ESTIMATING COST PER LANE MILE FOR ROUTINE HIGHWAY OPERATIONS AND MAINTENANCE

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16. Abstract

The disparity between maintenance budgets and maintenance requirements causes agencies to make difficult choices about maintenance priorities. There is a growing need to effectively link maintenance costs and condition to provide clear evidence of impacts due to budget tradeoffs decisions. The focus of this research was to develop mathematical relationships between expenditures for highway maintenance and the resulting maintenance condition by analyzing historic cost and condition data. The research involved analyzing maintenance condition and cost data over three years, 2004, 2005, and 2006 from the state transportation agencies in Michigan, Ohio, and Wisconsin for highway components including pavement, shoulders, roadside vegetation, drainage, signs, and pavement markings. The maintenance management systems at the states use different categorization schemes for their maintenance activity costs and different rating systems for maintenance condition, thus direct comparison between states was not possible.

The primary result of this research is a set of probabilistic distribution functions for annual maintenance costs for a wide range of maintenance activities. Confidence intervals can be constructed around the average using the chosen level of confidence (i.e., 95%). The functions are useful for sensitivity and simulation analyses.

The researchers hypothesized that data would reveal relationships between cost and condition. A regression tree analysis approached was used to search for relevant model equations. However, the statistical analysis of the data revealed weak evidence of these relationships. This finding is common for all three of the states that were investigated. There are at least two clear limitations of the data. First, to see trends overtime, three years of data may not be enough. Furthermore, even with budget cuts, noticeable deterioration in condition, deficiencies, or maintenance backlog may take longer than three years. Second, the available cost and condition data are aggregated over many highway miles. Maintenance management and cost records generally do not include precise highway locations where maintenance was performance, the specific activities that were performed, nor the precise cost and timing of those activities. Consequently the trends and relationships between cost and condition are "washed out" by the lack of precision.

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EXECUTIVE SUMMARY

When transportation agencies prepare a design for new highway construction or major improvements to existing highways, they consider the agency's life-cycle and user costs in the project design decisions. However, after highway projects are completed, maintenance budgets rarely get adjusted to accommodate the maintenance of new lane miles. This problem is worsened by the fact that the number of vehicle miles traveled (VMT) per highway mile tends to increase over time. Maintenance budgets remain relatively constant, regardless of an increase in the number of vehicle miles traveled.

The disparity (real or perceived) between maintenance budgets and maintenance requirements causes agencies to make difficult choices about maintenance priorities. When this happens, maintenance concerns related to safety and operational efficiency tend to override preservation of capital investment. There is a growing need to effectively link both maintenance costs and condition to provide clear evidence of impacts due to budget tradeoffs decisions. In addition, estimates for maintenance costs are useful for establishing and evaluating bid prices in maintenance contract agreements.

The focus of this research was to develop mathematical relationships between expenditures for highway maintenance and the resulting maintenance condition by analyzing historic cost and condition data. The research involved analyzing data from the state transportation agencies in Michigan, Ohio, and Wisconsin. The scope includes maintenance of all highway components within an agency's right-of-way including pavement, shoulders, roadside vegetation, drainage, signs, and pavement markings. Winter operations, bridges, and roadside facilities such as rest areas and weigh stations were not included in the project scope. The analysis looks at maintenance cost and condition in 83 Michigan counties, 88 Ohio counties, and 72 Wisconsin counties over three years, 2004, 2005, and 2006.

The project did not involve direct comparisons between the states. The maintenance management systems at the states use different categorization schemes for their maintenance activity costs and different rating systems for maintenance condition. Similarly, the maintenance costs available from the states include different cost items. Maintenance costs in Michigan include labor and material but not overhead. The available maintenance costs for Ohio include labor, materials, and overhead. Similarly, maintenance costs for Wisconsin are total expenditures including labor, materials, equipment and overhead. Consequently, direct comparisons between the states were not possible. For Michigan, the maintenance components are divided into 5 categories: surface maintenance, shoulder maintenance, roadside maintenance, general maintenance, and traffic services. For Ohio, the maintenance components are organized into 8 categories including: guardrail, pavement, pavement drop-off, vegetation obstruction, litter, drainage ditch obstruction, sign deterioration, and pavement markings. For Wisconsin, the maintenance components are organized into nine groups: asphalt traveled way, concrete traveled way, unpaved shoulders, paved shoulders, mowing, litter pickup, woody vegetation, noxious weeds, and ditches. Maintenance condition in Michigan is expressed as an averaged rating per county on a scale of 0-5. In Ohio, maintenance condition is expresses as absolute total deficiency for each maintenance item, In Wisconsin, maintenance conditions is expressed as percentage of features that are deficient.

The researchers hypothesized that data would reveal various relationships between cost and condition. For example, that maintenance condition deteriorates as maintenance expenditures decrease or that various county-level characteristics such as size, responsible lane miles, and weather would have some impact on the relationship between maintenance cost and maintenance condition. However, the statistical analysis of the data revealed weak evidence of these intuitive relationships.

The researchers used regression analysis to find relevant model equations. Various tools were used to analyze the data. The primary analysis tool is the regression tree modeling algorithm, GUIDE (Generalized, Unbiased, Interaction, Detection and Estimation). A regression tree is a piecewise constant or piecewise linear estimate of a regression function, constructed by recursively partitioning the data and sample space. The regression tree approach provides a way to find county groups and the corresponding model for each group. Within each tree, models capture differences among the counties depending upon county size or lane miles, vehicle miles traveled, population density, and other relevant variables such as soils and precipitation. The algorithm automatically searches over numerous multiple linear models to fit different subsets of the data and uses cross-validation to pick groupings and corresponding models that minimize the least squares of error on the prediction. The result is sets of models that may be applicable to counties in other states with similar characteristics. Other analysis tools include scatter plots and MINITAB regression analysis.

The overall finding from this research is that the available data is not useful for optimizing maintenance budget management and allocation. This finding is common for all three of the states that were investigated. A wise person once said, "If we torture data long enough, it will tell us whatever we want." This project may be the exception.

There are at least two clear limitations of the data. First, to see trends overtime, three years of data may not be enough. With biennial state budgets, three years is only one and one-half budget cycles. The analysis showed little change over the three year period. Furthermore, even with budget cuts, noticeable deterioration in condition, deficiencies, or maintenance backlog may take longer than three years. Second, trends and relationships between cost and condition are washed out by the lack of precision and accuracy of the maintenance activities and associated costs. The available cost and condition data are aggregated and generalized over large areas for many highway miles. Maintenance management and cost records generally do not include the precise highway location where maintenance was performance, the specific activities that were performed, the precise cost and timing of those activities. To overcome the problem, maintenance activities and costs must be more clearly tied to the maintenance elements that are assessed for maintenance condition.

Among the salient results of this research are a set of probabilistic distribution functions for annual maintenance costs for a wide range of maintenance activities. Confidence intervals can be constructed around the average using the chosen level of confidence (i.e., 95%). The functions are useful for sensitivity and simulation analyses.

Chapter 1. INTRODUCTION

1.1 Problem Statement

When transportation agencies prepare designs for new highway construction or major improvements to existing highways, the agency and user life-cycle costs are considered in project design decisions. However, after highway projects are completed, maintenance budgets are rarely adjusted to accommodate the routine maintenance of new lane miles.

This problem is worsened by the fact that each year the number of vehicle miles traveled (VMT) per highway mile has a tendency to increase over time, while on the other hand, maintenance budgets do not seem to be adjusted to accommodate these increases. Figure 1 shows the trends of million VMT and expenditures/million VMT in Wisconsin from 2000 to 2006. It shows that between the years 2001 and 2004 while VMT was increasing from 57 million to 60 million, the money spent for highway maintenance per million VMT was decreasing from 3.5 to 2.5 million dollars.

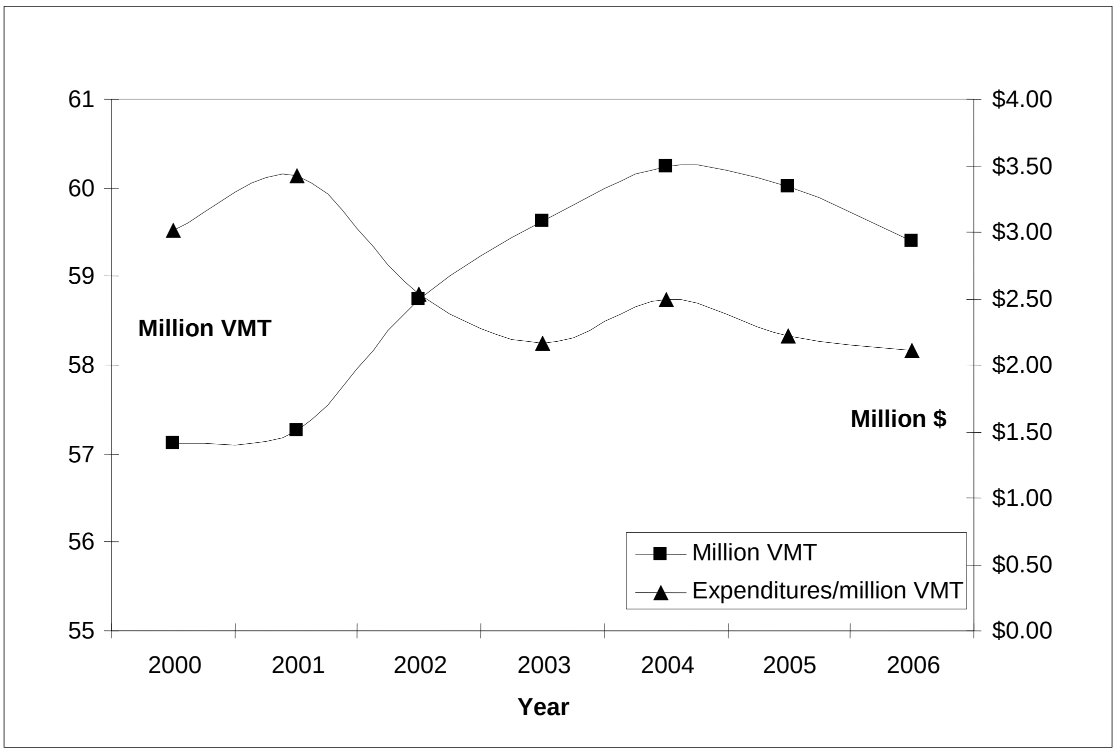


Figure 1. Trend for Miles Traveled and Maintenance Expenditures in Wisconsin

The disparity between maintenance budgets and maintenance requirements causes agencies to make difficult choices about maintenance priorities. When this happens, maintenance activities will usually not get the priority because in addition to concerns about preserving capital investment, highway operations and maintenance bureaus have concerns about safety and loss of operational efficiency due to deteriorating condition of roadways. There is a growing need to efficiently link both maintenance costs and condition to allow decision makers to better address concerns about preserving capital investment and maintaining operational efficiency (1).

1.2 Objectives

The focus of this research is to develop a way to estimate cost of ongoing routine operations and the maintenance cost components of total highway life-cycle cost using historical data. The research involves analysis of data from three state transportation agencies: MDOT, ODOT and WisDOT. There are two main tasks:

- Perform a correlation study to characterize the relationship between maintenance cost and maintenance condition.
- Develop model equations for estimating the recurring annual cost for routine, county-level highway maintenance.

It is hypothesized that maintenance condition will deteriorate as maintenance expenditures decrease. It is also expected that different sized counties based on parameters such as lane miles will perform differently with regard to the relationship between maintenance cost and maintenance condition. The objective of this project is to determine if this is indeed the case for both Ohio and Michigan over the 3 year period of 2004-2006. Addition objectives include developing equations that will give transportation decision makers the tools required to make informed decisions regarding transportation maintenance budget. Two types of equations will be modeled, one predicts condition given cost and the other predicts cost given condition. Equations that predict condition can be used to determine the effects of increased or decreased funding on condition. Equations that predict cost can be used to determine the cost to achieve certain levels of condition.

1.3 Scope

The scope of the project includes maintenance of all highway components within an agency's right-of-way including pavement, shoulders, roadside vegetation, drainage, signs, and pavement markings. Winter operations, bridges, and roadside facilities such as rest areas and weigh stations are not included in the project scope.

The analysis uses data from the state transportation agencies in Michigan, Ohio, and Wisconsin. The maintenance and cost data cover fiscal years 2004, 2005, and 2006. The geographic extent of is the county level in each state. The analysis looks at maintenance cost and condition in 83 Michigan counties, 88 Ohio counties, and 72 Wisconsin counties over a three year period. The maintenance management system at each state influences the level of detail for the available data. For Michigan, the maintenance components are divided into 5 categories: surface maintenance, shoulder maintenance, roadside maintenance, general maintenance, and traffic services. For Ohio, the maintenance components are organized into 8 categories including: guardrail, pavement, pavement drop-off, vegetation obstruction, litter, drainage ditch obstruction, sign deterioration, and pavement markings. For Wisconsin, the maintenance components are organized into nine groups: asphalt traveled way, concrete traveled way, unpaved shoulders, paved shoulders, mowing, litter pickup, woody vegetation, noxious weeds, and ditches.

It is difficult to directly compare cost and condition among the states. Maintenance conditions are expressed using different measurement scales and some specific maintenance items are not directly comparable. Maintenance condition in Michigan is expressed as an averaged rating per county on a scale of 0-5. In Ohio, maintenance condition is expresses as absolute total deficiency for each maintenance item, In Wisconsin, maintenance conditions is expressed as percentage of features that are deficient. Similarly, the maintenance costs available from the states include different cost items. Maintenance costs in Michigan include labor and material but not overhead. The available maintenance costs for Ohio include labor, materials, and overhead. Similarly, maintenance costs for Wisconsin are total expenditures including labor, materials, equipment and overhead.

A set of independent variables were evaluated to model the relationships between maintenance cost and condition among the counties in each state. The variables are limited to what is available in each agency's inventory and condition inspection data sets. In addition, the research team added environmental, operational, and socio-economic variables.

1.4 Methodology

The research involved statistical analysis of cost and condition data with the goal of finding relationships and trends that reveal insights for improving the effectiveness of maintenance expenditures. Much work has been done on developing statistical guideline for designing a Maintenance Quality Assurance (MQA) data collection and analysis plan. One example is shown in Table 1. Much less work has been done on relating MQA cost to condition and there are no guidelines upon which the methodology could be modeled.

Table 1. MQA Questions and Statistical Approaches (Schmitt et al. 2006)

Question	Statistical Approach
Determining number of samples to yield valid information	Statistical distributions and statistical parameters can assist in determining sample size. LOS confidence interval estimation equations can provide an interrelationship of sample size, variability, confidence level, precision, and data distribution parameters.
Developing confidence in an estimate	Confidence intervals can be constructed around the average using the chosen level of confidence (i.e., 95%), underlying variability, and sample size.
Stratifying data in terms of geographical or highway features	Analysis of variance can detect whether there is a difference between features of data (region, crews, etc.), while incorporating the variability into the determination. Some states may have significant differences between regions that can be detected using Analysis of Variance.
Comparing results of MQA data collectors	T-tests can detect the mean difference between data sets generated by two different MQA data collectors. Then, with the assistance of power curves, the "true" mean difference between them can be measured and controlled. A whole host of standard statistical tests are available with which to compare data sets obtained by different MQA technicians or teams.
Are years different or not	F-tests and t-tests can provide a statistical comparison of means. Paired-sample t-tests are used when data are collected from the same roadway segment from year-to-year, while a two-sample t-test is used when the roadway segments are independent of each other.
Looking for trouble signs	Outliers, or data points that are abnormal from a distribution, can detect trouble signs. Several standard tests for outliers exist, and the chi-square or other goodness-of-fit tests can be used to check normality.
Reporting data	Beginning with simple fundamental statistical measures is always the best start (plot the data, calculate the average and standard deviation, etc.). The sampling design largely drives if/how a statistically valid analysis can proceed, so effort must be placed on sampling design at the beginning.

The research process for data analysis is shown in Figure 2. The first step was to collect cost and condition data from the state Departments of Transportation. The research team collected various county-level environmental and socio-economic parameters as well.

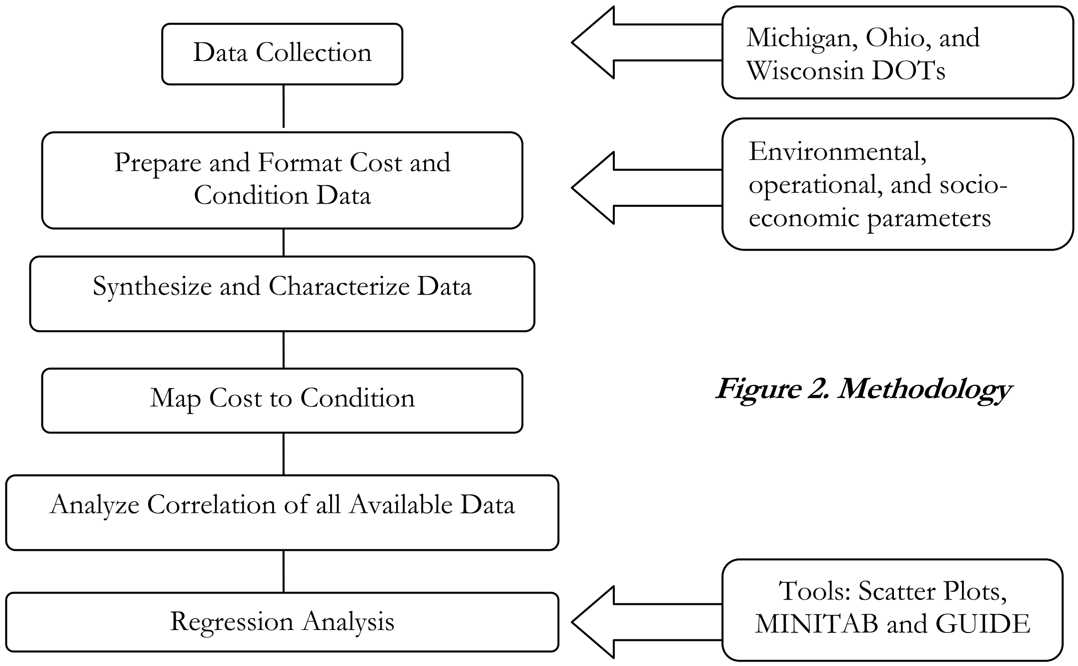


Figure 2. Methodology

Next, the team prepared and formatted the available data for characterization and analysis. The synthesis and characterization step included determining sample sizes, averages, standard deviations and ranges. In addition, we characterize the cost and condition data independently for the 3-year period of 2004-06. This includes scatter plots of cost versus total lane mile and condition versus total lane mile for each maintenance category. Scatter plots also serve to visualize outliers or any abnormal data within the 3-year period.

The forth step is to map cost to condition using available parameters followed by analysis of correlation among the parameters to identify the parameters that most influence cost and condition.

The final step in the analysis methodology is the regression analysis to find relevant model equations. Various tools were used to analyze the data. The primary analysis tool is the regression tree modeling algorithm, GUIDE (Generalized, Unbiased, Interaction, Detection and Estimation). Other analysis tools include scatter plots and MINITAB regression analysis.

A regression tree is a piecewise constant or piecewise linear estimate of a regression function, constructed by recursively partitioning the data and sample space (6). The regression tree approach provides a way to find county groups and the corresponding model for each group. Within each tree, models capture differences among the counties depending upon county size or lane miles, vehicle miles traveled, population density, and other relevant variables. The algorithm automatically searches over numerous multiple linear models to fit different subsets of the data and uses cross-validation to pick groupings and corresponding models that minimize the least squares of error on the prediction. The result is models with improved prediction accuracy and the effect of the outliers alleviated. Additionally, the models are much simpler and easier to use than transformed (non-linear) models based on the scatter plots (7). The result is sets of models that may be applicable to counties in other states with similar characteristics.

1.5 Organization of Report

This report is organized into five chapters. Chapter 2 summarizes our findings on maintenance activity costs per lane mile in each of the three states. The chapter includes distribution functions and statistical parameters for cost at the activity level.

In Chapter 3, maintenance activities are rolled up to the category level. Typical categories are pavements, roadsides, shoulders, drainage, signs, etc. The state use similar categories but not there are slight differences that make comparisons unlikely. Trends for maintenance costs at the category level were explored by partitioning the data set by year and by responsible lane miles for of the maintenance jurisdiction. Finally the chapter includes distribution functions and statistical parameters for cost at the category level.

Chapter 4 contains a brief introduction to the maintenance condition assessment program in each state. The agencies organized the condition evaluation data into maintenance categories. The categories are the same as those used in Chapter 3.

Chapter 5 presents the analysis for relating maintenance cost to condition at the category level. . The chapter presents the procedure and results of the GUIDE regression tree and MINITAB regression analyses for determining analytical models that relate condition and cost.

Finally, Chapter 6 presents conclusions.

Chapter 2. MAINTENANCE ACTIVITY COSTS

This chapter looks at distributions of individual maintenance activities cost using three years of data from the state departments of transportation at Michigan, Ohio and Wisconsin. This study examined the data from 2004, 2005 and 2006. The costs were adjusted for inflation and location to make the results useful for predicting the maintenance costs in future years and other locations.

The detail and scope of the cost data varies from state to state. For Ohio and Wisconsin, the analysis of costs focuses at the county-level. For Michigan, cost data for maintenance performed by contracts with counties and cities was available by route segments. Thus segment-level data was used to prepare distribution functions. Costs were at the county-level for work performed by direct forces at Michigan's state garages.

Costs for each state included labor, equipment and materials and the labor costs included fringes. The analyses for Michigan and Wisconsin used direct costs for maintenance activities – administrative costs were ignored. For Ohio, the analysis used total costs including direct and indirect.

2.1 Adjustment for Inflation

Cost data was adjusted for inflation using the urban consumer price index (CPI) to base year 2006 costs. The urban CPI allows data from the years 2004 and 2005 to be compared with year 2006 data. The urban CPI for the years 2004-2006 are listed in Table 2 and the formula for adjusting cost is show below.

