].[Event Cost],
                   [Repair Cost Information].[Event Cost]*(1.0423)^YRS AS ADJCost,
                   [Equip Info].[Total Cost],
                   [Equip Info].[Equip Status Desc],
                   [Equip Info].[Salvage Value]
FROM               (ANums INNER JOIN [Repair Cost Information]
ON                 ANums.A_Num = [Repair Cost Information].[A#])
INNER JOIN         [Equip Info]
ON                 ANums.A_Num = [Equip Info].[A Number]
WHERE              [Repair Cost Information].[Cost Year]=[Equip Info].[Fiscal Year];
```

Note that the line [Repair Cost Information].[Event Cost]*(1.0423)^YRS AS ADJCost creates an adjusted cost as a function of 4.23% to the power of the number of years old the vehicle is. ANums is the table that contains the unique identifiers of the vehicles; i.e., A Numbers.

Data Loading

The required fields retrieved from the dataset are as follows:

A Number, Class Key, Repair Date, Cost Year, Fiscal Year, Life Usage, Years Old (age), Object Code, Equipment Status Description. There are two derived or calculated fields: YRS (number of years from the time the repair/maintenance event occurred on the vehicle until the present) and ADJCost (repair cost adjusted to the set inflation rate, i.e., 4.23% to the power of age of the vehicle in years).

The line ([Repair Cost Information].[Event Cost]*(1.0423)^YRS AS ADJCost,) was the normalizing function for all vehicles across all years. The INNER JOIN was necessary because the Iowa DOT data were not historically synchronized. Thus, the INNER JOIN causes the query to return only maintenance data for which the years coincided with equipment information data.

This query result is then saved as a new database table object. The table result is then exported from the Access database object into Excel.

Once the missing data fields have been filled in and the adjusted maintenance events have been calculated, we migrate the data into Excel for further manipulation. The Excel workbook contains PivotTable computations and visualizations to create the DSS model.

DSS Model

Home Tab

The user enters the vehicle type and the total vehicle purchase price (this value, which is calculated, can be found on the Inventory tab). The user also has the option to vary the number of years to simulate as well as the number of years to reach steady state.

Years to Simulate

The DSS will run multiple analyses varying the replacement model. By simulating over a long period of time, we are able to view trends from the perspective of a normal distribution. By increasing our simulation years and by replicating the simulations, we are able to calculate an average cost and avoid short-term variations in the data. Thus, we can observe the average cost of selling vehicles every one year, two years, three years, and so on, or we can observe selling the 10 most expensive vehicles, 20 most expensive vehicles, and so on. By most expensive, we mean in terms of maintenance costs.

Years to Steady State

When running simulations, it is necessary to establish a steady state. That is to say, when simulations begin, they are often affected by initial inputs with greater degrees of variation. It is common practice to allow a simulation to reach a steady state before observing the results. The length of the steady state run can vary, and we allow the users to adjust this, with a minimum of 20 years.

Replications per Policy Level

We repeat each sale policy to observe results that are normally distributed. In general statistical terms, a minimum of 30 observations are required to estimate a population. Thus, by repeating each policy (30 times) we can say the results will be contained in a normal distribution. We set the maximum replication to 30 for statistical power, but allow the simulation to have fewer replications for testing and observation. (It takes less time to run fewer replications.)

In addition, the DSS system contains two buttons on which macro code is written to take the input parameters and values from the Home Page tab and other necessary tables to generate the replacement analysis results either by resale year (age) or by cost.

Inventory Tab

The Inventory Tab contains four attributes:

- Asset ID
- Cumulative Maintenance
- Purchase Price
- Age

Asset ID

This is the A Number unique to each vehicle.

Cumulative Maintenance

This is the total cumulative maintenance costs for each vehicle. This value comes from the [Repair Cost] table attribute [Event Cost]. The values of [Event Cost] need to be adjusted for inflation. We adjusted the values by 4.23% based on analysis of the data and discussion with Iowa DOT personnel. Additionally, many values in the [Repair Cost].[Event Cost] field were 0, but hours had been spent working on the equipment. Therefore, it is necessary to assign values to those fields to derive an accurate cumulative maintenance cost. This was accomplished by assigning an hourly rate times the number of hours spent on the repair task. An example update query is shown setting a $40.37 hourly rate times the number of hours per repair event:

```
UPDATE    [Repair Cost Information] SET [Event Cost] = Hrs * 40.37
WHERE     ((([Repair Cost Information].[Repair Date]) Between #1/1/2013# And
          #12/31/2013#) AND (([Repair Cost Information].[Event Cost])=0));
```

This hourly rate is adjusted for each year. The adjustment was determined through discussion with Iowa DOT personnel.