Table 2. Urban Consumer Price Index

Year	Urban CPI
2004	186.1
2005	191.6
2006	195.9

$$\text{Cost}_i = \text{Cost}_j \left(\frac{\text{Urban CPI}_i}{\text{Urban CPI}_j} \right)$$

2.2 Adjustment for Location

Labor costs within each state were adjusted to accommodate the variations in labor rates across the state. In this section the researches present the development of the location indices for Michigan. Hourly labor rates across the state of Michigan were adjusted to the Detroit-Warren-Livonia area as the base location. For Ohio, labor costs were adjusted to be equivalent with the Cleveland area. The researchers adjusted labor rates for Michigan and Ohio based on the hourly labor rates published by the Bureau of Labor Statistics – Occupational Employment Statistics website (http://www.bls.gov/oes/2007/ may/oes_2600004.htm). Individual counties were identified for each area using the Bureau of Labor Statistics metropolitan and nonmetropolitan area definitions (http://www.bls.gov/oes/2007/may/msa_def.htm#12980).

The Bureau of Labor Statistics website provides the highway maintenance labor rate for many areas but not all. The website did not defined hourly rates for ten counties in Michigan (Bay, Berrien, Calhoun, Clinton, Eaton, Ingham, Jackson, Monroe, Muskegon, and Ottawa). For these counties, the rate was obtained by comparing common rates (e.g. construction laborer hourly rates) between the county and its neighbors. The highway maintenance hourly rate was then derived according to the relationship (increase or decrease) between the common rates from the neighboring counties. The results are shown in Table 3. The values in the index column were used to convert labor costs to equivalent Detroit labor costs.

Table 3. Estimated hourly labor rates for highway maintenance workers in Michigan

Area	Hourly Rate	Index
Ann Arbor, MI	$18.81	96.41
Detroit-Warren-Livonia, MI	$19.51	100.00
Flint, MI	$17.65	90.47
Grand Rapids-Wyoming, MI	$19.30	98.92
Kalamazoo-Portage, MI	$17.33	88.83
Saginaw-Saginaw Township North, MI	$20.32	104.15
South Bend-Mishawaka, IN-MI	$15.38	78.83
Warren-Troy-Farmington Hills, MI Metro Division	$19.76	101.28
Upper Peninsula of Michigan non-Metro Area	$17.79	91.18
Northeast Lower Peninsula of Michigan non-Metro Area	$17.37	89.03
Northwest Lower Peninsula of Michigan non-Metro Area	$17.46	89.49
Balance of Lower Peninsula of Michigan non-Metro Area	$17.18	88.06

Source: http://www.bls.gov/oes/2007/may/oes_2600004.htm

For Wisconsin, labor rates were obtained from the state's Highway Maintenance System (HMS). Labor rates across the state were adjusted to be equivalent to highway maintenance labor rates in Milwaukee County (county with the highest labor rate in 2006).

2.3 Cost Transformation Functions

The histogram in Figure 3 shows the distribution of maintenance costs per lane mile (litter pickup). A normal fit is super imposed on the histogram. Clearly the data does not follow a normal distribution. The probability plot in Figure 3 confirms that the values do not follow a normal distribution because they do not resemble a straight line.

The maintenance costs do not follow normal distributions but many can be transformed to fit a normal distribution. Box-Cox or Johnson transformations correct the non-normality so that the data can be used for analysis methods that require a normal distribution. Various simulation and risk analysis procedures require normalized data. This section presents a brief review of the Box-Cox and Johnson transformations and how the transformation functions would be used in a cost stimulation analysis.

2.3.1 Box-Cox Transformation

The formula for the Box-Cox transformation function is,

$$Y = X^{\lambda}$$

Where, Y is the transformed value of X. Each value of X is one of the original cost values in dollars, and λ is the transformation parameter. λ is in the range of -0.5 to 0.5. For λ= 0, the Box-Cox transformation function is:

$$Y = \log_e X$$

If a set of cost data can fit a normal distribution using the Box-Cox transformation, then we would be given the transformation parameter, λ, along with the mean, μ, and standard deviation,

σ, of the fitted normal distribution. For example, if $\lambda = 0.214$, then the cost data could be transformed using the Box-Cox transformation function:

$$Y = X^{0.214}$$

The formula was applied to each cost value in Figure 3. A histogram of the transformed cost data is shown in Figure 4. The histogram of the transformed values now resembles a normal distribution. As shown, the transformed data fits a normal distribution with $\mu = 3.46$, and $\sigma = 0.4717$. The probability plot shows that the values now follow a normal distribution after the Box-Cox transformation since they resemble a straight line.

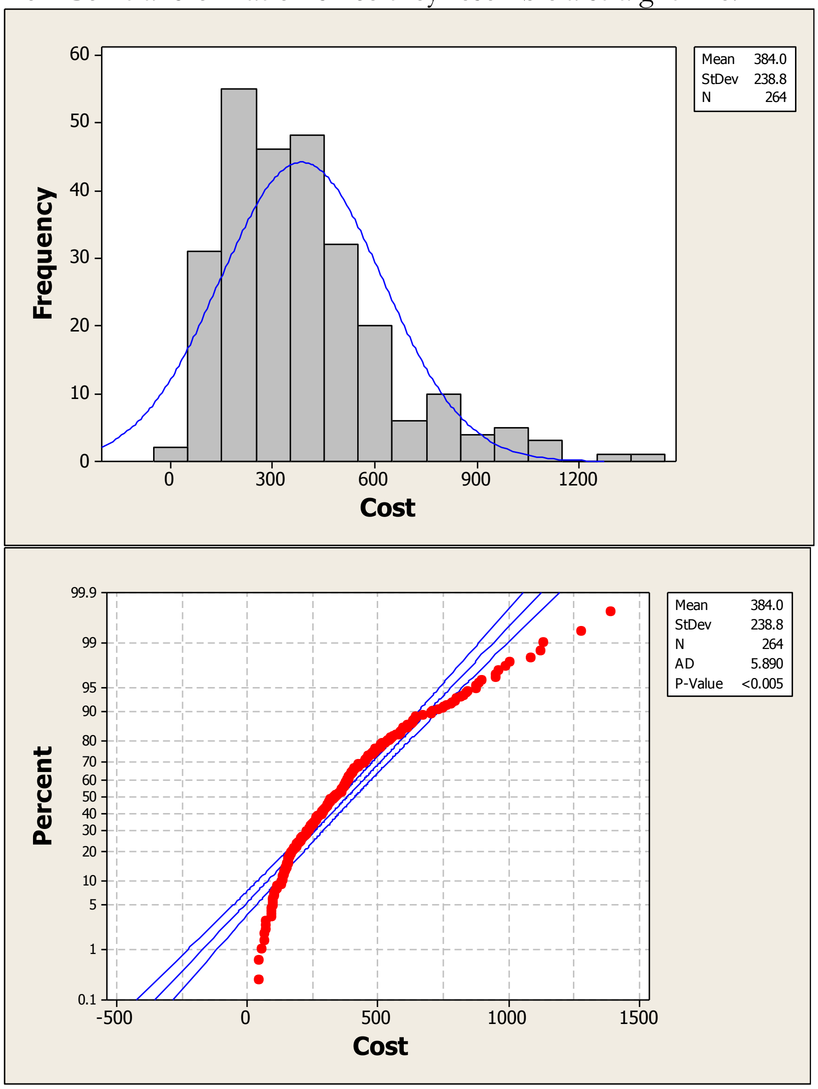


Figure 3. Histogram and probability plot for non-normal cost data.

The transformation function can be used to model the cost data for a simulation analysis. Cost per lane mile can be randomly sampled from the normal distribution ($\mu = 3.46$, $\sigma = 0.4717$). The sampled value can be input to the inverse transformation function to obtain an estimated cost from the original cost non-normal distribution. For this example, the inverse of the transformation function is:

$$X = Y^{\left(\frac{1}{0.214}\right)}$$

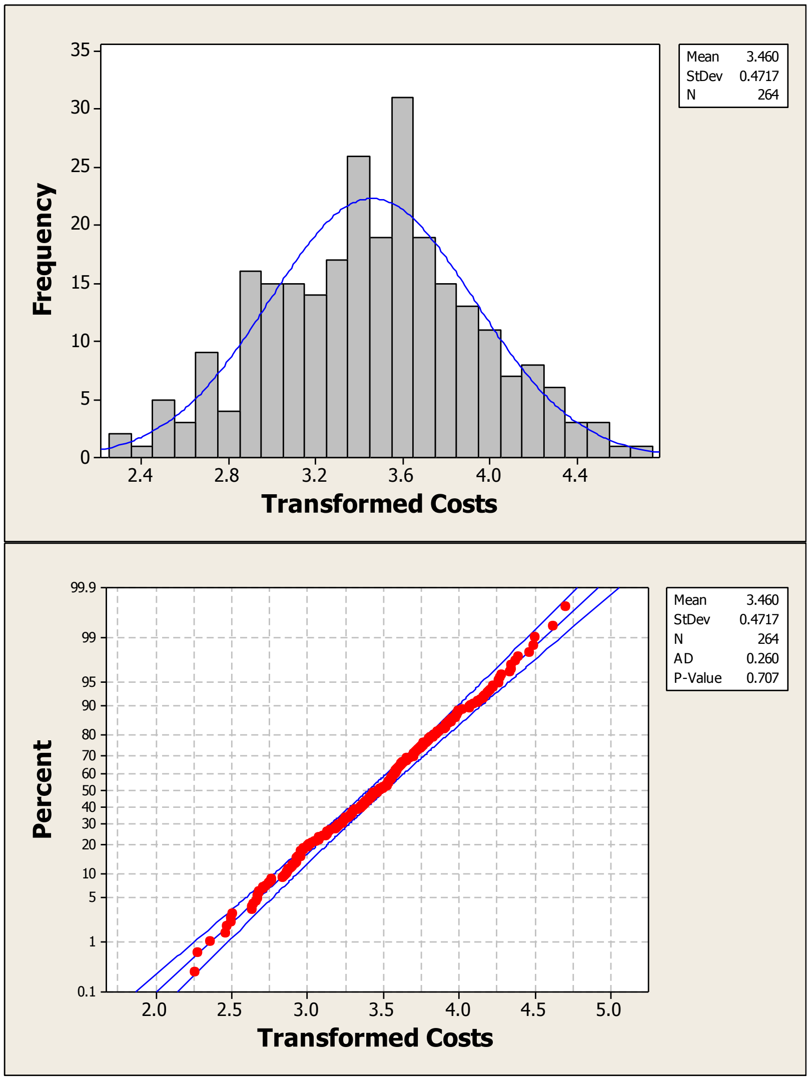


Figure 4. Transformed costs using Box Cox transformation function.

2.3.2 Johnson Transformation

The Johnson transformation is another method to correct non-normality. Figure 5 shows another histogram of the cost samples. The data are not normal but can be normalized using a Johnson transformation function:

$$Y = -3.897 + 3.563 \operatorname{Asinh}((X - 1303.29) / 2246.62)$$

Where, Y is the transformed value of X. Each X is one of the original sampled costs in Figure 5. The transformed costs follow a normal distribution with mean μ = -0.026, and standard deviation, σ = 1.035. Each data set has unique a unique Johnson transformation function.

In order to predict the cost for an activity we need to sample from the normal distribution and then compute the associated cost for the original distribution. For example, in order to calculate the cost associated with a value, Y, from the normalized curve we use the following inverse of the transformation function: The value X would give us the dollar amount.

$$X = 2246.62 \sinh((Y+3089719)/3056296)+1303.29$$

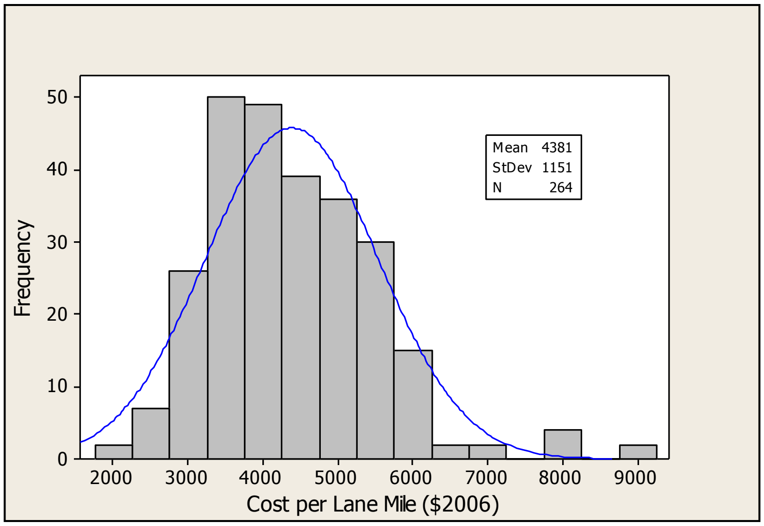


Figure 5. Histogram of non-normalized cost per lane mile.

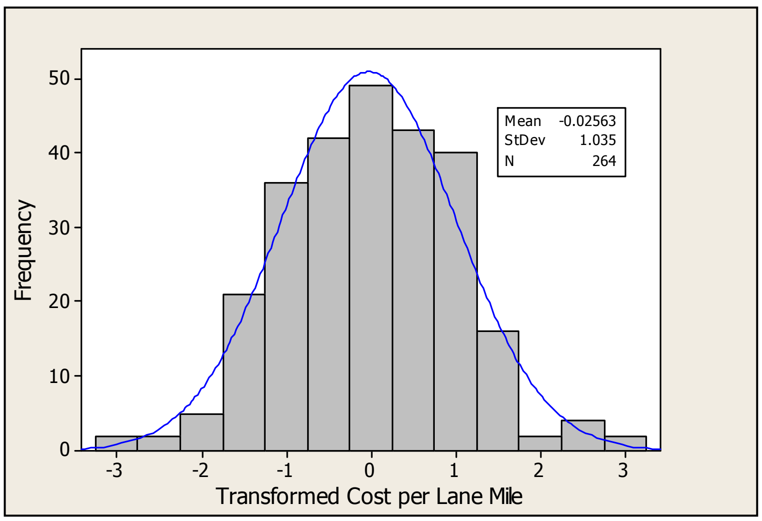


Figure 6. Histogram of transformed and normalized cost per lane mile

2.4 Maintenance Activity Costs per Lane Mile (CPLM)

Distribution functions were found for the maintenance activity costs per lane mile for three states: Michigan, Ohio and Wisconsin. The researchers used the quality tools built into Minitab®. These tools provide statistical assessment for various candidate distributions. The distribution with the best fit (lowest AD value and a high enough P-value (>0.05 for alpha = 0.95) was selected.

Each state handles their maintenance contracting and cost accounting differently. The important differences for this project are the level of detail for maintenance work breakdown, resolution of the roadway sections to which costs are assigned, and finally details of the cost items such as whether administrative overhead is included or not. Before presenting summary tables of the cost distribution functions, this report briefly reviews the maintenance management and cost accounting in each state.

2.4.1 Highway Maintenance in Michigan

In Michigan, maintenance is conducted through contracts with the counties and local agencies, or by direct forces at state maintenance garages. Figure 7 shows the geographic location and maintenance mechanism for each of the state's 83 counties. The approximate distribution of lane miles is 5% for cities and 70% for counties through contract agreements, and 25% for the state using direct forces. Maintenance in certain counties are managed by one or more state maintenance garages, so county level estimates are not possible.

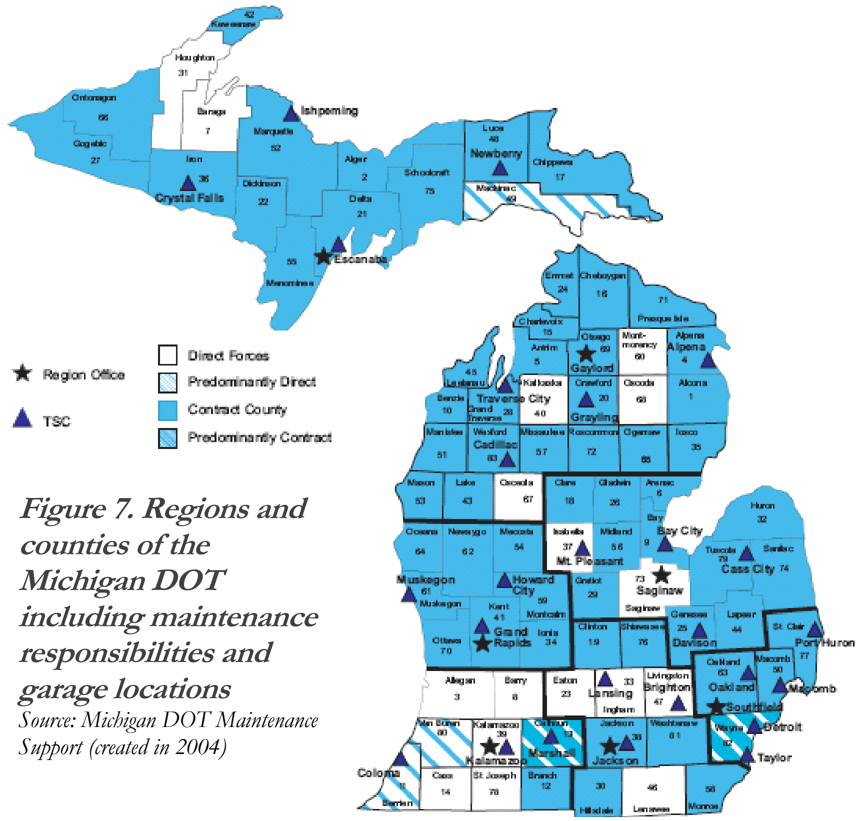


Figure 7. Regions and counties of the Michigan DOT including maintenance responsibilities and garage locations
Source: Michigan DOT Maintenance Support (created in 2004)

The MDOT maintenance cost data was obtained from the department's Michigan Architectural Project (MAP) database. Table 4 and Table 5 summarize the costs per lane mile for the contracted maintenance and Table 6 summaries costs per lane mile for maintenance activities performed by direct forces. The costs are listed in equivalent 2006 dollars for the Detroit area with no administrative overhead. For direct forces, fringe benefits are included. The original data set did not contain costs for direct forces for the year 2006. Thus, Table 6 is based on years 2004 and 2005, while Table 4 and Table 5 are based on data for years 2004, 2005 and 2006.

2.4.2 Highway Maintenance in Ohio

The Ohio Department of Transportation (ODOT) manages 12 districts that oversee 88 counties (Figure 8). The district offices are responsible for maintenance including winter services such as snow and ice removal.

Figure 8. Transportation districts and counties in Ohio
Ohio DOT, http://www.dot.state.oh.us/dist.asp

Ohio's maintenance costs are managed by ODOT's web-based project management system, Ellis (4). This contains the contracted portion of ODOT's activities in maintaining assets. Table 7 lists the eight cost groups (guardrail, pavement deficiency, vegetation obstruction, litter, drainage/ditch obstruction, sign deterioration, and pavement markings) from the Ellis system that were made available for analysis.

2.4.3 Highway Maintenance in Wisconsin

In Wisconsin, county crews perform maintenance on state roads within its jurisdiction. The state monitors maintenance costs with the Highway Maintenance System (HMS).

Maintenance costs are documented in the Highway Maintenance System (HMS). Maintenance expenditures are recorded according to designated activity codes (3). Maintenance activity groups that are used for this study are show in the Table 8.

Figure 9. Transportation regions and counties in Wisconsin
http://www.dot.state.wi.us/about/locate/dtd.htm#nc

2.5 Distribution Functions for Maintenance Expenditures

Distribution functions for the cost per lane mile (CPLM) of individual maintenance activities are listed in Table 4 to Table 8. The column for "statewide average" is the total cost for the activity divided by the total number of responsible lane miles for which costs were incurred. Using this method, only the lane miles on which work was performed get included in computing the average cost. The "average" cost for the county, contract agency, or garage were calculated by averaging of the cost per lane mile for each county, agency or garage. For the latter method, large maintenance projects were weighted the same as small maintenance projects.

The columns for average and standard deviation do not include route segments for which no maintenance was performed. Instead, the table shows a probability of expenditures based on the number of nonzero cost samples for each of the activity. The total number of samples is the same for each activity. The probability column is the percentage of statewide lane miles for which costs were incurred.

The distribution functions are useful for conducting simulation and sensitivity analysis of maintenance cost estimates. The Mean (μ) and standard deviation (σ) are for normal distributions using the Box Cox and Johnson Transformation functions

Some activities have very few cost observations. For this reason, distributions could not be computed for some activities.