Purchase Price

The Total Cost value provided by the Iowa DOT was on A costs (truck without add-ons). The Iowa DOT did not provide B on A costs for add-on equipment such as snow blades or salt spreaders. To simulate costs that are closer to real total costs, we added a percentage to the A costs to approximate B equipment costs. The percentage was calculated using a sample of actual costs that was then applied to all vehicles. The research team recommends that the Iowa DOT actually collect total purchase price to increase the accuracy of the simulation. For the purposes of this simulation for FY 2015, we estimated B on A costs for A07 vehicles as about 38% of the A costs and about 41.3% for A12 vehicles.

Age

The age of the vehicle in year 2013 was necessary for the simulation. Note that all vehicles on the Inventory Tab were currently set with an Active status in the Equipment Status Descriptor. Due to the status tabs created by the DOT, there may be other active vehicles but with a better status descriptor. For simplicity, we selected only those with the Active status indicator. We recommend that the Iowa DOT staff consider modifying and consolidating vehicle status tags for future analysis. For example, another status used by Iowa DOT is Loaner. Thus, vehicles under the Loaner status were not included in the analysis.

Repair Cost Distribution Tab

The Repair Cost Distribution Tab contains the required maintenance cost input parameters for the simulation. The values in this distribution were generated from the data. All maintenance costs were calculated for vehicles at each yearly age. So, maintenance costs for all vehicles one year old were summarized. The same was done for two-year-old, three year old, and so on, up to year 18. It is necessary to adjust the maintenance costs by year, because a one-year-old vehicle in 2013 would have higher maintenance costs than a one-year-old vehicle in 2000 due to inflation.

The Excel workbook is retrieved from the Access dataset with the required parameters. To construct the Repair Cost Distribution Tab, we need to implement a PivotTable in Excel. The PivotTable should have Class Key as the Filter, so you can distinguish between A07 and A12 vehicles. The columns should contain the A Numbers. The rows should contain Years Old, and the summary values should contain the sum of the adjusted maintenance costs. Additionally, select the filter on row labels to show only those vehicles with years 0 through 18.