Table 4. Activities and costs per lane mile for contracts with Michigan's cities

Activity Group	Maintenance Activity		Statewide Average ($2006)	Contracts with Michigan's Cities			
	Code	Description		Average ($2006)	Std. dev ($2006)	Probability %	Distribution
Pavements	109	Surface Maintenance	371.02	422.75	862.74	75	Box-Cox: μ=2.416, σ=0.568, λ = 0.165
Shoulders	119	Shoulders	77.39	108.30	128.75	17	Johnson: μ=0.063, σ=0.92 1.682+0.635 Ln((X-0.083)/(842.968-X))
Vegetation Control	121	Trees & Shrubs	142.86	204.94	371.73	35	Johnson: μ=0.05, σ=1.03 -3.392+0.774 Ln(X+4.724)
	126	Grass & Weed Control	96.69	327.29	516.16	40	Johnson: μ=-0.05, σ=1.042 2.665+0.682 Ln((X+2.383)/(7139.90-X))
	127	Brush Cutting	NA	NA	NA	NA	No data
Drainage	122	Drainage & Back Slopes	243.07	305.29	628.15	59	Box-Cox: μ=1.452, σ=0.175, λ =0.078
	123	Ditch Cleaning	NA	NA	NA	NA	Only 1 data point
	128	Culvert/Under Drain Maintenance	218.55	406.61	497.86	4	Johnson: μ=-0.044, σ=0.942 1.033+0.476 Ln((X-5.630)/(2078.87-X))
Litter	124	Full Width Litter Pickup	97.32	122.18	260.87	24	Johnson: μ=0, σ=0.974 2.434+0.56 Ln((X-0.747)/(3195.44-X))
	132	Sweeping & Flushing	444.77	654.01	2518.57	90	No Fit
Signs	160	Traffic Signs	126.92	99.47	238.15	48	Johnson: μ=-0.008, σ=0.986 4.957+0.681 Ln((X+0.528)/(51435.0-X))
Pavement Markings	162	Pavement Marking	59.49	87.69	131.97	13	Johnson: μ= 0.09, σ= 0.99 2.497+0.68 Ln((X+1.066)/(1446.91-X))
	164	Delineators	NA	NA	NA	NA	No data
Guardrails	165	Attenuators	NA	NA	NA	NA	No data
	130	Guardrail & Guard Posts	117.45	153.08	187.20	4	Johnson: μ= -0.064, σ= 1.015 1.261+0.559 Ln((X+1.286)/(903.645-X))
Other	137	ROW Fence Repair	NA	NA	NA	NA	Only 2 data points
	139	Structures	335.21	761.71	975.92	3	Johnson: μ=-0.054, σ= 1.02 1.039+0.466 Ln((X+9.259)/(3909.56-X))
	161	Traffic Signals	310.61	535.79	2008.47	37	Johnson: μ=0.03, σ= 1.025 -3.725+0.591 Asinh((X-0.437)/0.374808)

Table 5. Activities and costs per lane mile for contracts with Michigan's counties

Activity Group	Maintenance Activity		Statewide Average ($2006)	Contracts with Michigan's Counties			
	Code	Description		Average ($2006)	Std. dev ($2006)	Probability %	Distribution
Pavements	109	Surface Maintenance	417.35	433.34	1606.64	97	Johnson: μ=-0.023, σ=1.029 -2.84+0.61 Ln(X+0.812)
Shoulders	119	Shoulders	164.24	231.10	501.70	92	No Fit
Vegetation Control	121	Trees & Shrubs	55.01	61.55	86.72	86	Johnson: μ=-0.513, σ=1.025 2.316+0.697 Ln((X+0.268)/(886.107-X))
	126	Grass & Weed Control	220.54	173.94	233.53	95	No Fit
	127	Brush Cutting	27.04	47.73	79.49	3	No Fit
Drainage	122	Drainage & Back Slopes	111.47	137.07	288.37	88	Box-Cox: μ=1.213, σ=0.094, λ =0.05
	123	Ditch Cleaning	41.33	47.50	55.84	12	No Fit
	128	Culvert/Under Drain Maintenance	56.83	68.41	120.53	27	Johnson: μ=0.056, σ=1.03 2.162+0.554 Ln((X+0.02)/(1004.89-X))
Litter	124	Full Width Litter Pickup	193.65	130.54	311.76	96	No Fit
	132	Sweeping & Flushing	173.65	132.78	294.13	77	Johnson: μ=0.033, σ=0.997 -2.392+0.652 Ln(X+0.39)
Signs	160	Traffic Signs	86.37	78.36	120.19	92	No Fit
Pavement Markings	162	Pavement Marking	18.61	104.04	264.54	2	Johnson: μ=-0.009, σ= 0.899 -0.86+0.33 Asinh((X-1.918)/0.739)
	164	Delineators	22.38	19.38	29.12	33	Box-Cox: μ=1.299, σ= 0.190, λ= 0.113
Guardrails	165	Attenuators	267.39	329.13	741.48	9	Johnson: μ= -0.030, σ= 1.030 2.001+ 0.443 Ln((X - 0.173) / (6348.31 - X))
	130	Guardrail & Guard Posts	123.00	99.17	177.33	68	Box-Cox: μ=1.289, σ=0.15, λ = 0.071
Other	137	ROW Fence Repair	66.06	63.74	127.01	18	Johnson: μ= -0.021, σ= 0.997 2.633+0.595 Ln((X+0.295)/(1796.81-X))
	139	Structures	115.17	97.88	261.52	26	Box-Cox: μ=1.285, σ= 0.21, λ= 0.08
	161	Traffic Signals	124.54	157.07	277.87	20	Johnson: μ= -0.02, σ= 0.925 1.693+0.434 Ln((X-0.006)/(2207.00-X))

Table 6. Activities and costs per lane mile for Michigan's direct maintenance forces

Activity Group	Maintenance Activity		Statewide Average ($2006)	Maintenance Garage			
	Code	Description		Average ($2006)	Std. dev ($2006)	Probability %	Distribution
Surface Maintenance	10100	Joint & Crack Filling	126.82	143.09	192.17	77	No Fit
	10200	Remove/Replace Pavement (Fast Set Concrete)	127.95	140.33	254.11	69	Box Cox: μ=1.461, σ=0.313; λ = 0.1071
	10300	Patrol Patching	125.53	130.24	134.31	91	Box Cox: μ=3.5378, σ=1.233; λ = 0.2845
	10500	Bituminous Maintenance & Repair	58.01	60.42	74.02	62	Johnson: μ=-0.035, σ=1.015 1.182 + 0.509 Ln((X + 0.114) / (329.933 - X))
	10800	Bump Removal	19.99	23.86	34.19	53	Johnson: μ=-0.011, σ=1.113 -2.361 + 0.885 Asinh((X - 1.275) / 1.485)
Shoulder Maintenance	11000	Routine Blading	26.76	30.63	36.54	75	Johnson: μ=0.028, σ=0.9334 1.406 + 0.549 * Ln((X - 0.0585) / (207.514 - X))
	11200	Gravel Shoulder Maintenance	128.62	137.11	159.38	86	Johnson: μ=0.029, σ=0.998 2.051 + 0.744 Ln((X - 0.431) / (1268.98 - X))
	11400	Paved Shoulder Maintenance	67.28	76.80	150.13	46	Johnson: μ=0.049, σ=0.991 -2.005 + 0.553 Asinh((X - 0.857) / 0.964)
Vegetation Control	12000	Tree Removal	39.93	43.78	44.81	78	No Fit
	12100	Stump Removal	6.33	8.40	11.38	51	Johnson: μ=-0.011, σ=0.986 1.588 + 0.562 Ln((X + 0.038) / (66.411 - X))
	12600	Area Moving	27.55	31.40	42.22	74	Johnson: μ=0.023, σ=1.011 1.407 + 0.526 Ln((X + 0.061) / (202.380 - X))
	12700	Brush Control	34.67	37.14	39.74	82	Johnson: μ=-0.061, σ=1.047 1.087+0.605 Ln ((X+0.5996)/(171.709-X))
	17100	Tree Trimming	11.37	12.92	31.76	43	Johnson: μ=0.093, σ=0.883 -1.075+0.691 Ln(X+0.705)
	17200	Vegetation Control	11.65	11.75	13.45	29	Box Cox: μ=1.480, σ=0.478; λ = 0.215
Drainage	12200	Catch Basin Cleanout	27.26	31.75	53.42	51	Johnson: μ=-0.063, σ=0.885 1.108 + 0.312 Ln((X - 0.093) / (236.214 - X))
	12300	Ditch Cleanout	56.52	57.52	64.45	74	Johnson: μ=-0.011, σ=0.941 -5.0698 + 1.266 * Ln(X + 14.720)
	12800	Culvert & Underdrain Cleaning	19.26	21.12	27.84	69	Box Cox: μ=1.614, σ=0.405; λ = 0.192

Activity Group	Maintenance Activity		Statewide Average ($2006)	Maintenance Garage			
	Code	Description		Average ($2006)	Std. dev ($2006)	Probability %	Distribution
	12810	Culvert & Underdrain Cleaning	97.22	104.02	127.69	83	Johnson: μ=-0.027, σ=0.972 2.866 + 0.903 Ln((X + 8.357) / (1822.56 - X))
Litter	12400	Litter Pickup	65.05	70.41	75.35	90	No Fit
	13200	Approach Sweeping	10.38	12.45	14.83	77	Box Cox: μ=1.572, σ=0.4758; λ = 0.228
	13600	Curb Sweeping	17.23	17.96	19.77	34	Johnson: μ=0.00006, σ=0.9993 0.864 + 0.434 Ln((X - 0.107) / (73.414 - X))
Guardrails	13000	Guardrail Repair	52.09	52.53	55.08	83	Johnson: μ=-0.029, σ=0.9901 2.040 + 0.888 * Ln((X + 4.984) / (444.600 - X))
	13010	Guardrail Ending Repair	15.72	18.93	30.33	62	Johnson: μ=0.0007, σ=0.944 -1.608 + 0.738 Ln(X + 0.532)
Other	13700	Right of Way Fence Repair	21.42	25.23	50.01	62	Johnson: μ=0.033, σ=0.948 1.785+0.426 Ln((X-0.051)/(368.019-X))

Table 7. Activities and costs per lane mile for counties in Ohio

Activity Group	Maintenance Activity		Statewide Average ($2006)	County			
	Code	Description		Average ($2006)	Std. dev ($2006)	Probability %	Distribution
Guardrail	6230	End Assembly Installation and Maintenance	34.45	30.08	47.63	59	Johnson: μ=0.003, σ=1.00, 2.0690 + 0.5909 Ln((X + 0.0169) / (399.70 - X))
	6233	Repair, Replacement, or Removal	161.21	164.93	139.58	97	No Fit
	6235	Crash Attenuator Repair or Replacement	23.77	18.24	39.15	19	Johnson: μ=0.072, σ=0.921 1.8658 + 0.4306 Ln((X - 0.0393) / (265.16 - X))
	6237	Concrete Median Barrier Repair, Replacement, Restoration, Removal	8.34	7.46	8.26	14	Johnson: μ=0.005, σ=0.945, 3.2354 + 0.9300 Ln((X + 0.2239) / (167.43 - X))
	6333	Guardrail Betterment	28.62	24.97	63.57	27	Johnson: μ=0.032, σ=1.031 -0.8990 + 0.5100 Asinh((X - 2.6384) / 1.1621)
Pavement Deficiency	6120	Pavement Underseal/Fill Voids	2.23	2.298	1.81	4	Box Cox: μ=0.533, SC=0.834, λ = 0
	6121	Pothole Patching	337.21	318.3	262.60	100	Johnson: μ=-0.033, σ=1.004, 2.6524 + 1.1335 Ln((X + 18.72) / (3029.60 - X))
	6122	Surface Repairs	212.56	223	280.20	87	No Fit.
	6123	Full Depth Repair	102.15	118.62	249.34	78	Johnson: μ=-0.006, σ= 1.00 -1.6388 + 0.5871 Asinh((X - 4.4339) / 3.6576
	6124	Fill and Seal Joints and Cracks	167.33	176.03	160.78	72	Box-Cox: μ=5.264, σ=1.847, λ = 0..341
	6125	Surface Treatment	218.03	237.4	244.7	35	No Fit
	6126	Pavement Jacking	4.04	4.15	3.44	2	Box Cox: μ= 0.596. σ=0.214, λ = -0.5
	6127	Planning Bituminous Pavement	29.50	29.23	36.15	76	Johnson: μ=-0.0124, σ=1.000, 2.2019 + 0.7175 Ln((X - 0.3079) / (341.43 - X))
	6129	Surface Paving	215.08	216.4	265.80	43	Gamma: S=0.535, SC=404.06
	6136	Partial Depth Repair	117.17	120.02	157.63	40	Johnson: μ=-0.0004, σ=0.961, 1.3218 + 0.4945 Ln((X - 0.2150) / (788.36 - X))
	6321	Roadway Betterment	31.72	34.33	60.03	30	Johnson: μ=-0.0177, σ=0.968, -1.4509 + 0.4380 Asinh((X - 1.0177) / 0.4418)
Pavement Drop Off	6130	Spot Berming	186.75	191.47	171.12	100	Johnson: μ=-0.020, σ=1.026, 4.4614 + 1.3696 Ln((X + 25.73) / (4648.43 - X))
	6131	Blading-Restore Unpaved Berm and/or Shoulders	308.46	331	257.73	100	Box Cox: μ=16.648, σ=7.36, λ= 0.5
	6132	Repair Curbs and or Gutters	8.79	9.26	15.33	19	Johnson: μ=-0.054, σ=1.022, 2.2233 + 0.605 Ln((X + 0.0084) / (148.74 - X))

Activity Group	Maintenance Activity		Statewide Average ($2006)	County			
	Code	Description		Average ($2006)	Std. dev ($2006)	Probability %	Distribution
	6331	Berm and/or Shoulder Betterments	52.41	56.38	110.79	73	Johnson: μ=-0.0152, σ=1.022, 3.76 + 0.6848 Ln((X + 0.2848) / (5024.23 - X))
Vegetation Control	6220	Weed Eating	34.59	36.08	34.29	35	Box Cox: μ= 2.516 σ=0.784. λ =0.285
	6221	Mowing	397.74	415.83	185.14	100	Johnson: μ=-0.013, σ=0.988, 0.4544 + 1.9991 Ln((X + 294.54) / (1302.4 - X))
	6222	Chemical Spray Vegetation Management	47.44	47.66	39.17	78	No Fit
	6223	Care of Shrubs, Plants and Trees	355.19	366.02	327.30	100	Johnson: μ=0.0037, σ=0.981, -2.3852 + 1.4605 Asinh((X - 26.01) / 108.45)
Litter	6231	Cleaning Curbs, Gutters & Along Median Barriers	65.48	57.94	97.94	83	Box Cox: μ=1.28, σ=0.145. λ = 0.077
	6232	Litter Pickup	399.54	384.01	238.78	100	Box Cox: μ=3.471, σ=0.474, λ = 0.214
	6236	Litter Patrol	107.22	106.19	138.09	82	No Fit
Drainage	6133	Repairing Slopes	34.32	34.66	37.43	75	Johnson: μ=0.073, σ=0.998 1.664 + 0.6570 Ln((X - 0.5027) / (239.35 - X))
	6134	Repairing Slips and Slides	131.72	129.7	308.20	67	Johnson: μ=-0.0197, σ=0.969, 2.377 + 0.4634 Ln((X - 0.2774) / (4136.29 - X))
	6135	Ditch & Shoulder Relocation	38.29	43.95	104.91	35	Johnson: μ=-0.0421, σ=1.025, -1.7415 + 0.6568 Ln(X + 0.1358)
	6140	Culvert Inspection	21.73	22.96	32.80	76	Johnson: μ=-0.0178, σ=0.983, 1.6963 + 0.556 Ln((X - 0.1422) / (210.70 - X))
	6141	Cleaning & Reshaping Ditches	310.46	314.81	299.62	99	Johnson: μ=-0.0069, σ=0.995, -7.8403 + 1.383 Ln(X + 62.383)
	6142	Cleaning Channels	31.72	33.86	45.52	73	Johnson: μ=-0.021, σ=1.099, 1.915 + 0.665 Ln((X - 0.1084) / (300.85 - X))
	6143	Clean Drainage Structures	120.64	120.25	87.88	100	Johnson: μ=0.010. σ=0.9501, 2.192 + 1.132 Ln((X + 6.295) / (814.97 - X))
	6144	Repair Drainage Structures	169.20	174.57	147.65	100	Box Cox: μ=5.368, σ=1.727, λ = 0.3423
	6145	Clean Ditches with Tiger Ditcher	47.67	51.23	47.24	35	Johnson: μ=-0.0215, σ=0.964 0.8839 + 0.543 Ln((X + 0.2176) / (206.23 - X))
	6146	Inspect and Clean Underdrain Outlets	13.44	12.64	17.51	59	Box Cox: μ=1.288, σ=0.221, λ = 0.1322

Activity Group	Maintenance Activity		Statewide Average ($2006)	County			
	Code	Description		Average ($2006)	Std. dev ($2006)	Probability %	Distribution
	6343	Culvert Betterment	128.01	134.63	168.12	84	Johnson: μ=-0.0470, σ=1.017, 1.792 + 0.627 Ln((X + 0.6676) / (1299.1 - X))
	6344	Catch Basin Repair, Replace, or Install	26.48	27.41	34.90	77	Johnson: μ=0.0116, σ=1.0335, 1.836 + 0.644 Ln((X - 0.0558) / (242.81 - X))
Signs	6521	Ground-Mounted Flat Sheet Sign Maintenance	191.10	193.13	93.66	100	Johnson: μ=0, σ=0.9924 3.074 + 1.948 Ln((X + 34.238) / (1211.29 - X))
	6522	Delineator Maintenance	36.19	37.56	42.37	74	No Fit
	6523	Ground Mounted Extrusheet Signs	30.33	29.33	37.42	81	Box-Cox: μ=1.5507, σ=0.3071, λ = 0.1561
	6524	Overhead Mounted Extrusheet Signs	10.00	9.90	15.91	32	Johnson: μ=-0.0057, σ=0.947, 2.3639 + 0.608 Ln((X - 0.0322) / (197.38 - X))
	6525	Overhead Sign Support Maintenance	3.81	3.69	4.68	19	Johnson: μ=0.0374, σ= 0.993, 1.8876+ 0.639 Ln((X - 0.1276) / (33.08 - X))
	6554	Overhead Mounted Flat Sheet Sign Maintenance	60.93	72.60	124.20	14	Johnson: μ=-0.0696, σ=0.929, 1.0513 + 0.286 Ln((X - 0.2942) / (474.20 - X))
Pavement Marking	6531	Auxiliary Pavement Markings	20.79	22.64	29.33	89	Johnson: μ=0.0027, σ=1.015, -2.849 + 1.059 Ln(X + 0.9864)
	6532	Center Line and Tee	11.52	11.77	11.93	66	Box Cox: μ=1.461, σ=0.280, λ = 0.1827
	6533	Edge Line Marking	50.95	51.71	63.65	77	Johnson: μ=-0.0093, σ=1.039, -2.924 + 0.874 Ln(X + 1.464)
	6534	Lane Line Marking	3.37	3.51	3.30	18	Johnson: μ=0.0433, σ=0.988, -1.501 + 0.920 Asinh((X - 0.636) / 0.663)
	6535	Raised Pavement Markers Maintenance	41.38	43.20	53.25	45	Johnson: μ=0.0177, σ=1.000 1.615 + 0.6230 Ln((X + 0.8518) / (320.33 - X))
	6536	Remove Markings	14.40	15.77	68.26	37	Box-Cox: μ=0.8557, σ=0.1898, λ = -0.1638

Table 8. Activities and costs per lane mile for contracts with Wisconsin's counties

Activity Group	Maintenance Activity		Statewide Average ($2006)	Wisconsin's Counties			
	Code	Description		Average ($2006)	Std. dev ($2006)	Probability %	Distribution
Roadways - Asphalt	1	Spot Repair / Pothole Repair	149.67	121.81	101.95	100	Johnson: μ=0.0767, σ =1.0402 -8.35 + 1.74*Ln(X + 29.11)
	2	Crack Sealing / Filling	122.19	126.56	109.99	94	Box Cox: μ= 5.72943; σ= 2.28057; λ = 0.382913
	3	Sealcoating	36.99	57.36	133.07	27	No Fit
	4	Wedging / Rut Filling	38.74	44.62	72.23	61	Johnson: μ= -0.045, σ = 0.9507 1.35 + 0.38*Ln((X - 0.02)/(380.99 - X))
	5	Milling	13.70	13.59	20.84	56	Johnson: μ= 0.028, σ =1.022 2.096+0.602*Ln((X-0.05)/(173.78-X))
	8	Thin Resurfacing	70.58	91.96	149.37	65	Box Cox: μ= 1.57; σ= 0.49; λ = 0.141
Roadways - Concrete	11	Emergency Repair	9.27	9.17	19.91	48	Johnson: μ= -0.048, σ = 1.013 2.71+0.57*Ln((X-0.01)/(325.84-X))
	12	Non-Emergency Repair	45.88	47.24	70.01	68	Box Cox: μ= 1.68; σ= 0.53; λ = 0.177
	13	Repair of Distressed Pavement	33.74	26.32	46.50	50	Johnson: μ= 0.009, σ = 1.065 1.72+0.43*Ln((X-0.0056)/(291.92-X))
Roadways - Shoulders	21	Grading Gravel Shoulders	157.33	166.93	91.93	100	Johnson: μ= -0.011, σ = 1.007 -12.4203+2.36754*Ln(X+39.8533)
	22	Repairing Paved Shoulders	9.32	9.83	26.03	64	Johnson: μ= 0.015, σ = 1.107 -2.48+0.62*Asinh((X-0.05)/0.08)
Litter	31	Sweeping Pavement	41.12	30.84	38.35	98	Johnson: μ= 0.021, σ =1.011 -2.863+1.051*Asinh((X+0.588)/2.554)
	42	Litter Pickup	178.90	128.00	192.66	100	Johnson: μ= -0.0001, σ=0.958 -2.22+0.81*Asinh((X-3.27256)/7.90)
Vegetation Control	41	Mowing	140.40	129.00	60.08	100	Johnson: μ= 0.010, σ =0.992 1.75+1.63 Ln((X+12.38)/(508.32-X))
	43	Woody Vegetation	99.23	104.19	70.33	100	Johnson: μ= -0.018, σ = 1.023 3.32+1.65*Ln((X+24.88)/(959.57-X))
	44	Noxious Weed Control	22.85	22.01	28.52	86	Box Cox: μ= 1.65; σ= 0.47; λ = 0.203
Drainage	51	Clean / Repair Drainage Structure	59.44	51.27	71.99	99	Johnson: μ= 0.03, σ = 1.015 -2.90+0.88*Ln(X+1.19)
	52	Roadside Drainage	67.51	66.42	61.65	100	Box Cox: μ= 2.28; σ= 0.44; λ = 0.216
Guiderails	55	Safety Appurtenances	45.56	38.77	35.53	96	Box Cox: μ= 2.731; σ= 0.849; λ = 0.301

Activity Group	Maintenance Activity		Statewide Average ($2006)	Wisconsin's Counties			
	Code	Description		Average ($2006)	Std. dev ($2006)	Probability %	Distribution
Sign Repair	81	Routine Repair	27.85	28.06	19.68	100	Box Cox: μ= 4.90; σ= 2.02; λ = 0.5
	85	Emergency Repair	4.51	4.77	6.40	88	Johnson: μ= -0.027, σ = 0.987 2.30+0.69 Ln((X+0.00082)/(71.23-X))
Pavement Marking	90	Pavement Marking	166.85	256.91	384.77	28	Johnson: μ= -0.009, σ = 1.039 -1.70+0.69 Asinh((X-27.31)/14.51)

Chapter 3. CATEGORICAL MAINTENANCE COSTS

This chapter presents statistical analysis and distribution functions for cost per lane mile (CPLM) of common maintenance activities grouped into typical maintenance categories. The scope of maintenance categories includes pavements, shoulders, drainage, litter, vegetation control, pavement markings, signs, and guardrails. The purpose for defining maintenance categories is to explore economies scope that might exist depending on the range of activities. The specific activities in each category vary among the three states, thus direct comparisons of the magnitude of costs are not possible.