Once the PivotTable has been created, you will copy the values (not including the Grand Totals) into the top 19 rows of the Repair Cost Distribution sheet. On that sheet, rows 22 through 40 are a set of formulas that calculate a running total. The Repair Cost Distribution is based on the running totals of adjusted maintenance costs. The Min, 25th, 50th, 75th, and Max of each row (for each year) are at the far right side of the Running Totals table. This table is essential for the simulation estimates.

The Inventory table generation requires data preparation in Excel. Initially, a PivotTable is generally utilizing all the fleet data extracted for a particular class (A07s or A12s). The PivotTable is generated to get summed adjustment cost of each vehicle over its age. The Values field is populated with sum of Adjusted Cost, Columns field with A Number of the vehicle, and the Rows field is populated with Years Old (age). See Figure A-1 for the PivotTable options.

Sum of ADJCost	Column Labels									
Row Labels	A26705	A26718	A27628	A27632	A27634	A27637	A27639	A27642	A27643	A27646
0										
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
12			8517.234211			2983.241225		4626.94635	9701.941645	31536.61408
13			1257.508981	6886.623007	17265.08861	3874.163135	13553.92282	7514.061864	7928.665358	4709.597928
14		6586.813978	5558.473591	5847.495612	3854.677853	3616.835207	3176.715676	2687.559357	5775.768352	12154.78707
15	1397.650826	6404.991171	15044.92911	1703.87968	2263.188984	11065.68683	6050.339074	12428.14479	5774.620225	4582.306517
16	6919.854324	11883.02437	2044.721517	6916.263399	7249.047882	4667.926696	16889.20615	1759.067621	3682.460293	3559.207653
17	2577.674652	6081.091459	2214.343119	1338.641927	17229.45144	3510.265027	7964.412549	3413.483623	1116.536041	11541.76273
18	6227.296678	8988.378437		4832.67245	7607.59357	1309.066503	6658.168792			2078.338759
19	5212.206954	5774.793612		4490.285941	26.72517653		3225.84831			
20	2559.209673						380.898112			
Grand Total	**24893.89311**	**45719.09303**	**34637.21053**	**32015.86202**	**55495.77351**	**31027.18462**	**57899.51148**	**32429.2636**	**33979.99191**	**70162.61474**

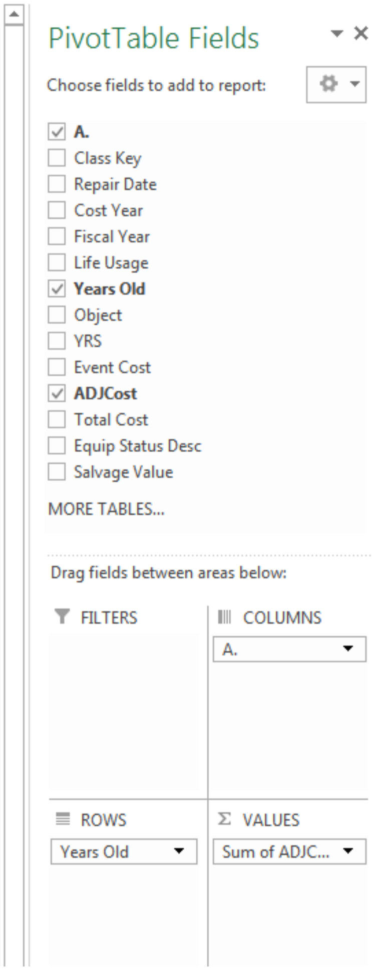


Figure A-1. PivotTable generation

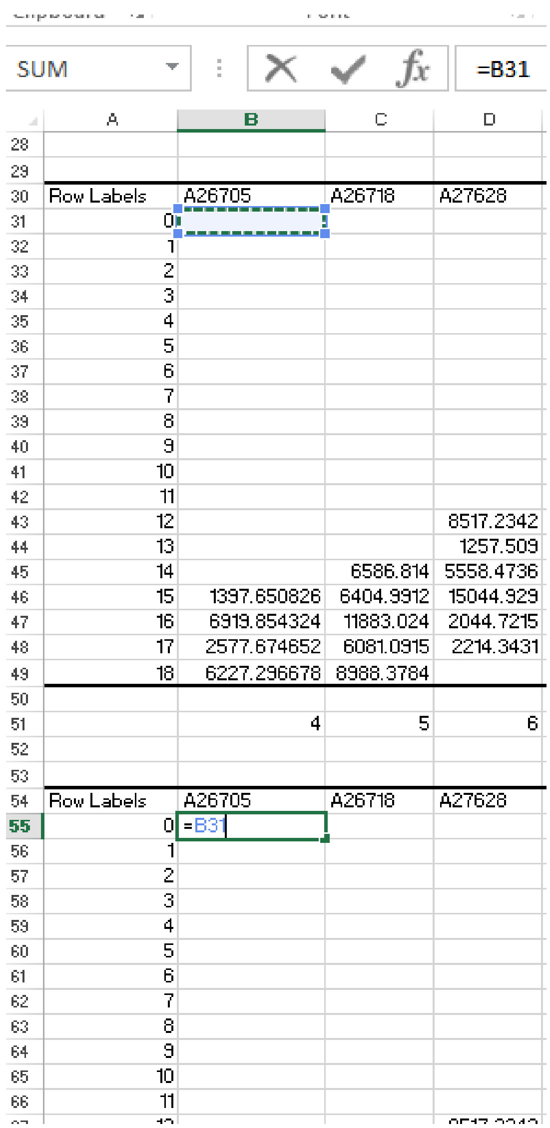
Further, we aim to retrieve the cumulated values of adjusted cost with increasing age of the vehicle. That is, we need the adjusted cost of a vehicle at any point of vehicle age, to be the sum of the past and current repair cost.

Sum of ADJC	Column Lab																			
Row Label	A267 5	A26718	A27628	A27632	A27634	A27637	A27639	A27642	A27643	A27646	A28 75	A28 76	A28 77	A28 78	A28 79	A28 8	A28 81	A28 82	A28 85	A2
1																				
2																				
3																				
4																				
5																				
6																				
7																				
8																				
9																				
10																				
11											11232.412	15160.101	9532.6818	10434.714	10955.267	18902.79	12045.6	5178.5209	9581.5611	54
12			8517.2342			2983.2412		4626.9464	9701.9416	31536.614	11933.88	9154.7814	10930.388	2897.7607	2894.2593	1691.1434	3783.3788	11987.471	12251.618	4
13			1257.509	6886.623	17265.089	3874.1631	13553.923	7514.0619	7928.6654	4709.5979	5376.0419	14437.863	2675.7118	6383.6731	4330.4575	2184.59	11409.764	14647.888	9138.5481	92
14		6586.814	5558.4736	5847.4956	3854.6779	3616.8352	3176.7157	2687.5594	5775.7684	12154.787	9654.8095	8476.4459	14247.117	6832.6244	4917.6743	6545.0977	14809.119	21326.808	7629.1815	2
15	1397.650826	6404.9912	15044.929	1703.8797	2263.189	11065.687	6050.3391	12428.145	5774.6202	4582.3065	9754.7802	10005.959	6717.7233	12450.11	10560.012	6116.5553	9558.5886	9336.5379	7756.3831	5
16	6919.854324	11883.024	2044.7215	6916.2634	7249.0479	4667.9267	16889.206	1759.0676	3682.4603	3559.2077	1244.1285	16830.883	3488.1617	3826.9023	16309.654	1729.7907	11305.952	15003.552	2794.9183	6
17	2577.674652	6081.0915	2214.3431	1338.6419	17229.451	3510.265	7964.4125	3413.4836	1116.536	11541.763		12349.476	7673.6238	4477.2819	13366.488			11183.845		68
18	6227.296678	8988.3784		4832.6724	7607.5936	1309.0665	6658.1688			2078.3388		2745.6579	7355.8551	719.23912	6558.5581			972.08025		30
Grand Total	**17122.4765**	**39944.3**	**34637.2**	**27525.6**	**55469**	**31027.2**	**54292.8**	**32429.3**	**33980**	**70162.6**	**49196.1**	**89161.2**	**62621.3**	**48022.3**	**69892.4**	**37170**	**62912.4**	**89636.7**	**49152.2**	**4**

Row Labels	A26705	A26718	A27628	A27632	A27634	A27637	A27639	A27642	A27643	A27646	A28075	A28076	A28077	A28078	A28079	A28080	A28081	A28082	A28085	A2
0																				
1																				
2																				
3																				
4																				
5																				
6																				
7																				
8																				
9																				
10																				
11											11232.412	15160.101	9532.6818	10434.714	10955.267	18902.79	12045.6	5178.5209	9581.5611	54
12			8517.2342			2983.2412		4626.9464	9701.9416	31536.614	11933.88	9154.7814	10930.388	2897.7607	2894.2593	1691.1434	3783.3788	11987.471	12251.618	4
13			1257.509	6886.623	17265.089	3874.1631	13553.923	7514.0619	7928.6654	4709.5979	5376.0419	14437.863	2675.7118	6383.6731	4330.4575	2184.59	11409.764	14647.888	9138.5481	92
14		6586.814	5558.4736	5847.4956	3854.6779	3616.8352	3176.7157	2687.5594	5775.7684	12154.787	9654.8095	8476.4459	14247.117	6832.6244	4917.6743	6545.0977	14809.119	21326.808	7629.1815	2
15	1397.650826	6404.9912	15044.929	1703.8797	2263.189	11065.687	6050.3391	12428.145	5774.6202	4582.3065	9754.7802	10005.959	6717.7233	12450.11	10560.012	6116.5553	9558.5886	9336.5379	7756.3831	5
16	6919.854324	11883.024	2044.7215	6916.2634	7249.0479	4667.9267	16889.206	1759.0676	3682.4603	3559.2077	1244.1285	16830.883	3488.1617	3826.9023	16309.654	1729.7907	11305.952	15003.552	2794.9183	6
17	2577.674652	6081.0915	2214.3431	1338.6419	17229.451	3510.265	7964.4125	3413.4836	1116.536	11541.763		12349.476	7673.6238	4477.2819	13366.488			11183.845		68
18	6227.296678	8988.3784		4832.6724	7607.5936	1309.0665	6658.1688			2078.3388		2745.6579	7355.8551	719.23912	6558.5581			972.08025		30

Figure A-2. PivotTable alteration to get cumulative cost values

We use this second table to calculate the cumulative values. Now, once again, copy the whole table, as shown at the top of Figure A-3,(for the third time) to rows below. Delete all the repair cost values in the copied rows, retaining only row and column labels (age and A Numbers).