The analysis does provide insight on relative trends in CPLM. The statistical analysis of the mean CPLM for each maintenance category focuses on significant annual trends over the three year study period and trends in CPLM among the service providers in each state. The CPLM observations were assigned to lane mile (LM) groups based on responsible lane miles. The purpose for defining LM groups is to be able to explore economies of scale and scope that might exist depending on the volume of maintenance work and range of activities. The significance differences were based on a 95% confidence interval.

Individual distribution functions were identified for characterizing the maintenance CPLM for each category and state. For most categories, maintenance CPLM follows normal distributions after transformation using Box-Cox or Johnson transformation functions. If analysis of the mean indicated significant difference among costs for LM groups, then specialized distribution functions were identified. Normal distribution functions are desirable for statistical simulation and sensitivity analysis and could be use for the forecasting.

3.1 Michigan's Maintenance Costs per Lane Mile

3.1.1 Maintenance Activity Categories and Lane Mile (LM) Groups

Maintenance responsibility for Michigan's is divided among the cities, counties and state forces. Data sets for Michigan include activity costs for contracts with cities and counties, and direct forces at state maintenance garages in 83 counties over the three year period. Table 9 lists the activity breakdown for each of the eight each maintenance categories.

The CPLM observations were assigned to lane mile (LM) groups based on responsible lane miles of the service provider and to a lesser degree by the length in the route sections maintained each of the three maintenance provider groups. Maintenance activities were performed on sections of highways of various lengths which allowed the researchers to separate the data in groups by the corresponding lane miles. The data set did not include route segments for the maintenance costs incurred for direct forces at the state's maintenance garages. As such, route segment lane miles were not used to group the maintenance garages. The LM groups were found using the K-means clustering of observations. This procedure uses non-hierarchical clustering of observations according to MacQueen's algorithm (11). Each observation was assigned to the cluster whose centroid it is closest to.

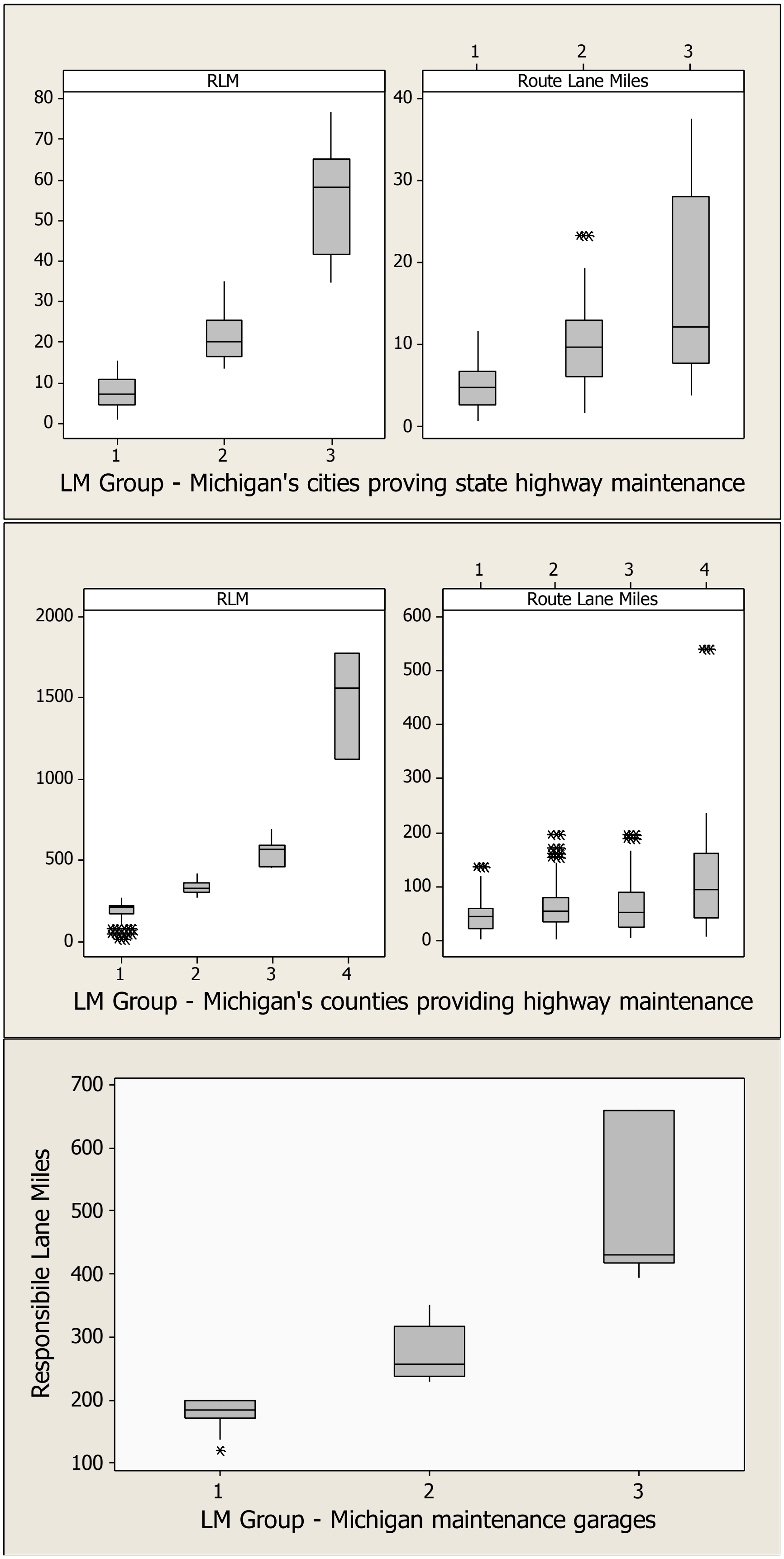
Table 10 and Figure 10 show the ranges of responsible lane miles and route segment lane miles for each group. The table lists the ranges for each group and the boxplots illustrate those ranges. The samples column in Table 10 indicates the number of maintenance activity costs for the full scope of activities in the maintenance categories. The asterisks in Figure 10 indicate outliers. (Section 3.1.2 contains a full description of how to interpret the boxplots.) Multiple asterisks may be for a single county or route segment because there are multiple activities observations. The outliers were not removed.

Table 9. Maintenance categories for analysis of Michigan's maintenance costs

Maintenance Category	Maintenance Activities for Michigan Local Agency and Counties		Maintenance Activities for Michigan State Maintenance Garages	
	Code	Description	Code	Description
Surface	1090	Surface Maintenance	10100	Joint & Crack Filling
			10200	Remove/Replace Pavement (Fast Set Concrete)
			10300	Patrol Patching
			10500	Bituminous Maintenance & Repair
			10800	Bump Removal
Shoulders	1190	Shoulders	11000	Routine Blading
			11200	Gravel Shoulder Maintenance
			11400	Paved Shoulder Maintenance
Drainage	1220	Drainage & Back Slopes	12200	Catch Basin Cleanout
	1230	Ditch Cleaning	12300	Ditch Cleanout
	1280	Culvert/Under Drain Maintenance	12800	Culvert & Underdrain Cleaning
			12810	Culvert & Underdrain Cleaning
Vegetation Control	1210	Trees & Shrubs	12000	Tree Removal
			12100	Stump Removal
			17100	Tree Trimming
	1260	Grass & Weed Control	12600	Area Mowing
			17200	Vegetation Control
	1270	Brush Cutting	12700	Brush Control
Litter	1240	Full Width Litter Pickup	12400	Litter Pickup
	1320	Sweeping & Flushing	13200	Approach Sweeping
			13600	Curb Sweeping
Signs	1600	Traffic Signs	No Activities	
Markings	1620	Pavement Marking		
	1640	Delineators		
Guardrails	1300	Guardrail & Guard Posts	13000	Guardrail Repair
	1650	Attenuators	13010	Guardrail Ending Repair

Table 10. Lane mile (LM) groups for Michigan's highway maintenance providers

Provider	LM Group	Samples	Responsible Lane Miles			Route Segment Lane Miles		
			Min	Mean	Max	Min	Mean	Max
Cities	1	318	0.77	7.41	15.59	0.75	4.99	11.70
	2	180	13.31	21.69	35.16	1.60	9.74	23.35
	3	69	34.6	53.75	77.04	3.81	16.74	37.51
Counties	1	435	10.7	195.3	265.5	1.34	46.38	136.86
	2	273	265.5	334.9	421.4	1.70	59.86	194.95
	3	234	453.9	544.3	688.6	4.25	62.64	195.80
	4	120	1125.0	1499.5	1774.8	7.60	110.42	541.53
State Garages	1	20	120.5	178.5	200.0			
	2	35	230.3	275.1	351.0			
	3	34	393.6	497.9	659.4			



The decision to use three lane mile groups for cities and garages and four groups for counties is not arbitrary. If more groups were used, the samples are fewer and thus less representative sizes become smaller. If fewer groups are used then data trends attributed to responsible lane miles may not be visible. As shown, the ranges of responsible lane miles for the cities and garages are narrower than for the counties. On average the cities are responsible for maintaining fewer lane miles and shorter sections than the counties and state maintenance garages.

Figure 10. Lane mile (LM) groups for Michigan's highway maintenance providers

3.1.2 Cost Trends for LM Groups

This analysis looks for significant differences and trends in cost per lane mile (CPLM) among the service providers grouped by responsible miles. The plots in Figure 11 to Figure 13 show the expenditures in CPLM for each maintenance category for the three procurement methods: contracts with cities and counties, and direct forces at state maintenance garages.

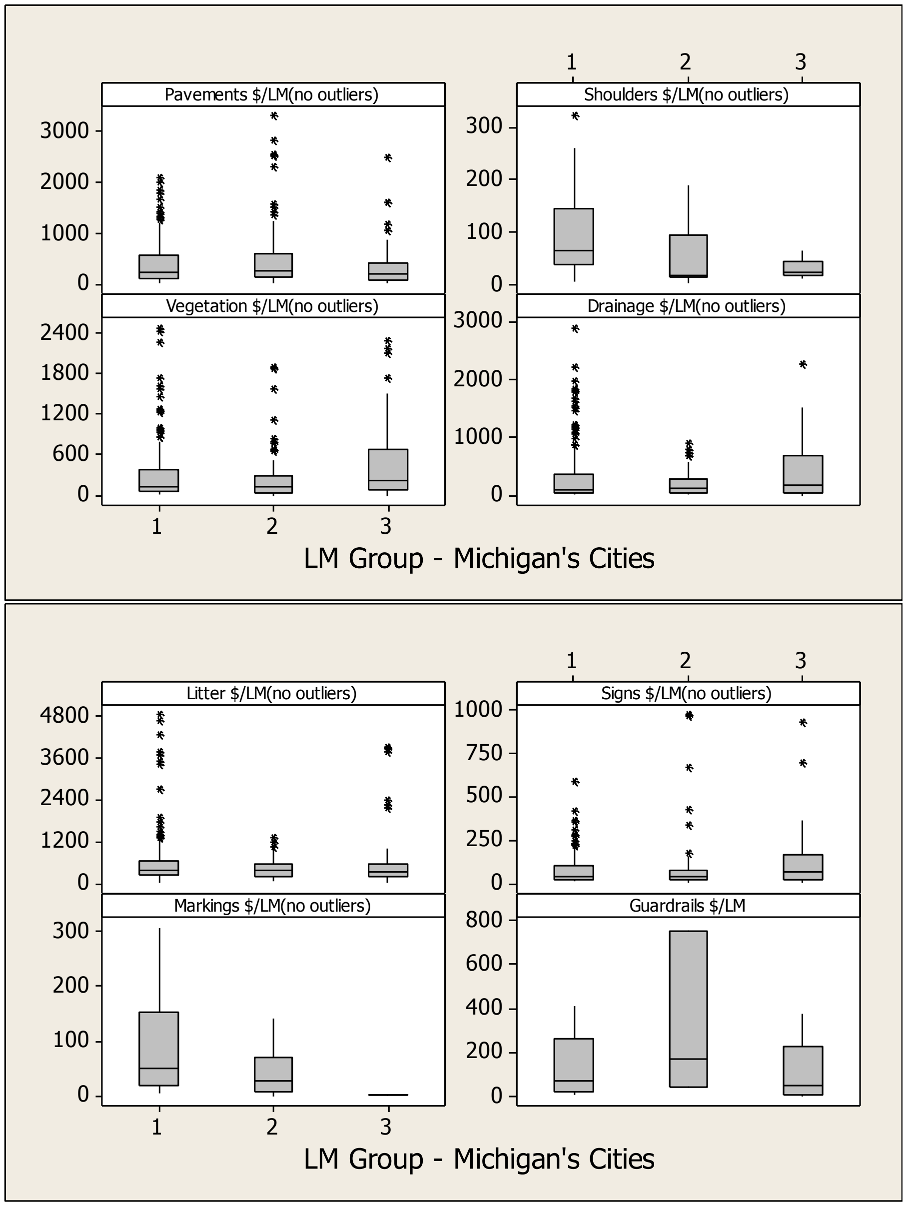


Figure 11. CPLM trends for LM groups – contracts with Michigan's cities.

The boxplots (also called box-and-whisker plots) are useful to assess and compare the cost distributions. Each box encloses the range for half of the cost data for the LM group and maintenance category. The top of the box is the third quartile (*Q3*) - 75% of the CPLM values are less than or equal to this value. The bottom of the box is the first quartile (*Q1*) - 25% of the CPLM values are less than or equal to this value. The line across each box is the median - the middle of the data. Half of the observations are less than or equal to the median. The lower whisker extends to the lowest CPLM value within the lower limit. (Lower limit = $Q1 - 1.5\ (Q3 - Q1)$.) The upper whisker extends to the highest CPLM value within the upper limit. (Upper limit = $Q3 + 1.5\ (Q3 - Q1)$.)

The asterisks beyond the whiskers are outliers - unusually large observations. A few extremely high CPLM values were removed from the data to prevent skewing of results. Those costs appear to be for major rehabilitation maintenance projects. Most of the remaining outliers occur in the plots for contracts with Michigan's cities (Figure 11). This is most likely due having fewer samples for costs and the narrow range of lane miles within each LM group for the cities.

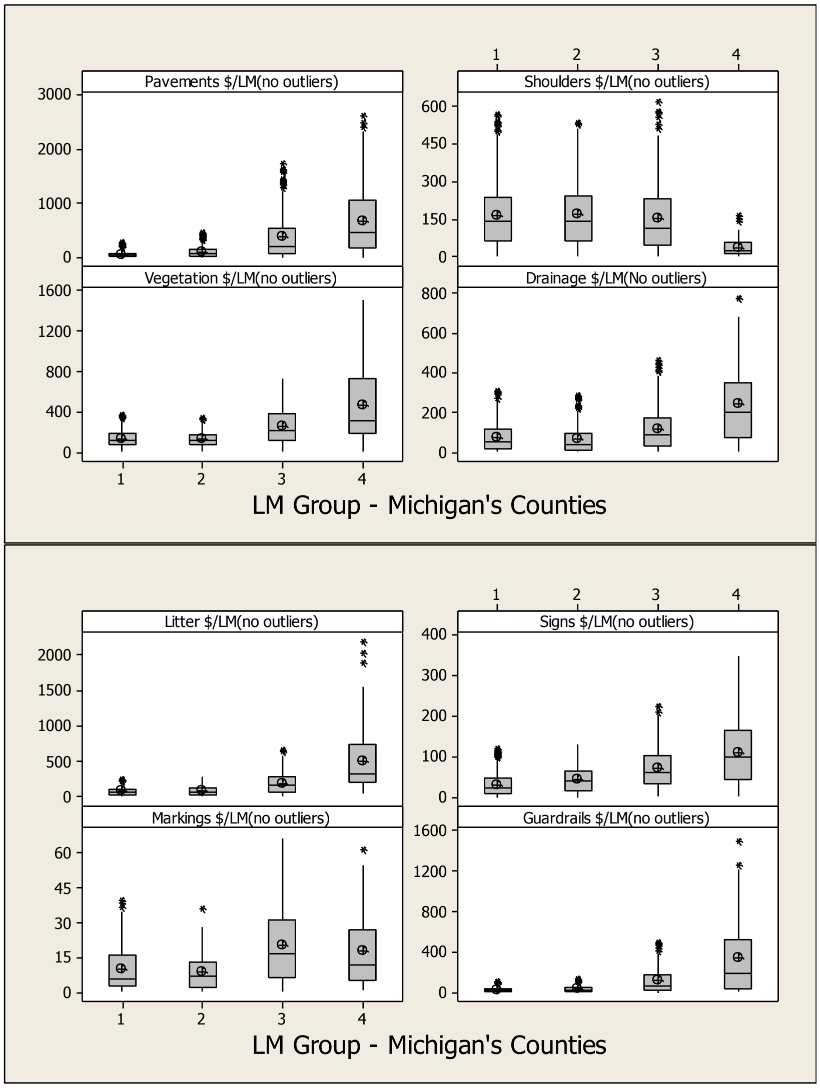


Figure 12. CPLM trends for LM groups – contracts with Michigan's counties

Among the service providers, CPLM for contracts with Michigan's counties show clear trends (Figure 12). CPLM for pavements, vegetation control, drainage, litter, signs, guardrails, and to a lesser extent markings, tend to increase as the number of responsible lane miles increases. From the plots, it might be concluded that the CPLM increases as the scale of the maintenance operation increases. The CPLM for shoulder maintenance shows an inverse relationship. As the number of responsible lane miles increases, the maintenance CPLM decreases. Areas with many lane miles may be more likely to have paved shoulders. Paved shoulders require less maintenance than the unpaved shoulders which likely occur in areas with fewer lane miles.

Table 11 summarizes the statistical analysis of the mean. The mean CPLM of each LM group was compared to the population mean for all LM groups. The analysis

Table 11. Analysis of the mean CPLM for LM groups – Michigan (95% CI)

Maintenance Category	Mean CPLM differs from population mean for LM groups:		
	Cities	Counties	State Garages
Pavements	No difference	1,2,3,4	No difference
Shoulders	1	1,2,4	No difference
Drainage	2	1,2,4	2,3
Vegetation Control	3	1,2,3,4	No difference
Litter	2	1,2,3,4	No difference
Signs	No difference	1,2,3,4	No data
Markings	1	1,2,3	No data
Guardrail	No difference	1,2,4	No difference

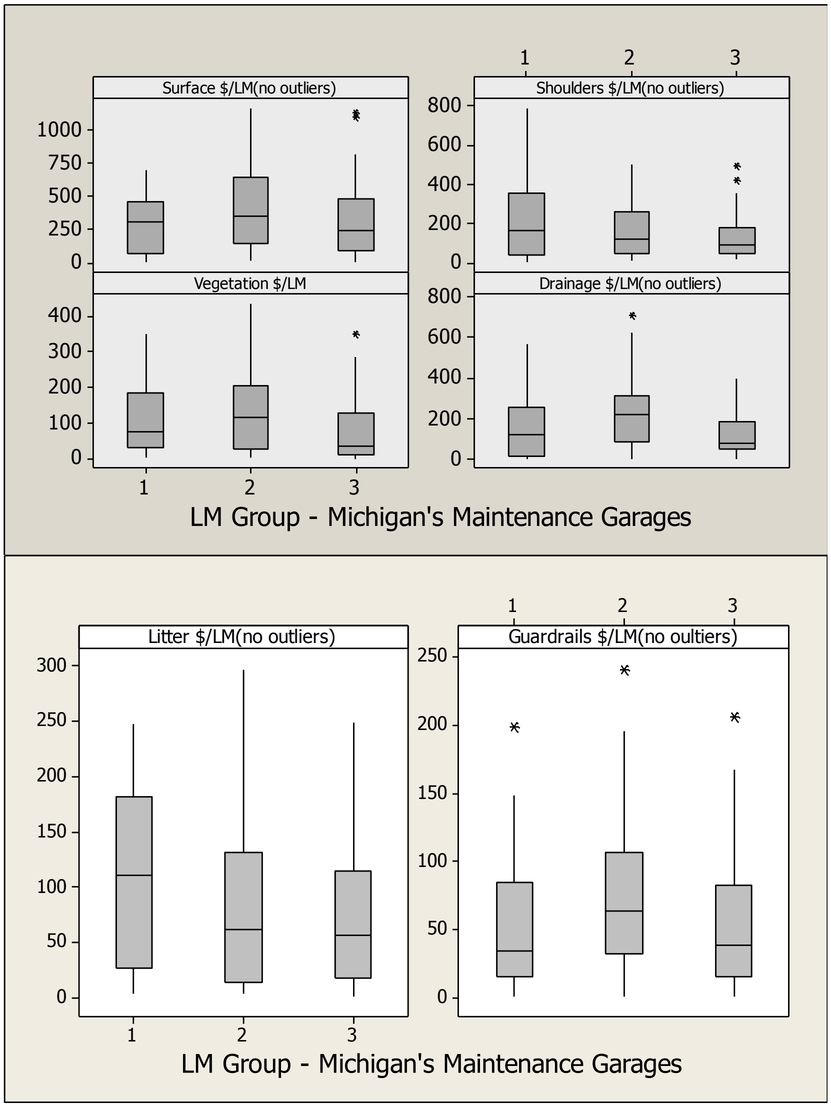


Figure 13. CPLM trends for LM groups – direct forces at Michigan's maintenance garages.

used a confidence interval of 95%. The numeric values in Table 11 are the LM groups with mean CPLM that differs from the population mean for the maintenance category. For drainage maintenance, the mean CPLM for LM group 2 is different from the population mean for all cities; the means of LM groups 1, 2 and 4 are different from the population mean for all counties; and the mean CPLM for LM groups 2 and 3 are different from the population mean for the state garages. The analysis indicated little difference in CPLM among state garages except for the drainage category. Overall, CPLM for drainage maintenance experienced the most difference among LM groups for all maintenance providers.