	A	B	C	D
28				
29				
30	Row Labels	A26705	A26718	A27628
31	0			
32	1			
33	2			
34	3			
35	4			
36	5			
37	6			
38	7			
39	8			
40	9			
41	10			
42	11			
43	12			8517.2342
44	13			1257.509
45	14		6586.814	5558.4736
46	15	1397.650826	6404.9912	15044.929
47	16	6919.854324	11883.024	2044.7215
48	17	2577.674652	6081.0915	2214.3431
49	18	6227.296678	8988.3784	
50				
51		4	5	6
52				
53				
54	Row Labels	A26705	A26718	A27628
55	0	=B31		
56	1			
57	2			
58	3			
59	4			
60	5			
61	6			
62	7			
63	8			
64	9			
65	10			
66	11			

Figure A-3. First cell calculation

Go to the first cell of the table, which is the cell corresponding to Age 0 of the first vehicle (A26705, in this case), and make this value equal to the corresponding value in the above table as shown in the bottom part of Figure A-3. Go to the next cell, which is cell corresponding to Age 1 and the first vehicle (A26705, in this case). Here, the cell value is the sum of the current value of the field from the above table (cell corresponding to Age 1 of A26705) and the value of the cost for the previous age period (cell corresponding to Age 0) of the same table, as shown in the bottom part of Figure A-4.

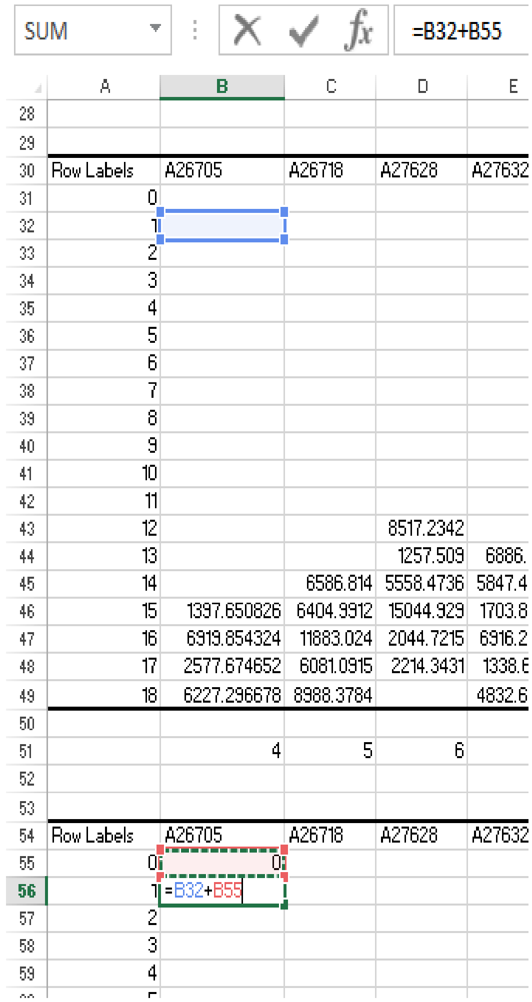


Figure A-4. Second cell calculation

Repeat these steps for all cumulative repair cost values for the first vehicle across all of the age groups (0–18).

Now, drag the formula of each cell of this vehicle corresponding to an age group, horizontally, to spread the formula to all the vehicles of that particular age group. This operation will copy the formula of the cell to subsequent horizontal cells of that age group. To elaborate, the formula of repair cost at age 0 will get copied and applied to all of the vehicle repair costs at their age 0 periods.

Repeat this step of formula replication (by dragging horizontally to copy the formula) for all of the vehicles across all age groups. This step would fill the table with cumulative values. However, the issue that we encounter is that, an empty value is represented by 0.

We need to then remove the zeros from the table. The resulting table is like the one shown in Figure A-5 with cumulative values highlighted.