3.1.3 Annual Cost Trends during the Study Period

The boxplots in Figure 14 show the range of annual CPLM for each maintenance categories for contracts with the counties and Figure 15 shows the same plots for contracts with the cities. The plots indicate no significant changes in expenditures during the study period.

Statistical analysis of the mean (Table 12) indicated that average CPLM for vegetation control in 2006 is significantly different than the average cost over the three year period. This may be due to the effects of the numerous outliers.

Annual CPLM for maintenance performed by direct forces at state maintenance garages are shown in Figure 16. Only two years of data was available. After adjusting to 2006$, the plots clearly show significant differences in 2004 and 2005 for all categories.

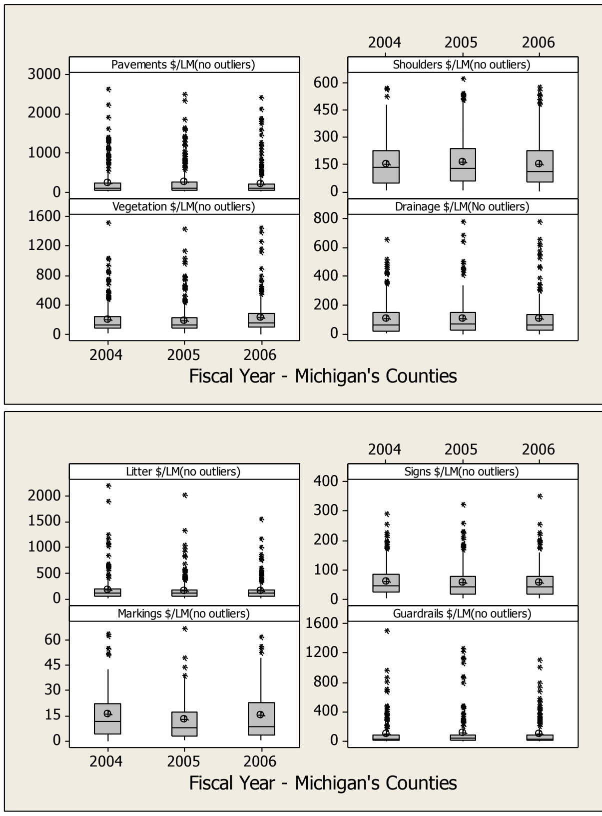


Figure 14. Annual CPLM trends - contracts with Michigan's counties

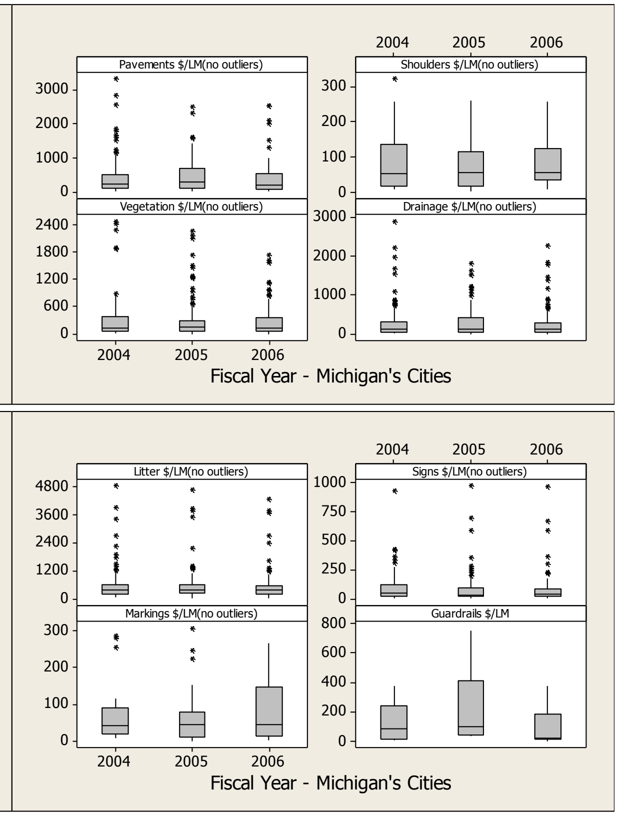


Figure 15. Annual CPLM trends - contracts with Michigan's cities

Table 12. Analysis of the mean annual CPLM – Michigan (95% CI)

Maintenance Category	Mean CPLM differs from population mean for fiscal years:		
	Cities	Counties	State Garages
Pavements	No difference	No difference	2004, 2005
Shoulders	No difference	No difference	2004, 2005
Drainage	No difference	No difference	2004, 2005
Vegetation Control	No difference	2006	2004, 2005
Litter	No difference	No difference	2004, 2005
Signs	No difference	No difference	No data
Markings	No difference	No difference	No data
Guardrail	No difference	No difference	2004, 2005

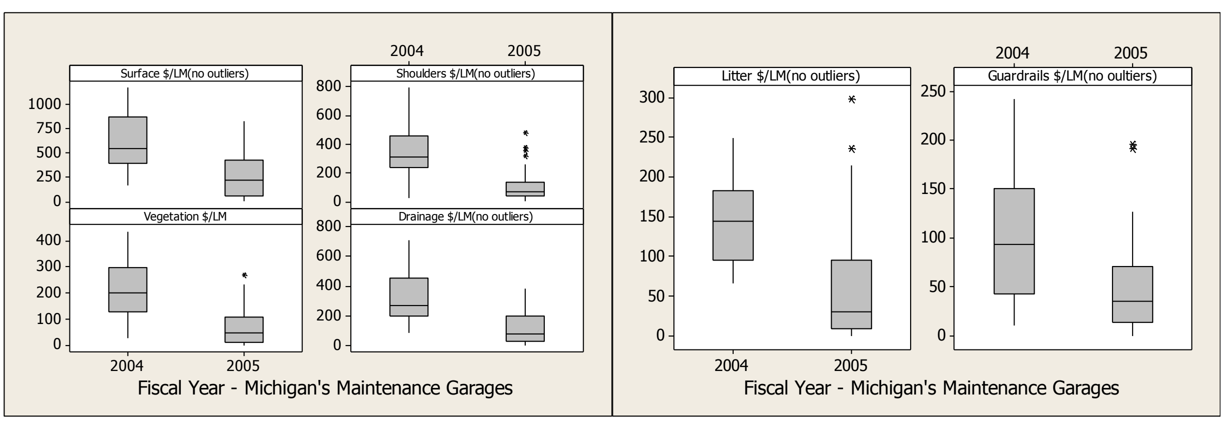


Figure 16. Annual CPLM trends - direct forces at Michigan's maintenance garages

3.1.4 Cost Distribution Functions for Maintenance Categories

Michigan's maintenance costs include labor plus benefits, equipment, and materials cost. The administrative costs were removed for this analysis. Table 13 to Table 15 list the cost distribution functions for the eight maintenance categories. The specific activities included in these categories are listed in Table 9. **The ranges for the LM groups are listed in Table 10**.

The set of LM groups for each distribution function was determined based on a pair-wise comparison of mean CPLM. The pair-wise comparisons used a 95% confidence level. Organizing the LM groups by this criterion generalized the distribution models for the CPLM.

The maintenance costs can be represented by normal distributions with only a few categories having no fit. The Box-Cox and Johnson transformation functions are explained in Section 2.3. The mean and standard deviation of CPLM are listed in the tables. For many categories the standard deviation is greater than the mean indicating very wide ranges.

Table 13. Categorical CPLM – contracts with Michigan's cities

Maintenance Category	LM Group	Probability %	Mean ($2006)	Std.dev. ($2006)	Transformation Function and Distribution
Pavements	1,2,3	75	388.01	479.02	Box-Cox: λ=0.2, μ = 2.93, σ=0.808
Shoulders	1,2,3	17	82.11	76.26	Johnson: μ=0.076, σ=0.936 1.074+0.609 Ln((X-0.366)/(344.77-X))
Drainage	1,3	56	336.11	490.33	Johnson: μ=-0.002, σ=0.976 1.966+0.577 Ln((X+0.48)/(4136.07-X))
Vegetation Control	1,2	57	276.55	401.03	Johnson: μ=-0.043, σ=0.999 2.980+0.749 Ln((X+3.462)/(7709.74-X))
	1,3	54	343.77	491.25	Johnson: μ=-0.028, σ=1.015 2.971+0.744 Ln((X+6.605)/(9293.41-X))
Litter	1,3	93	537.61	706.09	No Fit
	2,3	90	434.28	522.39	Johnson: μ=0.036, σ=1.033 -2.435+1.344 Asinh((X+11.582)/104.74)
Signs	1,2,3	48	83.39	140.46	Johnson: μ=-0.02, σ=0.988 2.874+0.671 Ln((X+0.316)/(2579.69-X))
Markings	1,3	13	86.59	92.93	Johnson: μ=0.055, σ=1.127 1.416+0.656 Ln((X-1.060)/(428.32-X))
	2,3	9	38.91	39.60	Johnson: μ=-0.046, σ=0.991 0.779+0.503 Ln((X+0.386)/(149.01-X))
Guardrails	1,2,3	4	153.08	187.20	Johnson: μ=-0.064, σ=1.015 1.261+0.559 Ln((X+1.286)/(903.65 - X))

Table 14. Categorical CPLM – Michigan's direct forces at state maintenance garages

Maintenance Category	LM Group	Mean ($2006)	Std.dev. ($2006)	Transformation Function and Distribution
Surface	1,2,3	346.78	299.90	Box-Cox: λ=0.5, μ = 16.445, σ=8.79
Shoulders	1,2,3	172.46	176.42	Johnson: μ=-0.001, σ=0.92 1.512+0.683 Ln((X+2.659)/(1126.26-X))
Vegetation Control	1,2,3	108.48	104.45	Johnson: μ=0.013, σ=1.022 0.948+0.586 Ln((X+4.402)/(441.55-X))
Drainage	1,2	203.38	175.03	Box-Cox: λ=0.5, μ = 12.61, σ=6.73
	1,3	126.31	122.90	Box-Cox: λ=0.5, μ = 9.746, σ=5.657
Litter	1,2,3	83.48	74.59	Johnson: μ=0.028, σ=0.984 0.825+0.521 Ln((X-0.282)/(302.09-X))
Guardrails	1,2,3	62.10	57.02	Johnson: μ=-0.004, σ=1.083 1.764+0.963 Ln((X+6.624)/(366.53-X))

The tables list the probability of expenditure for each category and LM grouping. The probabilities were computed using joint probability theory. The probability of expenditure for the category is equal to the probability of expenditure for at least one of the activities in the category. More simply, the probability of expenditure is equal one minus the probability of no expenditures. The probability of no expenditures can be computed by counting the number of samples with no expenditures for any of the activities and dividing by the total number of samples for the category.

Table 15. Categorical CPLM – contracts with Michigan's counties

Maintenance Category	LM Group	Probability %	Mean ($2006)	Std.dev. ($2006)	Transformation Function and Distribution
Pavements	1,2	97	80.42	84.44	Box-Cox: λ=0.234, μ = 2.514, SC=0.696
	3	96	378.55	423.30	Johnson: μ=0.021, σ=0.985 1.116+0.533 Ln((X+1.25)/(1821.7-X))
	4	97	682.75	641.01	Johnson: μ=-0.019, σ=0.958 1.007+0.63 Ln((X+17.06)/(2920.6-X))
Shoulders	1,2,3	94	163.31	130.29	No Fit
	4	73	38.45	36.65	Johnson: μ=0.003, σ=0.955 1.336+0.693 Ln((X-0.387)/(201.25-X))
Drainage	1,2	89	72.94	73.32	Johnson: μ=-0.026, σ=1.009 1.031+0.595 Ln((X+0.613)/(318.5-X))
	3	93	120.44	108.05	Johnson: μ=0.003, σ=1.013 1.104+0.709 Ln((X+3.18)/(508.7-X))
	4	94	241.70	198.89	Johnson: μ=0.014, σ=0.998 0.933+0.702 Ln((X+1.777)/(876.8-X))
Vegetation Control	1,2	98	137.64	79.13	No Fit
	3	95	264.27	176.75	Johnson: μ=0.028, σ=0.978 0.602+0.756 Ln((X+3.699)/(770.9-X))
	4	90	466.11	378.82	Johnson: μ=-0.11, σ=0.995 0.979+0.84 Ln((X+45.42)/(1884.7-X))
Litter	1,2	98	82.34	61.39	Johnson: μ=0.028, σ=0.978 0.943+0.783 Ln((X+2.36)/(291.97-X))
	3	94	187.00	148.13	Box-Cox: λ=0.5, μ = 12.38, SC=5.82
	4	98	501.20	440.67	Johnson: μ=-0.047, σ=0.984 1.581+0.802 Ln((X-25.86)/(2878.7-X))
Signs	1,2	90	37.53	30.47	Johnson: μ=-0.014, σ=1.0 0.855+0.701 Ln((X+0.861)/(132.6-X))
	3	98	73.94	51.12	Johnson: μ=0.023, σ=0994 1.297+1.053 Ln((X+8.23)/(302.91-X))
	4	98	109.70	75.26	Johnson: μ=0.001, σ=0.952 0.811+0.757 Ln((X+0.958)/(363.5-X))
Markings	1,2	26	9.68	9.24	Johnson: μ=0.011, σ=0.987 1.211+0.661 Ln((X-0.059)/(45.442-X))
	3,4	48	19.73	16.60	Johnson: μ=0.013, σ=0.946 0.850+0.643 Ln((X+0.421)/(71.21-X))
Guardrail	1,2	65	29.52	29.39	Johnson: μ=0.029, σ=1.001 1.155+0.628 Ln((X+0.376)/(134.9-X))
	3	72	116.98	127.55	Johnson: μ=-0.061, σ=1.002 1.02+0.552 Ln((X+0.765)/(533.82-X))
	4	87	343.06	370.78	Johnson: μ=0.024, σ=0.903 0.938+0.462 Ln((X-0.559)/(1525.6-X))

3.2 Ohio's Maintenance Costs per Lane Mile

3.2.1 Maintenance Activity Categories and Lane Mile (LM) Groups

The Ohio county cost data were assigned to lane mile (LM) groups based on responsible lane miles. Figure 17 shows the range of lane miles in each LM group.
Ohio data included 88 counties over the three year period. Table 16 lists the maintenance activities in eight categories.

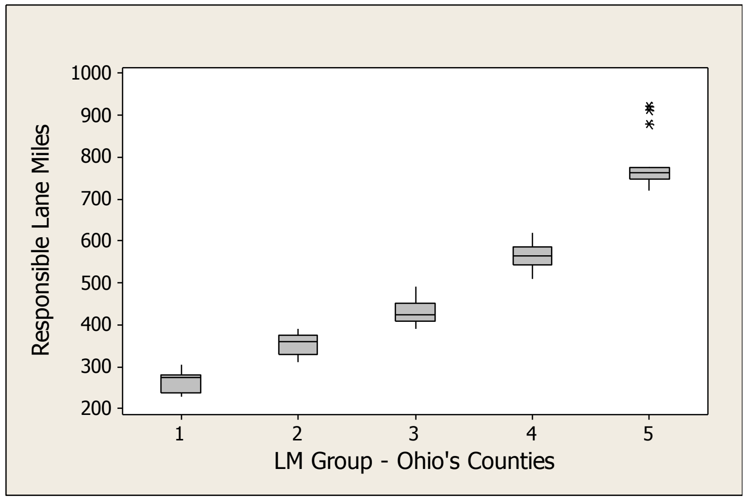


Figure 17. County lane mile (LM) groups - Ohio

3.2.2 Cost Trends for LM Groups

The box plots in Figure 18 show the ranges of CPLM for the eight maintenance categories and five LM groups. The plots show some variations in expenditures across the LM groups. The cost per lane mile for litter pickup shows an increasing trend as the responsible lane miles increase. The plots for pavement drop off, and mowing and vegetation maintenance categories show an inverse relationship. As the number of responsible lane miles increases the maintenance CPLM decreases.

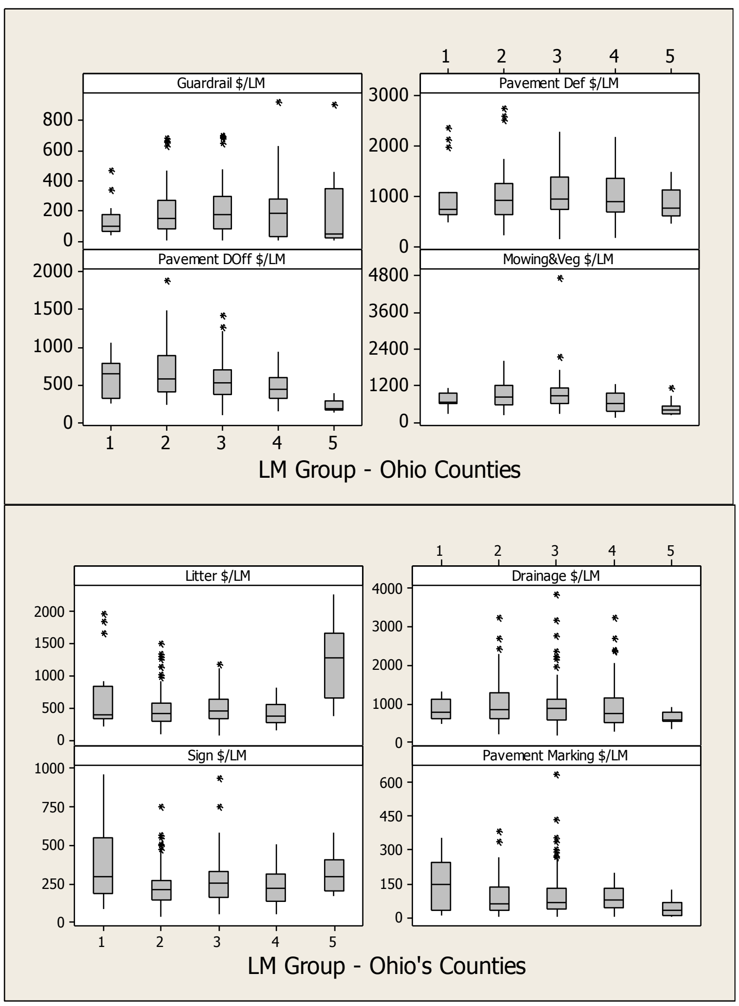


Figure 18. Cost per lane mile trends for LM groups – Ohio's Counties

Table 16. Maintenance categories for analysis of Ohio's maintenance costs

Category	Code	Description
Guardrail	6230	End Assembly Installation and Maintenance
	6233	Repair, Replacement, or Removal
	6235	Crash Attenuator Repair or Replacement
	6237	Concrete Median Barrier Repair, Replacement, Restoration, Removal
	6333	Guardrail Betterment
Pavement Deficiency	6120	Pavement Underseal/Fill Voids
	6121	Pothole Patching
	6122	Surface Repairs
	6123	Full Depth Repair
	6124	Filling and Sealing Joints and Cracks
	6125	Surface Treatment
	6126	Pavement Jacking
	6127	Planning Bituminous Pavement
	6129	Surface Paving
	6136	Partial Depth Repair
	6321	Roadway Betterment
Pavement Drop Off	6130	Spot Berming
	6131	Blading-Restoring Unpaved Berm and/or Shoulders
	6132	Repairing Curbs and or Gutters
	6331	Berm and/or Shoulder Betterments
Mowing and Vegetation Control	6220	Weed Eating
	6221	Mowing
	6222	Chemical Spraying Vegetation Management
	6223	Care of Shrubs, Plants and Trees
Litter	6231	Cleaning Curbs, Gutters & Along Median Barriers
	6232	Litter Pickup
	6236	Litter Patrol
Drainage Obstruction	6133	Repairing Slopes
	6134	Repairing Slips and Slides
	6135	Ditch & Shoulder Relocation
	6140	Culvert Inspection
	6141	Cleaning & Reshaping Ditches
	6142	Cleaning Channels
	6143	Cleaning Drainage Structures
	6144	Repairing Drainage Structures
	6145	Cleaning Ditches with Tiger Ditcher
	6146	Inspection and Cleaning Underdrain Outlets
	6343	Culvert Betterment
	6344	Catch Basin Repair, Replace, or Install
Sign Deterioration	6521	Ground-Mounted Flat Sheet Sign Maintenance
	6522	Delineator Maintenance
	6523	Ground Mounted Extrusheet Sign Maintenance
	6524	Overhead Mounted Extrusheet Sign Maintenance
	6525	Overhead Sign Support Maintenance
	6554	Overhead Mounted Flat Sheet Sign Maintenance
Pavement Marking	6531	Auxiliary Pavement Markings
	6532	Center Line Marking and Tee Marking
	6533	Edge Line Marking
	6534	Lane Line Marking
	6535	Raised Pavement Markers Maintenance
	6536	Pavement Marking Removal

3.2.3 Annual Cost Trends during the Study Period

The plots in Figure 19 show the annual CPLM for the maintenance categories over the 3-year study period. Expenditures for most are constant with the exception of signs and pavement markings. For these the statistical analyses indicate the mean CPLM differs across the years.