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	
Row Labels	A26705	A26718	A27628	A27632	A27634	A27637	A27639	A27642	A27643	A27646	A28075	A28076	A28077	A28078	A28079	A28080	A28081	A28082	A28085	A2
0																				
1																				
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5																				
6																				
7																				
8																				
9																				
10																				
11											11232.412	15160.101	9532.6818	10434.714	10955.267	18902.79	12045.6	5178.5209	9581.5611	54
12			8517.2342			2983.2412		4626.9464	9701.9416	31536.614	11933.88	9154.7814	10930.388	2897.7607	2894.2593	1691.1434	3783.3788	11987.471	12251.618	4
13			1257.509	6886.623	17265.089	3874.1631	13553.923	7514.0619	7928.6654	4709.5979	5376.0419	14437.863	2675.7118	6383.6731	4330.4575	2184.59	11409.764	14647.888	9138.5481	92
14		6586.814	5558.4736	5847.4956	3854.6779	3616.8352	3176.7157	2687.5594	5775.7684	12154.787	9654.8095	8476.4459	14247.117	6832.6244	4917.6743	6545.0977	14809.119	21326.808	7629.1815	2
15	1397.650826	6404.9912	15044.929	1703.8797	2263.189	11065.687	6050.3391	12428.145	5774.6202	4582.3065	9754.7802	10005.959	6717.7233	12450.11	10560.012	6116.5553	9558.5886	9336.5379	7756.3831	5
16	6919.854324	11883.024	2044.7215	6916.2634	7249.0479	4667.9267	16889.206	1759.0676	3682.4603	3559.2077	1244.1285	16830.883	3488.1617	3826.9023	16309.654	1729.7907	11305.952	15003.552	2794.9183	6
17	2577.674652	6081.0915	2214.3431	1338.6419	17229.451	3510.265	7964.4125	3413.4836	1116.536	11541.763		12349.476	7673.6238	4477.2819	13366.488			11183.845		68
18	6227.296678	8988.3784		4832.6724	7607.5936	1309.0665	6658.1688			2078.3388		2745.6579	7355.8551	719.23912	6558.5581			972.08025		30
	4	5	6	6	6	7	6	6	6	7	6	8	8	8	8	6	6	8	6	
Row Labels	A26705	A26718	A27628	A27632	A27634	A27637	A27639	A27642	A27643	A27646	A28075	A28076	A28077	A28078	A28079	A28080	A28081	A28082	A28085	A2
0																				
1																				
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5																				
6																				
7																				
8																				
9																				
10																				
11											11232.412	15160.101	9532.6818	10434.714	10955.267	18902.79	12045.6	5178.5209	9581.5611	54
12			8517.2342			2983.2412		4626.9464	9701.9416	31536.614	23166.292	24314.883	20463.07	13332.474	13849.526	20593.933	15828.979	17165.992	21833.179	9
13			9774.7432	6886.623	17265.089	6857.4044	13553.923	12141.008	17630.607	36246.212	28542.334	38752.746	23138.781	19716.148	18179.984	22778.523	27238.743	31813.879	30971.727	1
14		6586.814	15333.217	12734.119	21119.766	10474.24	16730.638	14828.568	23406.375	48400.999	38197.143	47229.192	37385.899	26548.772	23097.658	29323.621	42047.862	53140.688	38600.909	2
15	1397.650826	12991.805	30378.146	14437.998	23382.955	21539.926	22780.978	27256.712	29180.996	52983.306	47951.924	57235.151	44103.622	38998.882	33657.67	35440.176	51606.45	62477.226	46357.292	2
16	8317.50515	24874.83	32422.867	21354.262	30632.003	26207.853	39670.184	29015.78	32863.456	56542.513	49196.052	74066.034	47591.784	42825.784	49967.324	37169.967	62912.402	77480.778	49152.21	3
17	10895.1798	30955.921	34637.211	22692.904	47861.455	29718.118	47634.596	32429.264	33979.992	68084.276		86415.51	55265.407	47303.066	63333.812			88664.623		40
18	17122.47648	39944.299		27525.576	55469.048	31027.185	54292.765			70162.615		89161.168	62621.262	48022.305	69892.37			89636.703		4
19	4	5	6	6	6	7	6	6	6	7	6	8	8	8	8	6	6	8	6	

Figure A-5. Prepared data for generating data summaries of Inventory Tab

Now, we head to calculating the quartile values of repair cost of each vehicle across their age to get values in the form of the Inventory Tab.

At the right end of this final table with cumulated values, we calculate the Minimum, 25th, 50th, 75th, and Maximum value of the cumulated value of repair cost for each vehicle at the corresponding age. Figure A-6 shows the calculation and the required formulae are under the figure.

67	A33676	A3367	A3368	A3368	A3368	A3368	A3368	A3368	A3368	A3368	A3369	Age	Min	25th	50th	75th	Max
1.2	2143	96.47	256.5	99.99	48	88.2	420.8	625	598.3	68.3	384.5	0	$2.09	$152.58	$351.55	$777.08	$7,478.69
												1	$276.45	$1,665.01	$2,633.66	$3,838.20	$19,468.83
												2	$876.27	$3,692.46	$5,503.24	$7,711.36	$22,695.74
												3	$2,199.31	$5,677.44	$7,770.90	$11,927.55	$28,320.12
												4	$3,247.72	$8,477.33	$11,131.43	$15,905.58	$37,607.83
												5	$3,147.79	$11,117.89	$16,030.18	$23,720.91	$53,930.98
												6	$3,169.20	$11,492.75	$18,666.84	$30,859.06	$59,853.55
												7	$3,599.00	$17,108.75	$26,654.02	$39,690.11	$80,643.17
												8	$3,010.33	$21,130.41	$31,839.44	$47,816.16	$97,116.58
												9	$1,638.66	$22,176.75	$37,216.22	$56,042.47	$110,174.04
												10	$1,123.86	$20,469.43	$42,934.04	$64,290.44	$133,941.77
												11	$3,036.81	$23,426.96	$46,677.65	$68,907.49	$138,964.11
												12	$2,983.24	$29,363.90	$51,407.17	$76,067.88	$150,250.37
												13	$6,857.40	$35,996.15	$55,357.39	$80,365.18	$156,963.03
												14	$6,586.81	$41,151.03	$57,303.61	$80,458.82	$156,279.73
												15	$1,397.65	$45,124.11	$55,053.16	$76,815.19	$121,984.97
												16	$8,317.51	$50,172.97	$61,176.20	$84,864.88	$131,828.95
												17	$10,895.18	$52,397.37	$63,741.97	$87,766.90	$134,630.57
												18	$17,122.48	$54,143.90	$65,416.33	$83,836.69	$137,605.15

Figure A-6. Data summary generation

Formulae

Minimum: "=MIN(cumulated repair cost values of all vehicles across each age group)"
25th: ="QUARTILE(cumulated repair cost values of all vehicles across each age group, 1)"
50th: ="QUARTILE(cumulated repair cost values of all vehicles across each age group, 2)"
75th: ="QUARTILE(cumulated repair cost values of all vehicles across each age group, 3)"
Maximum: "=MAX(cumulated repair cost values of all vehicles across each age group)"

Figure A-7 shows an example of the Repair Cost Distribution Tab.

Repair Cost		Percentiles			
Year	Min	25th	50th	75th	Max
1	$276.4	$1,293.2	$2,004.9	$3,024.5	$19,374.4
2	$876.3	$3,346.5	$4,992.6	$6,889.3	$22,601.3
3	$2,199.3	$5,541.3	$7,472.0	$11,136.4	$28,320.1
4	$3,247.7	$8,298.4	$10,998.5	$15,121.0	$37,607.8
5	$3,147.8	$11,091.1	$15,905.5	$23,210.7	$53,931.0
6	$3,169.2	$11,492.8	$18,666.8	$30,797.8	$59,853.6
7	$3,599.0	$17,108.7	$26,498.8	$39,461.6	$77,813.2
8	$3,010.3	$21,130.4	$31,698.4	$47,816.2	$97,116.6
9	$1,638.7	$22,176.8	$37,216.2	$56,042.5	$110,174.0
10	$1,123.9	$20,469.4	$42,934.0	$64,290.4	$133,941.8
11	$3,036.8	$23,351.3	$46,349.1	$68,829.8	$138,964.1
12	$2,983.2	$29,363.9	$51,407.2	$76,067.9	$150,250.4
13	$6,857.4	$35,996.2	$55,357.4	$80,365.2	$156,963.0
14	$6,586.8	$41,151.0	$57,303.6	$80,458.8	$156,279.7
15	$1,397.7	$45,124.1	$55,053.2	$76,815.2	$121,985.0
16	$8,317.5	$50,173.0	$61,176.2	$84,864.9	$131,828.9
17	$10,895.2	$52,397.4	$63,742.0	$87,766.9	$134,630.6
18	$17,122.5	$54,143.9	$65,416.3	$83,836.7	$137,605.1

Figure A-7. Repair Cost Distribution Tab example

Depreciation Tab

The Depreciation Tab was created after consultation with Iowa DOT personnel. This tab provides an expected resale value of vehicles if sold in year 1, 2, 3, …, 17. We did not move beyond 17 years as the original data was fairly consistent with sales of vehicles occurring at or before that year. We created an exponential curve with the greatest devaluation occurring in the first four years and a more gradual decline in years 5 through 17 (see Table A-3).

Table A-3. Most likely estimated resale values for A07 and A12 vehicles by year sold

Resale at Year	Resale Value
1	70%
2	50%
3	40%
4	34%
5	31%
6	28%
7	26%
8	24%
9	22%
10	21%
11	19%
12	18%
13	17%
14	15%
15	14%
16	13%
17	12%

This table can be updated when more accurate historical data are collected. Figure A-8 provides a graph of the sale values as a percentage of the original purchase price.