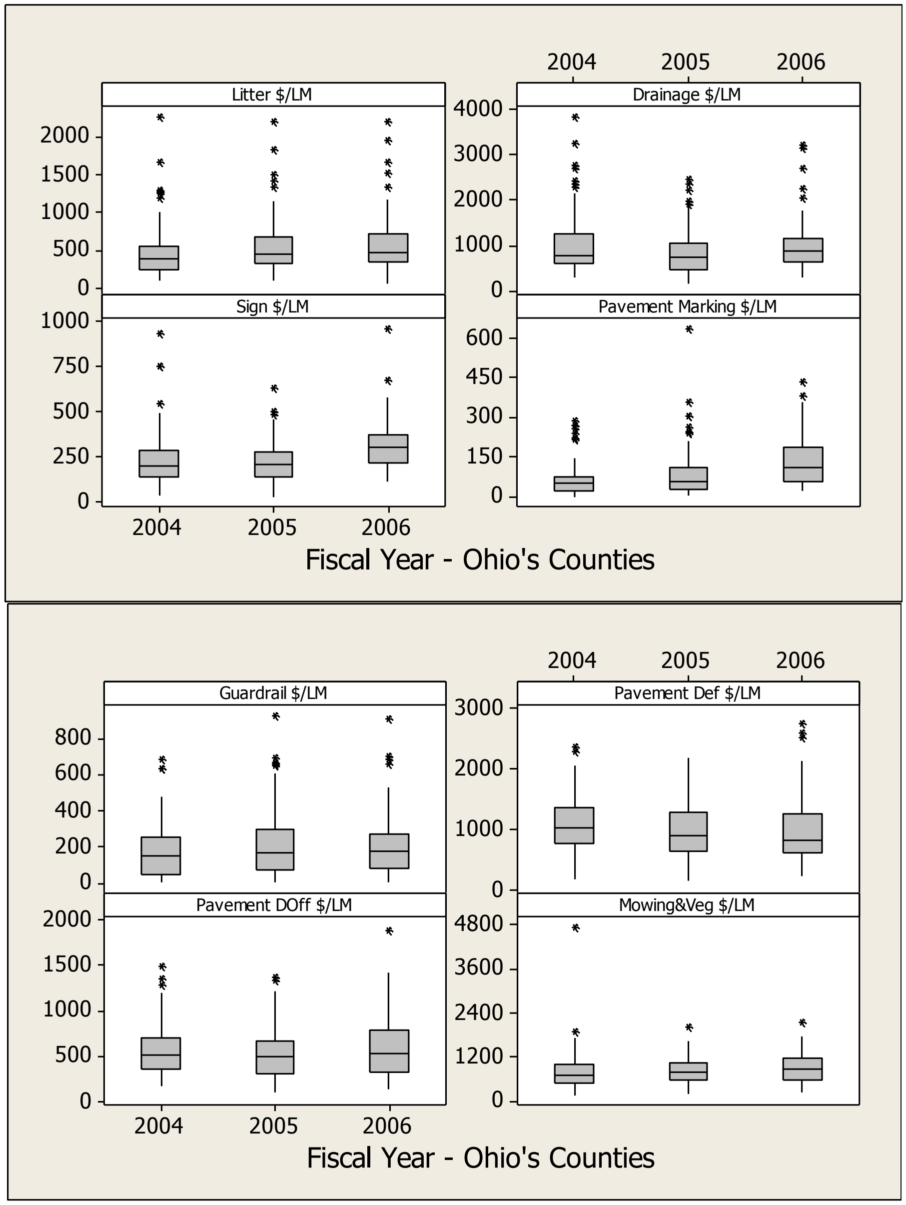


Figure 19. Annual trends for cost per lane mile – Ohio's Counties

Table 17 summarizes the results of the analyses of mean CPLM across LM groups and fiscal years. Groups and years listed in this table have significant differences in mean CPLM when compared to the overall mean of the category.

Table 17. Analysis of the mean CPLM for LM groups and fiscal years – Ohio (95% CI)

Maintenance Category	Mean CPLM differs from population mean for LM groups and year:	
	LM Group	Year
Guardrail	No difference	No difference
Pavement Deficiency	No difference	No difference
Pavement Drop Off	2, 4, 5	No difference
Mowing and Vegetation Control	3, 4, 5	No difference
Litter	4, 5	No difference
Drainage Obstruction	No difference	No difference
Sign Deterioration	1	2005, 2006
Pavement Markings	No difference	2004, 2006

3.2.4 Cost Distribution Functions for Maintenance Categories

Table 18 lists the observed means and standard deviations for each of the 8 maintenance categories and provides the best fit distribution function for each category. The sample size for each category was the 264 cost records. The transformation functions fit the observed data to a normal distribution with mean of 0 and standard deviation of 1. In this table μ and σ are the mean and standard deviation of the transformation functions. Normal distribution functions are desirable for statistical simulation and sensitivity analysis.

Table 18. Categorical CPLM and distribution functions – Ohio

Maintenance Category	LM Group	Probability %	Mean ($2006)	Std. dev. ($2006)	Transformation Function and Distribution
Guardrail	1,2,3,4,5	98	192.50	173.28	No Fit
Pavement Deficiency	1,2,3,4,5	100	988.52	478.26	Johnson: μ=-0.038, σ=0.994 4.126 + 2.24 Ln((X + 271.8)/8562.1 - X))
Pavement Drop Off	1,2,3	100	611.70	307.58	Johnson: μ=-0.01, σ=1.029 2.217+1.435 Ln((X - 48.69)/(2912.8 - X))
	4	100	464.39	185.15	Box Cox: λ=0.5, μ=21.119, σ=4.336
	5	100	227.42	82.46	Johnson: μ=0.006, σ=1.014 -7.961 + 1.674*Ln(X - 89.5265)
Vegetation Control	1,2,3	100	896.54	450.78	Johnson: μ=0.024, σ=0.933 -18.392 + 2.653 Ln(X + 206.879)
	4,5	100	615.57	315.27	Johnson: μ=0.011, σ=1.01 0.332 + 0.602 Ln((X - 166.5)/(1272.8-X))
Litter	1	100	664.14	597.39	Johnson: μ=0.049, σ=0.835 -0.622 + 0.367 Asinh((X - 306.72)/22.06)
	2,3,4	100	463.77	257.31	Johnson: μ=-0.007, σ=1.036 -16.777 + 2.633 Ln(X + 166.441)
	5	100	1232.28	652.69	Box Cox: λ=0.5, μ=33.87, σ=9.55
Drainage Obstruction	1,2,3,4,5	100	936.28	585.98	Johnson: μ=-0.024, σ=1.049 -2.874 + 1.684 Asinh((X - 131.7)/252.1)
Sign Deterioration	1	100	363.34	241.35	Johnson: μ=-0.055, σ=0.948 1.034+0.79 Ln((X - 57.42)/(1277.2 - X))
	2,3,4,5	100	251.94	130.12	Johnson: μ=0.043, σ=1.047 -19.832+3.352*Ln(X + 142.95)
Pavement Markings	1,2,3,4,5	98	95.92	89.86	Johnson: μ=-0.030, σ=1.081 2.375 + 1.072 Ln((X + 6.8) / (786.1 - X))

3.3 Wisconsin's Maintenance Costs per Lane Mile

3.3.1 Maintenance Activity Categories and Lane Mile (LM) Groups

The Wisconsin data set contains annual maintenance costs for various activities for the state's 72 counties over three a year period. Table 19 lists the activities that were grouped into nine categories. Cost data for Wisconsin is divided into labor, benefits, equipment and materials cost. The overhead cost was removed for this analysis. All highway maintenance is performed by the counties through contracts with the state. For this analysis, cost is analyzed on a county level. For Wisconsin, pavement maintenance costs are organized by surface type. The researchers kept them in separate categories.

Table 19. Categories for analysis of Wisconsin's maintenance costs

Category	Code	Description
Roadways - Asphalt	1	Spot Repair / Pothole Repair
	2	Crack Sealing / Filling
	3	Sealcoating
	4	Wedging / Rut Filling
	5	Milling
	8	Thin Resurfacing
Roadways - Concrete	11	Emergency Concrete Repair
	12	Non-Emergency Concrete Repair
	13	Repair of Distressed Pavement
Roadways - Shoulders	21	Grading Gravel Shoulders
	22	Repairing Paved Shoulders
Litter	31	Sweeping Pavement
	42	Litter Pickup
Roadsides - Vegetation	41	Mowing
	43	Woody Vegetation
	44	Noxious Weed Control
Drainage	51	Clean / Repair Drainage Structure
	52	Maintain Roadside Drainage
Guiderails	55	Maintain Safety Appurtenances
Sign Repair	81	Permanent Sign Repair
	85	Emergency Sign Repair
Pavement Marking	90	Pavement Marking

The counties were assigned to lane mile (LM) groups according to the number of responsible lane miles. Figure 20 shows the ranges of lane miles in each of the LM groups.

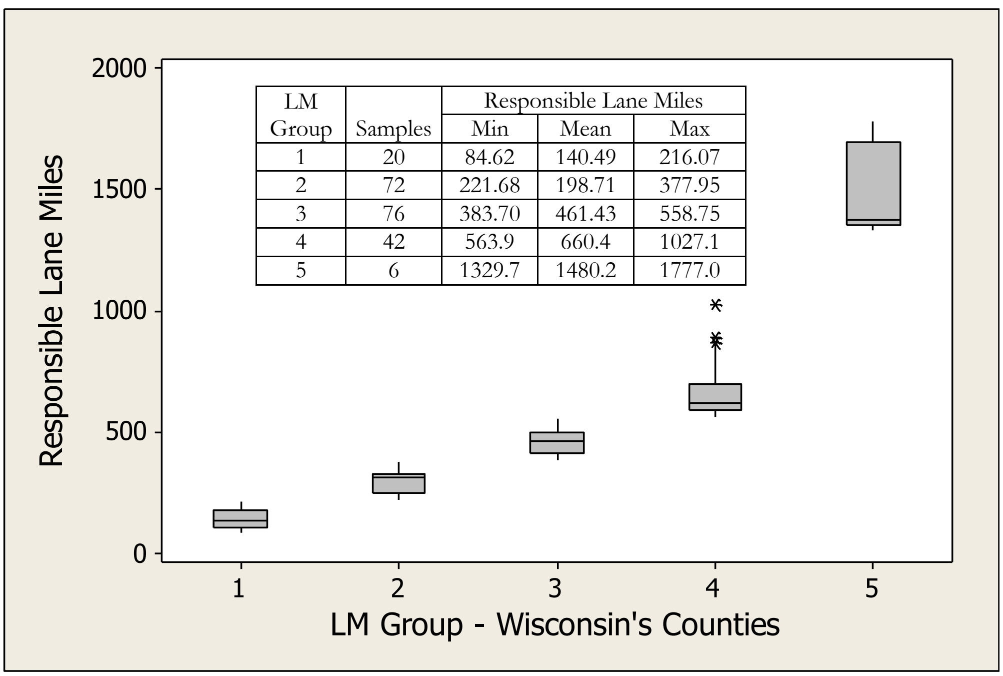


Figure 20. Lane mile (LM) groups – Wisconsin's counties

3.3.2 Cost Trends for LM Groups

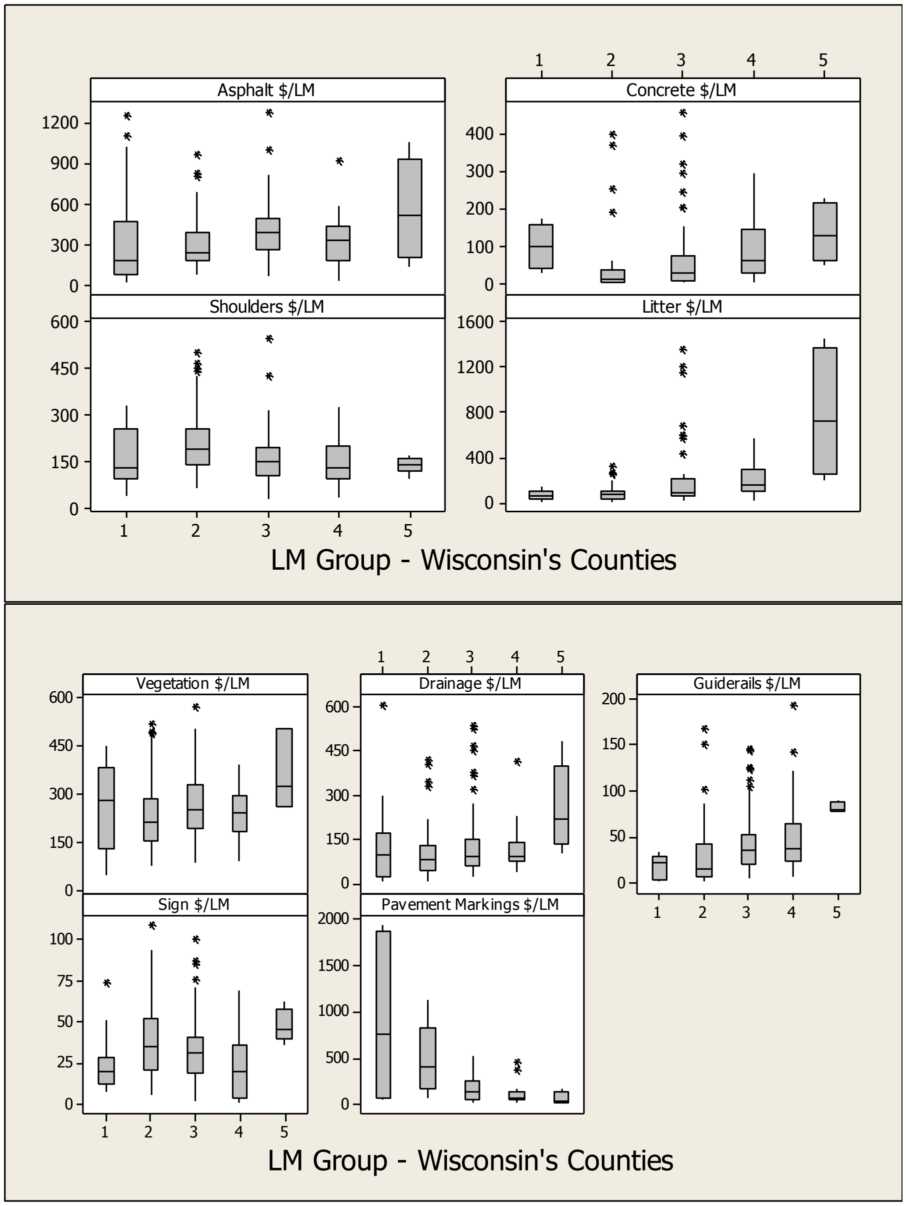
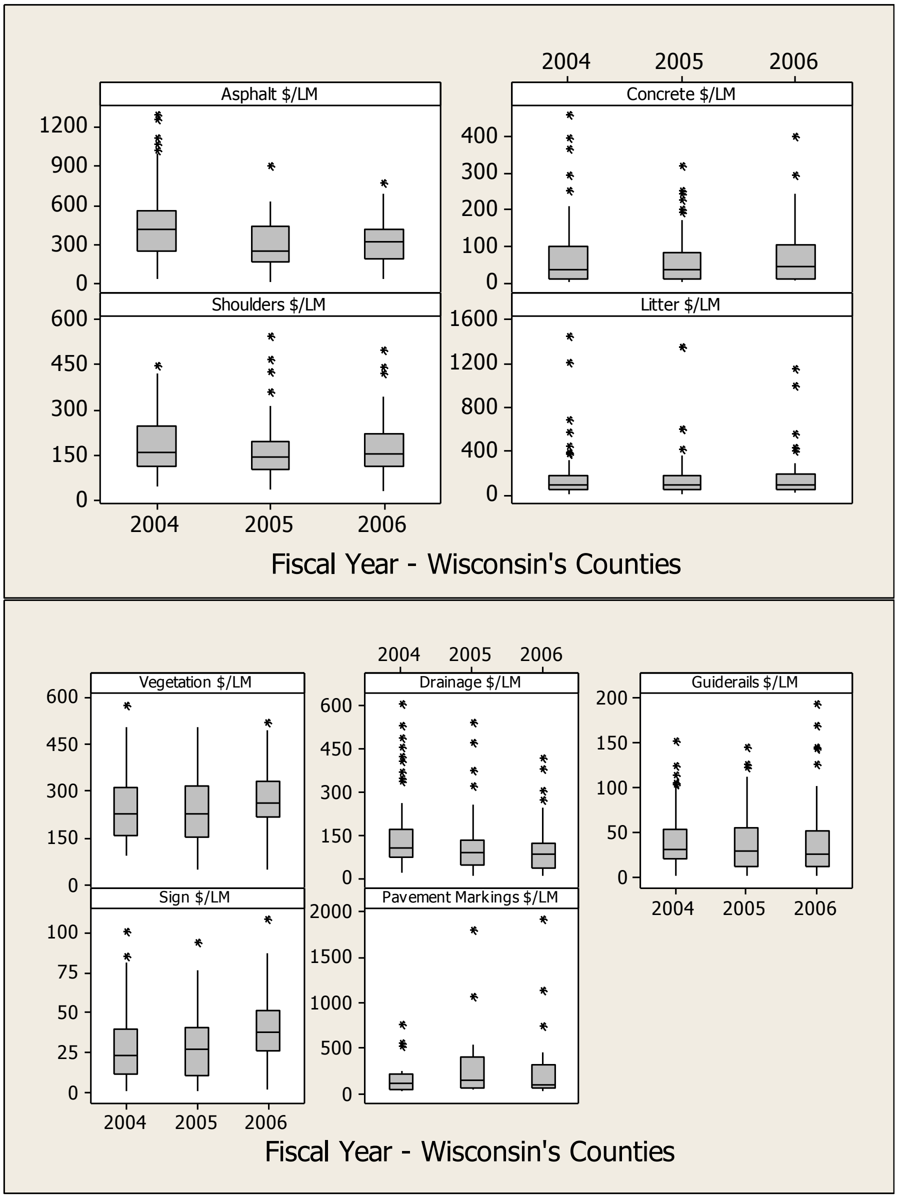


Figure 21. Wisconsin's cost per lane mile for maintenance categories and lane mile groups

The box plots in Figure 21 show the ranges of CPLM for the nine maintenance categories and five LM groups. For some maintenance categories the CPLM varies across the LM groups indicating possible economies of scale. For the litter, drainage and guiderails categories, the CPLM increases with increasing lane miles. However, the CPLM for the pavement markings category shows the opposite pattern. For pavement markings, the CPLM decreases with increasing lane miles.

Overall the mean CPLM does vary among the LM groups. The variance for LM group 5 is higher than for the other LM groups. This could be explained by the small number of samples; only six data samples. Two counties, Dane and Milwaukee, are in LM group 5.

3.3.3 Annual Cost Trends during the Study Period



The plots in Figure 22 show Wisconsin's categorical CPLM for each year of the study period. Expenditures for all maintenance categories do not appear to differ from year to year. Although, results of the analysis of the mean CPLM for asphalt pavements, drainage, and sign repair indicates some differences.

Figure 22. Annual trends for cost per lane mile for contracts with Wisconsin's counties.

The statistical analysis of the mean across LM groups and the fiscal years in Table 20 does not consider LM group 5 since the number of samples is small. The groups and years listed in the table have significant difference in means when compared to the overall mean CPLM for the maintenance category.

Maintenance Category	Mean CPLM differs from population mean for LM groups and years	
	LM Group	Year
Roadways-Asphalt	3	2004, 2005
Roadways-Concrete	X	X
Roadways-Shoulders	2	X
Litter	2, 3	X
Roadside-Vegetation	X	X
Drainage	X	2004
Guiderails	1, 2, 4	X
Sign Repair	2, 4	2006
Pavement Markings	1, 4	X

Table 20. Analysis of the mean CPLM for LM groups and years – Wisconsin (95% CI).

3.3.4 Cost Distribution Functions for Maintenance Categories

Table 21 lists the observed means and standard deviations for each of the nine maintenance categories and the best fit distribution function for each category. The transformation functions fit the observed data to a normal distribution with mean of 0 and standard deviation of 1. In this table μ represents the new normalized mean and σ represents the new normalized standard deviation.

The pair-wise comparison was done only for LM groups 1, 2, 3, and 4. Group 5 was excluded since it has only 6 samples from 2 counties. And in the report we did ANOVA only for 1,2,3,4

Table 21. Categorical CPLM and distribution functions – contracts with Wisconsin's counties

Category	LM Group	Probability %	Mean ($2006)	Std. dev. ($2006)	Transformation Function and Distribution
Roadways-Asphalt	1,2,3,4	100	345.39	217.41	Johnson: μ =-0.009; σ=0.934 -14.704+2.38*Ln(X + 174.13)
Roadways-Concrete	1,2,3,4	71	66.58	90.33	Box-Cox:: λ=0.181,μ =1.829, σ=0.567
Roadways-Shoulders	1,3,4	100	156.72	82.18	Johnson: μ =-0.025; σ=1.014 6.75+2.34 Ln((X+38.01)/(3389.96-X))
	2	100	207.71	104.68	Johnson: μ =0.022; σ=0.983 -1.72+1.461 Asinh((X-76.142)/71.029)
Litter	1,2	100	81.34	58.89	Johnson: μ =0.007; σ=1.043 1.864+0.989 Ln((X-6.925)/(437.6-X))
	3,4	100	186.38	219.87	Johnson: μ =-0.024; σ=1.04 -4.948+1.044 Ln(X-4.067)
Roadside-Vegetation	1,2,3,4	100	248.42	104.9	Johnson: μ =-0.04; σ=1.01 4.432+2.308*Ln((X+35.85)/(2092-X))
Drainage	1,2,3,4	100	113.04	101.56	Johnson: μ =0.294; σ=0.962 -1.607+1.169 Asinh((X-16.717)/35.85)
Guiderails	1,2	92	25.66	30.82	Box-Cox:: λ=0.174,μ = 1.593, σ=0.364
	3,4	99	46.11	35.91	Johnson: μ =0.294; σ=0.962 -4.792+1.321 Ln(X+2.248)
Sign Repair	1,4	100	22.75	17.75	Johnson: μ =-0.031; σ=1.03 0.812+0.717 Ln((X+0.616)/(78.09-X))
	2,3	100	35.41	21.92	Johnson: μ =0.027; σ=1.035 -13.778+3.305*Ln(X+33.044)
Pavement Markings	1,2	16	632.57	612.25	Johnson: μ =-0.035; σ=1.147 0.742+0.461*Ln((X-54.1)/(2051.6-X))
	3,4	33	141.16	127.71	Johnson: μ =-0.065; σ=0.972 -2.298+0.886*Asinh((X-18.01)/11.53)

Chapter 4. MAINTENANCE CONDITION ASSESSMENT

This chapter contains brief overviews of the maintenance condition assessment methods at each state. Michigan uses a sufficiency ratings assigned to each segment of roadway. Ohio uses a system that measures countywide deficiencies for a range of features. Wisconsin's system, somewhat similar to Ohio's, estimates the percentage of assets backlogged for maintenance.