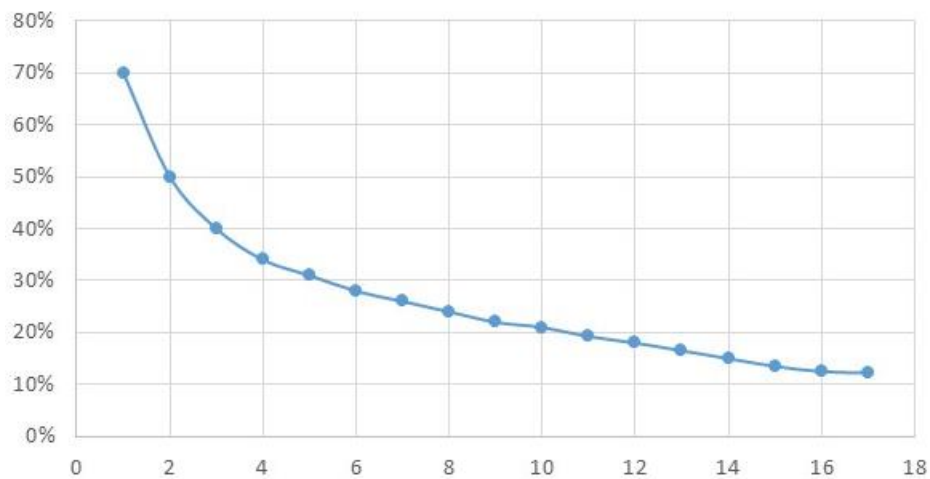

Figure A-8. Estimated resale values

For each year, we then calculate Most Likely, Maximum, and Minimum likelihood of estimated values (see Table A-4), and plot the values in Figure A-9 to get better insight about the variation of the resale values at particular years/age of the vehicles.

Table A-4. Estimated resale values for A07 and A12 vehicles by year sold

Year	Min	Most Likely	Max
1	60%	70%	80%
2	40%	50%	60%
3	31%	40%	49%
4	25%	34%	43%
5	23%	31%	39%
6	20%	28%	36%
7	19%	26%	33%
8	17%	24%	31%
9	16%	22%	28%
10	15%	21%	27%
11	14%	19%	24%
12	13%	18%	23%
13	13%	17%	21%
14	11%	15%	19%
15	11%	14%	17%
16	10%	13%	16%
17	10%	12%	14%

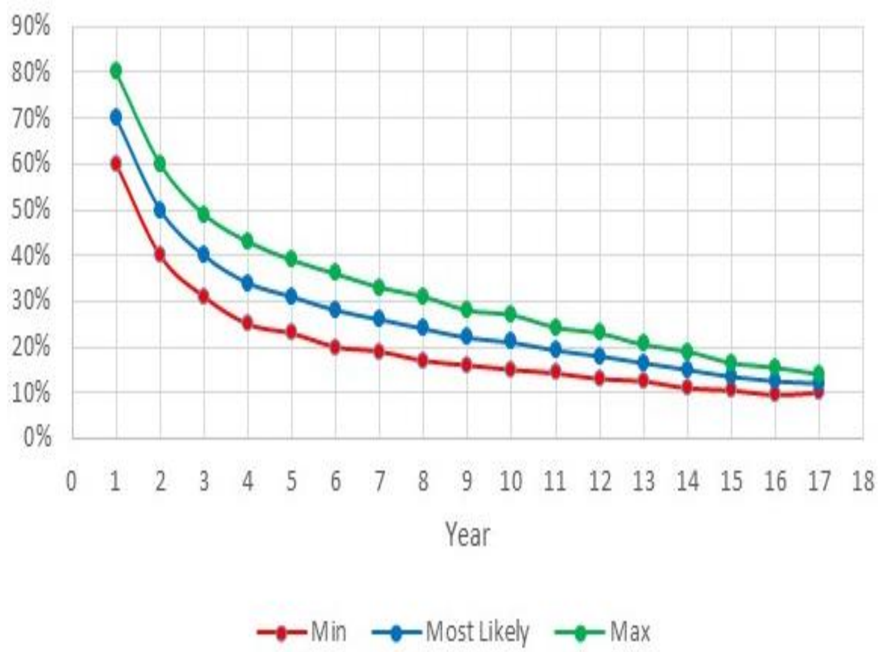

Figure A-9. Estimated resale values for A07 and A12 vehicles by year sold

This example provides a snapshot of the insights from the Depreciation Tab of the model. We see the decrease in the fluctuation with the vehicle age, so in year one, the potential variation is 20%, while in year 17, the potential variation is only 4%.

DSS Results by Age/Cost Tab

The DSS produces two kinds of simulations results: one based on resale year (age) and to the other base on maintenance cost. Results are based on the input parameters (vehicle type, purchase cost, and number of years specified to simulate). Each result page includes rows for the corresponding Average Annual Cost and the Standard Deviation, along with a graph that helps to show the behavior of the annual cost over either the replacement age or the number of vehicles replaced per year.