4.1 Michigan's Maintenance Quality Assurance Program

Michigan's maintenance quality assurance program (MQA) is overseen by Michigan's Transportation Asset Management Council. The Council is responsible for tracking the overall condition of roads and bridges, and the spending of allocated public dollars.

The Michigan DOT provided sufficiency ratings for pavements, shoulders, and drainage conditions for roadway sections for the years 2004, 2005, and 2006. The data is reported in lane miles. The sufficiency rating is determined from an annual "windshield survey" of the state's 43,000 miles of federal-aid eligible roads. Sufficiency ratings are based on observed road conditions, including cracking, potholes, sinking, drainage, and rutting. Table 22 to Table 24 list the sufficiency ratings for the predominant pavement surface, drainage, and shoulder condition for the segments. Bridge decks are not included. Intermediate codes (1.5, 2.5, 3.5 and 4.5) could be used to describe surface conditions that lie between those defined in the table. The terms occasional, frequent, or continuous refer to the time and resources spent to maintain the surface so that its condition is as good as the deterioration will permit.

Table 22. Michigan's sufficiency rating system for pavement surface and joint condition

Rating	Condition Description
1	*Excellent:* No deterioration. Distresses are non-existent.
2	*Good:* Some indication of initial deterioration, but not yet requiring appreciable amounts of maintenance. Distress items may include the start of transverse and/or longitudinal cracks. Slight rutting may be apparent in the wheel path.
3	*Fair:* Average deterioration requiring occasional routine maintenance. Distresses may include minor cracks becoming continuous throughout the segment. Severe cracking has been patched or sealed but may start to show through patching.
4	*Poor:* Excessive deterioration requiring frequent maintenance warrants repair or resurfacing soon. Distress may be evident in widening cracks and faulting joints. Cracks could be breaking through patches continuously.
5	*Very poor:* Extreme deterioration, requiring continuous maintenance, warrants repair, resurfacing, or total replacement. Distress items may include severe transverse and/or longitudinal cracking. Joints are failing. Rutting in wheel path may be severe and patches are no longer beneficial to pavement condition.

Table 23. Michigan's sufficiency rating system for drainage condition

Rating	Condition Description
1	*Excellent:* Excellent cross section design, ditch slopes 1:4 or flatter, ditches deep enough to carry very heavy rainfall. Curb and gutter sections have catch basins at all curb returns and usually at mid-block.
2	*Good*: Good cross section design, ditch slopes 1:4 or better, ditches can carry heavy rainfall. Curb and gutter sections have catch basins at the curb returns.
3	*Fair:* Cross section usually narrow, steep ditch slopes, ditches intermittent and not very deep. Curb and gutter sections do not have sufficient catch basins. Rutting may cause hydroplaning.
4	*Poor:* Cross section narrow, grade is at natural ground level or slightly above, ditches intermittent and shallow. Curb and gutter sections have few catch basins.
5	*Very poor:* Ground level higher than roadway and no ditches. Curb and gutter sections have no catch basins. Rutting could cause severe hydroplaning.

Table 24. Michigan' sufficiency rating system for shoulder condition

Rating	Condition Description
1	*Excellent:* Curbs are structurally in very good condition and curb heights are adequate for more than one resurfacing. Shoulders show no visible or apparent deterioration of surface.
2	*Good:* Curbs and shoulders show some deterioration. Curb heights may be adequate for more than one resurfacing. Cracking on paved shoulders is minor.
3	*Fair:* Curbs in average condition and height may be adequate for one resurfacing. Shoulders show average deterioration that may require occasional maintenance. Cracking on paved shoulders is continuous and edge breakaway may be evident. Lane/Shoulder drop may be apparent.
4	*Poor:* Structural condition of curbs is poor and curb heights are inadequate for resurfacing. Paved shoulders show frequent deterioration and may require continuous maintenance. Cracks are continuous and edges are breaking away. Lane/Shoulder drop may affect driver reaction.
5	*Very Poor:* Structural condition of curbs is very poor and curb heights are inadequate for resurfacing. Shoulders show extreme deterioration and are probably beyond normal maintenance repair. Pavement pop-outs are continuous and shoulder edge is broken away. Lane/Shoulder drop off may be severe.

While cost data are available for a wide range of maintenance activities, condition data are limited to the pavement, shoulder and drainage maintenance categories. Thus, only a subset of the cost activities codes is applicable. Table 25 shows the mapping and scope of cost and condition used in the analysis.

Table 25. Mapping cost to condition categories for Michigan.

Condition		Contract Maintenance		Direct Forces	
Maintenance Category	Features	Activity Code	Description	Activity Code	Description
Pavement	Surface & Joint Condition	109	Surface Maintenance	10100	Joint & Crack Filling
				10200	Remove/Replace Pavement (Fast Set Concrete)
				10300	Patrol Patching
				10500	Bituminous Maintenance & Repair
				10800	Bump Removal
Shoulder	Shoulder	119	Shoulder Maintenance	11000	Routine Blading
				11200	Gravel Shoulder Maintenance
				11400	Paved Shoulder Maintenance
Drainage	Drainage & Subbase Condition	122	Drainage & Back Slopes Maintenance	12200	Catch Basin Cleanout
		123	Ditch Cleaning	12300	Ditch Cleanout
		128	Culvert/Under Drain Maintenance	12800	Culvert & Underdrain Cleaning
				12810	Culvert & Underdrain Cleaning

4.2 Ohio's Maintenance Quality Survey (MQS) Program

This study uses Ohio's Maintenance Quality Survey (MQS) data for each county. The MQS program routinely assesses the condition of all highways under the jurisdiction of each district and county. The MQS is performed by two 2-person crews working out of the DOT's Office of Maintenance Administration. The crews survey one quarter of each county's state-maintained highways every three months. MQS deficiencies are collected via touch-screen laptop computers utilizing GPS technology (3).

The MQS data are used by the District Highway Management Administrators and County Managers to allocate their available resources on their County Work Plans. The MQS records maintenance deficiencies for eight categories: guardrail, pavement deficiency, pavement drop-off, vegetation obstruction, litter, drainage ditch obstruction, sign deterioration, and pavement marking as shown in Table 26. The deficiency standards describe the characteristics for determining whether features are deficient. The deficiency count indicates the unit for counting the number of deficiencies. Total deficiencies are compiled for each County and District, as well as statewide from the most recent rolling four quarters by the Office of Maintenance Administration. MQS furnishes a basis against which the success of maintenance efforts may be measured.

In addition, the department uses the Organizational Performance Index (OPI) to evaluate employee performance. The OPI system grades maintenance efforts according to the ranges of total deficiencies per lane mile as determined from the MQS data. The goal of OPI is to ensure the highest level of service possible with the resources available. OPI grades for the counties are fairly constant throughout the 3-year analysis period while the MQS deficiency counts are not.

For Ohio, maintenance cost and condition are related at the category level because they are consistently defined in both the Ellis and MQS systems. This means the sum of the deficiency counts for all features in a maintenance category is related to the sum of the expenditures for all activities in that category. As an example, for guardrails, the sum of the deficiencies for rails, posts, spacer blocks, concrete medians, bridge parapets, anchor assemblies, end terminals, and crash attenuators is related to the sum of the expenditures for activities codes 6230, 6233, 6235, 6237, and 6333.

4.3 Wisconsin Maintenance Quality Assurance Program

In the state of Wisconsin maintenance condition is documented in Compass (1), the quality assurance and asset management program for highway operations. Maintenance condition is cataloged according to elements and features. A maintenance element is defined as a logical grouping of features based on location or function along a highway. Examples of elements include asphalt and concrete pavements, shoulders, and traffic management. (An *element* is similar to a *category* used by other states.) A maintenance feature is defined as a physical asset or activity and its condition is measured in the field. There are one or more maintenance features for each element.

The state conducts an annual Compass survey of randomly selected roadway segments. The sample size is approximately 1% of the state-maintained highways. If a feature is in a condition at which it requires maintenance in the next 12 months, then it is designated as "backlogged". Table 27 lists the elements, their corresponding features, and the condition thresholds for being backlogged.

For continuous features measured by the mile, the threshold value includes both sides of the roadway for a mile segment. Condition information for asphalt and concrete pavements are taken from the agency's PMMS (pavement maintenance management system). State-maintained highway pavements in Wisconsin are inspected on a two-year cycle, with half of the state's pavements inspected in one year, and the other half in the next year. Compass and the PMMS are the data sources for maintenance condition in this study.

For this research, we strived to relate cost and condition at the lowest level possible. Table 28 shows the relationship between HMS cost codes and Compass elements/features as per the HMS cost code descriptions found in Exhibit 6.07 of the Wisconsin State Highway Maintenance Manual (3) and Compass feature descriptions.

The problems encountered when relating cost to condition result from the granularity of the information available. The relationships are either one-to-one, many-to-one, or many-to-many. The ideal situation is a one-to-one direct relationship between one HMS cost code and one Compass feature leaving little room for ambiguity. The two examples of one-to-one relationships in Table 28 are noxious weeds and ditches.

One-to-many relationships have one HMS cost code mapped to several Compass features. Relating one cost to maintenance of many features requires that we somehow combine condition measures. Equal weight was assumed among the measures. Other assumptions are independence of features (condition of one features does not influence the condition of another) and equal number of segments sampled from each feature. Examples of one-to-many relationships listed in Table 28 include the unpaved shoulders, drainage structures, and safety appurtenances.

Finally, many-to-many relationships between HMS cost codes and Compass features require more assumptions. Many-to-many relationships have more than one HMS cost code mapped to several Compass features. Assumptions include independence of features, equal number of segments sampled from each feature, and equal distribution of costs among the features. Two examples Table 28 in are asphalt and concrete pavements where multiple HMS costs codes relate to multiple features in the Compass elements. For these elements condition data is complete (not sampled). Therefore, the sampling assumption can be ignored.

Table 26. Ohio's maintenance quality survey (MQS) criteria.

Maintenance Category	Feature	Deficiency Standard	Deficiency Count
Guardrail	Rail	50% crushed, 50% torn, wrong height, or missing	Each rail panel
		Cable touching the ground	Every 100 linear feet of cable rail system
	Post	2 continuous rotten or missing posts excluding cable rail posts	Every two continuous posts
	Spacer block	Rotten, missing, or rotated block-out	Every 3 continuous block-outs
	Concrete median and bridge parapet	144 sq. inches of cross section missing	Every 12.5 feet of barrier
	Anchor assembly, end terminal, crash attenuator	Damaged or missing	Each or 2 deficiencies per terminal or attenuator
Pavement	Pavement deterioration	Pothole > 2 inch deep and 144 sq. inches in area	Each 6' x 6' area of adjacent paved surfaces
		Rutting > 2 inch deep within wheel tracks	Each 1/10th of a lane mile
		Shoving > 2 inch deep and 4' x 6' in area	Each 6' x 6' area of adjacent paved surface
	Pavement obstruction	Blow-out > 2 inch in height and 6 feet in width	Each
		Sag/slip > 2 inch deep, 15 linear feet, and 6 feet wide	Each
		Manhole or inlet > 2 inch above or below the paved surface	Each 6' x 6' area of adjacent paved surface
Vegetation Obstruction	Vegetation	Vegetation obscuring signage or guardrail	Each sign, guardrail, end treatment, or 100 linear feet of guardrail, or each guardrail run
Litter	Litter	Exceeding 10 countable litter items	Every 1/10th of a mile
	Large litter	8 inches high and 3' x 3' in area	Each
Drainage Ditch Obstruction	Ditch	≥ 50% filled, standing water ≥ 1 inch deep, covering ≥ 6 feet of the paved surface for 10 linear feet, or standing water ≥ 1 inch deep covering the wheel track within a traveled lane for 10 linear feet	Every 100 linear feet of ditch, paved surface, or highway lane
	Driveway pipe	50% or more of driveway pipe is silted in	Each driveway pipe
Sign Deterioration	Damaged sign	Sign cannot be clearly read	Each sign
	Missing sign	Missing sign	Each sign
Pavement Marking	Edge lines and lane lines	> 150 linear feet missing or significantly faded	Every 1/10th of a mile
	Auxiliary marking	Missing or significantly faded	Each stop bar or multiple element marking

Table 27. WisDOT compass elements, features, and thresholds (Compass 2005).

Element	Feature	Thresholds for BACKLOGGED
Pavement, asphalt	Alligator cracking	10% or more of the surface has unsealed alligator cracking (within a mile)
	Block cracking	10% or more of the surface has unsealed block cracking (within a mile)
	Edge raveling	Visible cracking is present for 10% or more of the mile
	Flushing	Flushing is present in more than small, isolated areas (within a mile)
	Longitudinal cracking	Any unsealed longitudinal cracking (within a mile)
	Longitudinal distortion	Significant distortion affects 1% or more of roadway (within a mile)
	Patch deterioration	Any patch is deteriorated enough to affect ride quality (within a mile)
	Rutting	Ruts are ¼ inch or deeper (within a mile)
	Surface raveling	The aggregate and/or asphalt binder has worn away and the surface texture is rough or pitted (within a mile)
	Transverse cracking	Any unsealed transverse cracks at least 6' in length (within a mile)
	Transverse distortion	Significant distortion affects 1% or more of roadway (within a mile)
Pavement, concrete	Distressed joints/ cracks	Distress in wheel path greater than 2 inches wide (within a mile)
	Longitudinal joint distress	Faulting or signs of distress are present (within a mile)
	Patch deterioration	Any patch is deteriorated enough to affect ride quality (within a mile)
	Slab breakup	Slab is divided into at least 2-3 large blocks, affecting 10% or more of the slab (within a mile)
	Surface distress	Any measurable surface distress is present (within a mile)
	Transverse faulting	Any measurable faulting (within a mile)
Traffic Control & Safety	Centerline/edgeline markings	Line with > 20% paint missing (within a mile)
	Delineators	Missing OR not visible at posted speed OR damaged (by delineator)
	Protective Barriers	Not functioning as intended (linear feet of barrier)
	Other signs (emergency)	Missing OR not visible at posted speed (by sign)
	Other signs (routine)	Beyond service life (by sign)
	Raised Pavement Markings	Missing OR damaged (by RPM)
	Regulatory/ warning signs	Missing OR not visible at posted speed (by sign)
	Reg./warn. signs (routine)	Beyond service life (by sign)
	Special Pavement Markings	Missing OR not functioning as intended (by marking)
Shoulders	Cracking	200 linear feet or more of unsealed cracks > ¼ inch (by mile)
	Cross-slope	200 linear feet or more of cross-slope at least 2x planned slope with the maximum cross slope of 8% (by mile)
	Hazardous Debris	Any items large enough to cause a safety hazard (by mile)
	Drop-off/ buildup	200 linear feet or more with drop-off or build-up > 1.5 inches (by mile)
	Erosion	200 linear feet or more with erosion >2 inches deep (by mile)
	Potholes/ raveling	Any potholes OR raveling > 1 square foot by 1 inch deep (by mile)
Drainage	Culvert	Culverts that are >25% obstructed OR where a sharp object-e.g., a shovel-can be pushed through the bottom of the pipe OR pipe is collapsed or separated (by culvert)
	Curb & gutter	Curb & gutter with severe structural distress OR >1 inch structural misalignment OR >1 inch of debris build-up in the curb line (by linear feet of curb & gutter)
	Ditches	Ditch with greater than minimal erosion of ditch line OR obstructions to flow of water requiring action (by linear feet of ditch)

Element	Feature	Thresholds for BACKLOGGED
	Flumes	Not functioning as intended OR deteriorated to the point that they are causing erosion (by flume)
	Storm sewer system	Inlets, catch basins, and outlet pipes with >=50% capacity obstructed OR <80% structurally sound OR >1 inch vertical displacement or heaving OR not functioning as intended (by inlet, catch basin & outlet pipes)
	Drains	Under- and edge-drains with outlets, endwalls or end protection closed or crushed OR water flow or end protection is obstructed (by drain)
Roadsides	Barriers	Noise barrier or retaining wall not functioning as intended (by LF of barrier)
	Fences	Fence missing OR not functioning as intended (by LF of fence)
	Litter	Any pieces of litter on shoulders and roadside visible at posted speed, but not causing a safety threat. (by mile)
	Graffiti	Any graffiti and non-natural encroachments visual at posted speed. (by mile)
	Mowing	Any roadside has mowed grass that is too short, too wide or is mowed in a no-mow zone (by mile)
	Mowing vision	Any instances in which grass is too high or blocks a vision triangle (by mile)
	Noxious weeds	Any visible clumps (by mile)
	Woody vegetation	Any instances in which woody vegetation blocks a vision triangle (by mile)
	Woody vegetation vision	Any instances in which a tree is present in the clear zone OR trees and/or branches overhang the roadway or shoulder creating a clearance problem (by mile)

Table 28. HMS cost activity codes mapped to Compass elements/features.

Relationship (cost-to-condition)	Partial Element	Compass Element: Features	HMS CostCode	HMS Cost Code Description
One-to-One	Noxious Weed	*Roadside:* noxious weeds	44	Control of unwanted vegetation
	Ditches	*Drainage:* ditches	52	Maintain roadside drainage
One-to-Many	Unpaved Shoulders	*Unpaved Shoulders:* cross-slope, drop-off/build-up, erosion	21	Gravel shoulders
	Paved Shoulders	*Paved Shoulders:* cracking, potholes/raveling	22	Paved shoulders
	Mowing	*Roadside:* mowing, mowing for vision	41	Mowing
	Litter Pickup	*Roadside:* litter *Shoulders:* hazardous debris	42	Litter pickup
	Woody Vegetation	*Roadside:* woody vegetation, woody vegetation control for vision	43	Woody vegetation
	Drainage Structures	*Drainage:* culverts, curb/gutter, flumes, storm sewer, under/edge drains	51	Clean/repair drainage structure
	Safety Appurtenances	*Traffic:* delineators, protective barriers *Roadsides:* barriers, fences	55	Maintain safety appurtenances
	Permanent Sign Repair	*Traffic:* routine other signs, routine regulatory/warning signs	81	Permanent sign repair
	Temporary/Emergency Sign Repair	*Traffic:* emergency other signs, emergency regulatory/warning signs	85	Temporary/emergency sign repair
	Pavement Markings	*Traffic:* centerline markings, edgeline, raised pavement markers, special pavement markings	3881	Powerplay traffic program code
			3882	Powerplay traffic program code
Many-to-Many	Asphalt Pavement	*Traveled Way, Asphalt:* alligator cracking, block cracking, edge raveling, flushing, longitudinal cracking, longitudinal distortion, patch deterioration, rutting, surface raveling, transverse cracking, transverse distortion	1	Spot repair/pothole repair
			2	Crack sealing/filling
			3	Seal coating
			4	Wedging/rut filling
			5	Milling/bump removal
			8	Thin resurfacing
	Concrete Pavement	*Traveled Way, Concrete:* distressed joints/cracks, longitudinal joint distress, patch deterioration, slab breakup, surface distress, transverse faulting	11	Emergency repair of concrete pavement
			12	Non-emergency repair of concrete pavement
			13	Repair of distressed pavement

Chapter 5. MODELS RELATING COST TO CONDITION

5.1 Analysis Methodology

Relationships between cost and condition were investigated using statistical analysis and there was no evidence of continuous function relationships. Instead, the researchers used a regression tree approach that looks for a set of piecewise constant or linear estimates of regression functions by recursively partitioning the data and sample space (6). Within each tree, the models capture differences among the data observations depending upon responsible lane miles, vehicle miles traveled, or other relevant variables.

After the best fit models were determined, the statistical program MINITAB was used to identify and remove outliers in order to determine a better fit model. We defined outliers among residuals as points that lay three or more standard deviations from the mean of all residuals (8). Cook's statistics, a methodology used for the detection of unusual observations in a dataset, was used to determine and reject outliers.

The modeling effort explored the relationship between the change in cost and the change in condition between two years. The analysis looked at county cost in consecutive years, cost per lane mile, change in cost and change in cost per lane mile between two consecutive years, condition, and change in condition between two consecutive years.

The regression tree analysis used the GUIDE modeling tool (2). Before running the regression analysis, the researchers analyzed the correlation between each variable used to understand how the variables influence each other. Each predictor variable in GUIDE is assigned either categorical (c) used only for splitting, dependent (d), numerical used for both splitting and fitting (n) or numerical used only for splitting (s).

5.2 Modeling Cost to Condition For Michigan

Scatter plots for cost per lane mile versus average condition for drainage, pavement and shoulder elements showed no obvious trends between condition and cost or any trends in condition over the 3 year period of 2004-2006. However, a regression tree analysis that explored the relationship between cost and condition relative to other variables revealed relationships for shoulder maintenance and culvert maintenance worthy of mention.

The following model equation predicts shoulder condition on a scale of 1 to 5 (according to the rating system in Table 24) with an R^2 of 0.61. R^2, the coefficient of determination, is the proportion of variability in a data that is accounted for by the statistical model.

$$ShdrCond_C = 0.513 + 0.124\,(SubCond_C) + 3.63(\Delta AADT) + 0.64(ShdrCond_P)$$

$ShdrCond_C$ and $ShdrCond_P$ are the current and previous years' shoulder condition. $SubCond_C$ is the current years' condition of the shoulder subbase. ΔAADT is the change in annual average daily traffic between the current and previous year.

The model equation for predicting drainage condition has an R^2 of 0.933. $DrainCond_C$ and $DrainCond_P$ are the current and previous years' average drainage condition. AADT is the annual average daily traffic, and $CPLM_P$ is the previous year's cost per lane mile for drainage maintenance in 2006 dollars.

$$DrainCond_C = -0.0305 + 1.17E\text{-}3\ (AADT) - 1.58\ CPLM_P + 1.01\ DrainCond_P$$

The above shoulder and drainage models were developed for the state of Michigan using county level averages. Each state defines maintenance costs and conditions in slightly different ways. The fit for Michigan is satisfactory. The models were not tested in other locations and there is no reason to expect the models to be applicable outside of Michigan where cost and condition are defined differently.

5.3 Modeling Cost to Condition For Ohio

Maintenance condition in Ohio is defined as total deficiency on a highway section. Total deficiency per section was normalized to deficiency per lane mile for each county and cost was adjusted for inflation then normalized by lane miles.

Parameters of the analysis are listed in Table 29. The analysis looked at relationships between cost and conditions for each of the maintenance categories. We found model equations for relationships between change in cost and change in condition for pavement, guardrail, and litter maintenance. Reliable models could not be determined for the other maintenance categories.

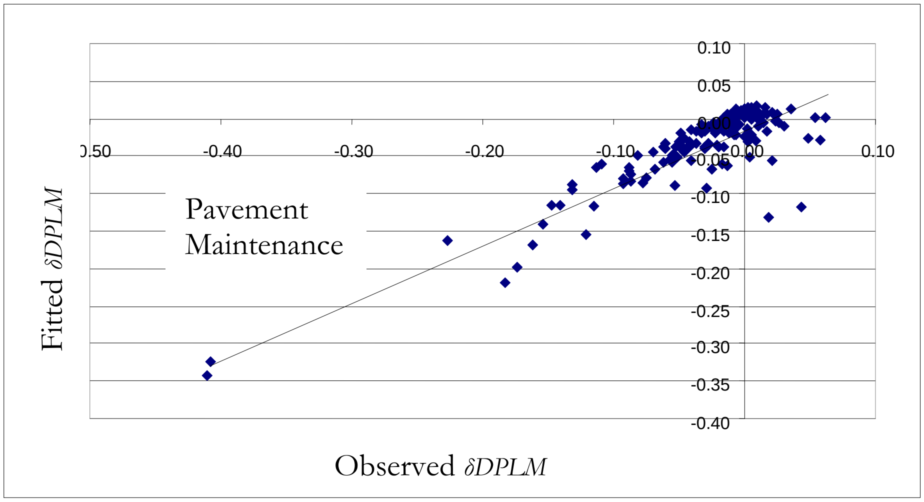
Table 29. Model parameters for guide analysis of cost and condition in Ohio.

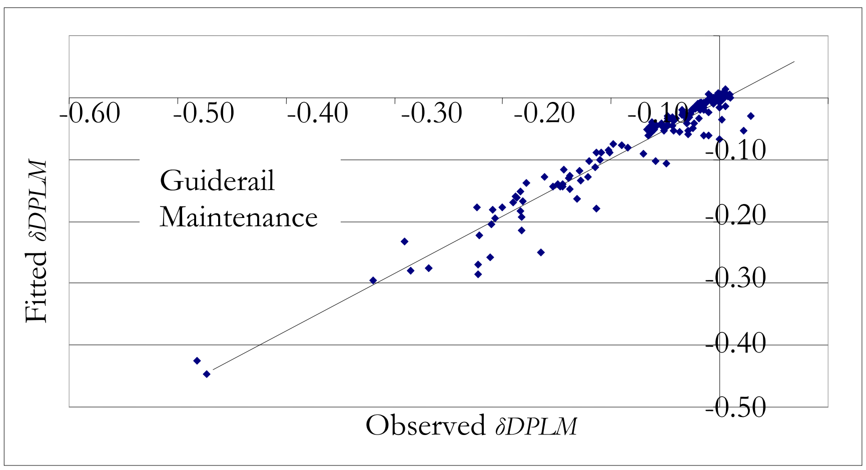
	Parameter	Description and Units (each county)
Current Cost & Conditions	TLM_c	Total Lane Miles
	DEF_c	Total deficiencies
	$DPLM_c$	Deficiencies per lane mile
	$COST_c$	Maintenance cost ($1000 in 2006)
	$CPLM_c$	Maintenance cost per lane mile ($2006)
Change From Previous Year	δCOST	Change in total cost from previous year ($1000)
	δDEF	Change in Total Deficiency (current year - previous year)
	δCPLM	Change in cost per lane mile
	δDPLM	Change in Deficiency per lane mile from previous year
Previous Costs & Conditions	$COST_p$	Change in cost per lane mile from previous year
	DEF_p	Total deficiencies in previous year
	TLM_p	Total Lane Miles (previous year)
	$DPLM_p$	Total Deficiency per lane mile for the previous year
	$CPLM_p$	Total Cost per lane mile from the previous year

The models are summarized in Table 30. For pavement, guardrails and litter maintenance, the fitted models estimate reductions in deficiency as expenditures increase. Figure 23 shows the observed versus fitted change in deficiency per lane mile for these models.

Table 30. Models that relate maintenance cost to condition in Ohio.

Element	Equation	Valid Conditions	R^2	Sample size
Pavement	$\delta DPLM = -0.0021 + 2.74E\text{-}8\ \delta COST + 2.83E\text{-}8\ COST_P - 0.818\ DPLM_P$	All	0.94	176
Guardrail	$\delta DPLM = 0.018 - 0.64\ DPLM_P - 4.62E\text{-}5\ CPLM_P$	All	0.72	176
Litter	$\delta DEF = -7.063 + 5.96E\text{-}4\ \delta COST - 0.704\ DEF_P + 0.28\ TLM_P$	All	0.72	176





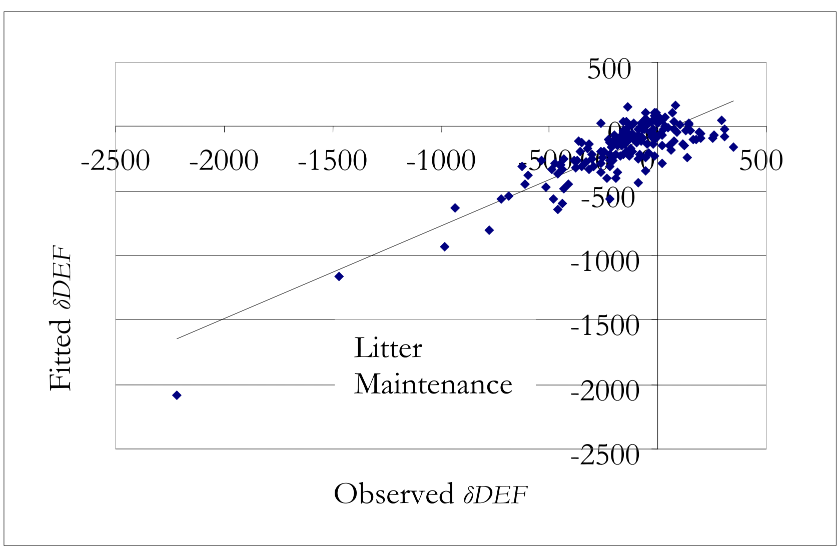


Figure 23. Observed deficiencies versus fitted models for Ohio

Ohio uses maintenance deficiency ranges from the MQS survey. Because the number of deficiencies are grouped into ranges, the models for elements could predict that condition deteriorate as maintenance costs increase. Maintenance OPI Index for Ohio is shown in Table 31. For example, to obtain an OPI score of 4, in the pavement deficiency category, the scale ranges from 0.65 to 0.86 deficiencies per lane mile. For any given year, the deficiency could increase or decrease slightly and still fall under the OPI score of 4. Although the deficiency counts change from year to year, the OPI scores may be consist.

Table 31. Deficiencies per lane mile ranges for Ohio's Maintenance OPI index

OPI Scores	Guardrail	Pavement Deficiency	Pavement Drop-Off	Vegetation Obstruction	Litter	Drainage Ditch Obstruction	Sign Scale	Pavement Marking
6	0.05	0.2	0.05	0.01	1.35	0.02	0.03	0.06
5	0.13	0.42	0.13	0.03	2.95	0.04	0.06	0.15
4	0.21	0.65	0.21	0.05	4.65	0.06	0.1	0.24
3	0.28	0.86	0.28	0.07	6.2	0.08	0.13	0.32
2	0.35	1.07	0.35	0.09	7.75	0.1	0.16	0.4
1	0.42	1.28	0.42	0.1	9.3	0.12	0.18	0.48

5.4 Modeling Cost to Condition For Wisconsin

Two types of relationships between cost and condition were explored. The first is the relationship of fixed cost to fixed backlog. This relationship is based on cost and condition in a single year. It allows for estimating the cost required to obtain a specific backlog or the backlog that will result from a specific level of spending. The second relationship is based on the changes in cost and condition between two years. It allows for estimating of change in backlog given current backlog and budget constraints. It also allows for estimating the budget adjustments required to achieve certain maintenance conditions. Finding these relationships equations would give maintenance engineers and decisions makers the tools they need for transportation maintenance budgeting.

Maintenance cost data by activity code at the county level along with maintenance condition data by feature at the county level were provided by WisDOT. The data processing involved first aggregating conditions and costs for each of the nine elements. The analysis is as follows:

1. For elements with multiple features, determine if the features are independent of each other in order to justify aggregating of condition backlog data.
2. For elements with multiple features, if features are independent then aggregate condition backlog to determine backlog for the element at the county level.
3. For elements with multiple features, aggregate cost code data to determine total cost for the element at the county level.
4. Analyze the relationship between (aggregate) condition and (aggregate) cost at the county level using scatter plots and regression tree analysis and draw conclusions.

5.4.1 Aggregating Element Condition and Maintenance Costs

A feature is considered backlogged if distresses are more severe than a specific threshold. A composite %backlog was computed for each element as the aggregate weighted backlog of the component features. If the presence of one backlogged feature does not influence the backlog of other features, then the features are independent. This aggregate value would not be valid the features are highly correlated.

One method to evaluate the independence among variables is to examine the correlation of backlogging among features of each element. Independence can be concluded if one distress is not highly correlated to another. The correlation coefficient can range in value from -100 to +100, and tells two things about the linear relationship between two variables. The larger the absolute value of the coefficient, the stronger the linear relationship between the variables. A correlation value of 100 indicates a perfect linear relationship, and zero indicates the absence of a linear relationship. The sign of the coefficient indicates the direction of the relationship. If both variables tend to increase or decrease together, the coefficient is positive. If one variable tends to increase as the other decreases, the coefficient is negative.

The correlation matrix for distressed features in the unpaved shoulders and paved shoulders in the fiscal years 2004-06 is shown in Table 32. The off-diagonal correlation percentages are low; the largest is 29% between unpaved cross slope and unpaved drop. This result indicated the features that comprise the unpaved and paved shoulders elements are independent.

Table 32. Correlation among features shoulder elements

	Unpaved Shoulder			Paved Shoulder	
	Drop Off	Cross Slope	Erosion	Cracking	Potholes
Drop Off	100				
Cross Slope	29	100			
Erosion	10	16	100		
Cracking				100	
Potholes				10	100

The correlation matrices for the remaining elements are shown in Table 33 through Table 35. The 88% correlation between transverse and longitudinal cracking in the element Asphalt Travel Way is large enough to require attention. Since these two features are so highly correlated, their backlog values were averaged and the averaged. If either or both features were backlogged then the combined transverse cracking/longitudinal cracking feature is backlogged.

Table 33. Correlation among features of mowing, litter pickup and woody vegetation

	Mowing	Mowing for Vision	Litter	Hazardous Debris	Woody Vegetation	Wdy Veg. Cntrl for Vision
Mowing	100					
Mowing for Vision	5	100				
Litter			100			
Hazardous Debris			18	100		
Woody Vegetation					100	
Woody Vegetation Control for Vision					16	100

Table 34. Correlation among features of asphalt travel ways

	Alligator Cracking	Block Cracking	Edge Raveling	Flushing	Longitudinal Distortion	Patch Deterioration	Rutting	Surface Raveling	Transverse / Longitudinal Cracking	Transverse Distortion
Alligator Cracking	100									
Block Cracking	-1	100								
Edge Raveling	7	3	100							
Flushing	0	2	0	100						
Longitudinal Distortion	2	0	-1	0	100					
Patch Deterioration	5	2	12	1	0	100				
Rutting	2	2	4	4	0	7	100			
Surface Raveling	7	2	6	0	2	4	1	100		
Transv/Long Cracking	13	15	6	2	2	3	8	5	100	
Transverse Distortion	4	1	1	0	0	0	1	0	1	100

Table 35. Correlation among features of concrete travel ways

	Dist Joints / Cracks	Long. Joint Distress	Patch Deterioration	Slab Breakup	Surface Distress	Transverse Distortion
Distressed Joints / Cracks	100					
Longitudinal Joint Distress	17	100				
Patch Deterioration	26	12	100			
Slab Breakup	1	14	7	100		
Surface Distress	18	2	21	-23	100	
Transverse Distortion	48	10	50	0	29	100

After verifying that features are independent, the backlog values were aggregated to derive a backlog for the element. Two methods of calculating element backlog were considered. They are referred to as the "average method" and the "extent method." Both methods compute county level backlog.

The "average method" uses Compass backlogs for features at the county level to determine element backlogs. Compass determines backlog by first separating condition data for each segment into two groups. One group has backlog values of 0 (no backlog) and the other group have backlog values greater than 0 (backlogged). Feature backlog is then calculated as

$$\text{Feature Backlog} = \frac{\text{Number of Backlogged Segments}}{\text{Total Number of Segments}}$$

Since the features are independent, the aggregate average element backlog is the sum of the feature backlogs divided by the number of features in the element. This average method is simple and reasonable when there is approximately the same number of observations for each of the features in the partial element.

$$\text{Average \%Backlog} = \frac{\sum_{Features} \text{Backlog}}{\text{Total Number of Features}}$$

For ditches the %backlog for years 2005 and 2006 was calculated based on the linear feet of ditch. The %backlog for ditched in 2004 were eliminated because the Compass data was based on number of segments rather than linear feet of ditch.

$$\text{Ditches \%Backlog} = \frac{\begin{array}{c}\text{Linear feet with more than minimal erosion} \\ \text{of ditch line or obstructions to the flow of} \\ \text{water requiring action}\end{array}}{\text{Total linear feet of ditch line}}$$

Independence of features is not a necessary condition for the extent method. In the "extent method" if any feature of an element on the segment is backlogged then the entire segment is backlogged. %backlog is then calculated as

$$\text{Extent \%Backlog} = \frac{\text{Number of Segments with} \geq 1 \text{ Backlogged Feature}}{\text{Total number of Segments}}$$

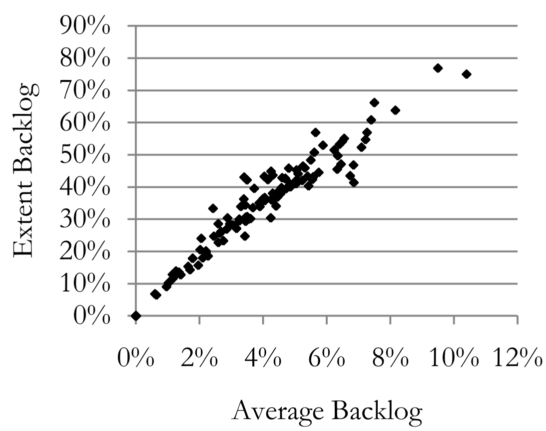


Figure 24. %Backlog for asphalt pavements in Wisconsin

The extent method led to higher %backlog values than the average method. This seems reasonable if maintenance crews correct multiple distresses when maintenance is performed. For example, crews would also repair cross slope when drop off is being addressed.

Although the magnitude of backlog is different for each method, the distributions are similar. Figure 24 shows a scatter plot comparison of %backlog of asphalt travel way computed using the average and extent methods. Regression tree analysis using average %backlog and extent %backlog yielded similar models in terms of the best fit parameters and the R^2 values. The average backlog method was selected for this study simply because it is easier to calculate.

The method for assigning maintenance costs to elements involved distributing and summing WisDOT's HMS activity costs (see Table 28 for HMS activity cost codes). Each activity cost was broken down into labor, equipment, materials. Overhead costs are included in activities 31 to 34 in the miscellaneous category. Administrative costs are included in activities 91 and 93 to 96 in the administration category. These were distributed to the elements based on the percent allocations determined by WisDOT. Summing the HMS costs determined the total cost for each of the nine elements. Costs were adjusted by the urban consumer price index (CPI) to year 2006 costs. This is the same cost index used by WisDOT (5).

The sign repair and pavement markings elements were not included in the study because the Compass features cannot be related directly to HMS codes. Furthermore, drainage structures and safety appurtenances were not included because the features are not expressed as distresses and a rational way to combine backlogs could not be identified. In addition, the features for drainage structures have costs that vary significantly and often included in the cost of repairing or replacing bridges which are out of the study scope.

5.4.2 Regression Tree Modeling Approach

$$\frac{\text{Cost}}{\text{mVMT}} = \frac{\frac{\text{FY 2006 Dollars}}{\text{Year}}}{\left(\frac{\text{Million Vehicle Miles Traveled}}{\text{Year}}\right)}$$

Expenditures normalized by million VMT per year enabled comparisons across years and counties. The normalized costs were plotted against %backlog to reveal trends or patterns relating cost and condition. Each data point on the scatter plots represents one county in one year. If observations were available in all counties for all years the total number of possible data points is 216 (72 counties multiplied by 3 years).

In addition, the change in %backlog relative to change in expenditures from years 2004 to 2005 and from 2005 to 2006 were plotted to determine trends or relationships. The equation for change in cost between years *i* (prior year) and *j* (current year) normalized by million vehicle miles traveled in each county is shown to the right. The maximum number of data points in the scatter plots is 144 (2 annual changes for 72 counties).

$$\frac{\Delta\text{Cost}}{\text{mVMT}} = \frac{\left(\frac{\text{FY 2006 Dollars}}{\text{Year}_j}\right) - \left(\frac{\text{FY 2006 Dollars}}{\text{Year}_i}\right)}{\left(\frac{\text{Million Vehicle Miles Traveled}}{\text{Year}_j}\right)}$$

The scatter plots did not show relationships between maintenance cost and condition. In analyzing change in cost versus change in %backlog plots, we expected most values to be in quadrants 2 and 4 indicating a positive change in budget causing a negative change in backlog and a negative change in budget causing a positive change in backlog. However this is not the case. Given the profound scatter in the data, a regression tree analysis was used to split and group the data in an effort to tease out relationships. The regression tree analysis used the parameters listed in Table 36.

Table 36. Model parameters for guide analysis of cost and condition in Wisconsin.

Parameter	Description
Cost	Annual maintenance cost 2006 FY dollars
%Backlog	Backlog – percentage (calculated using the average method)
mVMT	Million annual Vehicle Miles Traveled
LM	County Lane Miles
WSI	Winter Severity Index – Measure of winter severity per county
PopDensity	Population Density - Population per square mile per county
Income	Median Household Income per county - 2000 FY dollars
Latitude	Latitude Groupings – Numbered 1 to 5: North to South
SoilType	Soil Type – Numbered 1 to 5: Silty, Sandy, Loamy, Wetland, Sandstone
$Soil_{pH}$	Soil pH – Ranges from 5.0 – 7.3, average = 6.6
$Soil_K$	Soil Potassium Content - parts per million, range is 80–166, average = 134
$Soil_P$	Soil Phosphorus Content - parts per million, ranges is 30–153, average = 52
$Soil_{OM}$	Soil Organic Matter – percentage, ranges from 1.2 – 7.0, average = 3.0
AveAge	Pavement Average Age – Average years since last resurface or reconstruction
LandArea	Land Area - Square Miles per county
mTruckVMT	Million annual Truck Vehicle Miles Traveled
$LM_{concrete}$	Lane Miles of concrete traveled way per county
$LM_{asphalt}$	Lane Miles of asphalt traveled way per county
CLM_{ups}	Center Line Miles of unpaved shoulders per county
CLM_{ps}	Center Line Miles of paved shoulders per county
CLM	Center Line Miles per county

Million vehicle miles traveled (VMT) were based on traffic counts for one-third of the counties each year and were provided by WisDOT. The exception is Milwaukee County in which approximately one-third of the county is counted every year. Annual average daily traffic (AADT) estimates for counties not counted in the current year are estimated using a growth factor for the statewide seasonal factor group average. Vehicle miles traveled (VMT) estimates are based on AADT estimates (6). VMT was not available for the year 2006 at the time of the analysis so VMT from the year 2005 was used as data for 2006.

Lane mile data for each of the counties was also provided by WisDOT and came from the STN Database. The only model that used total lane miles as a variable was litter pickup because it was hypothesized that roadways with more lanes would have more litter than roadways with fewer lanes. Variables for lane miles of asphalt and concrete pavement were included for analysis of asphalt and concrete travel ways, respectively.

The winter severity index is a measure of the winter storm severity and frequency in Wisconsin counties and was obtained from Compass (7). It was hypothesized that counties with high winter severity indexes would behave differently than counties with lower winter severity indexes in that they would have higher %backlog for the maintenance of asphalt and concrete travel ways, unpaved shoulders, paved shoulders, and ditches. The winter severity index variable was used to group data.

The variables population density and land area were obtained from United States Census Bureau (8) and the variable median household income was obtained from State of Wisconsin Department of Administration (9). These were used as splitter variables for all nine partial elements as means to differentiate even further among the counties. It was hypothesized that these variables may have some influence over maintenance procedures are the county level.

Counties were assigned to latitude groups (Figure 25). This enabled the creation of a different model for each latitude group. The latitude groupings were numbered 1 to 5 with 1 being the northernmost and 5 being the southernmost counties.

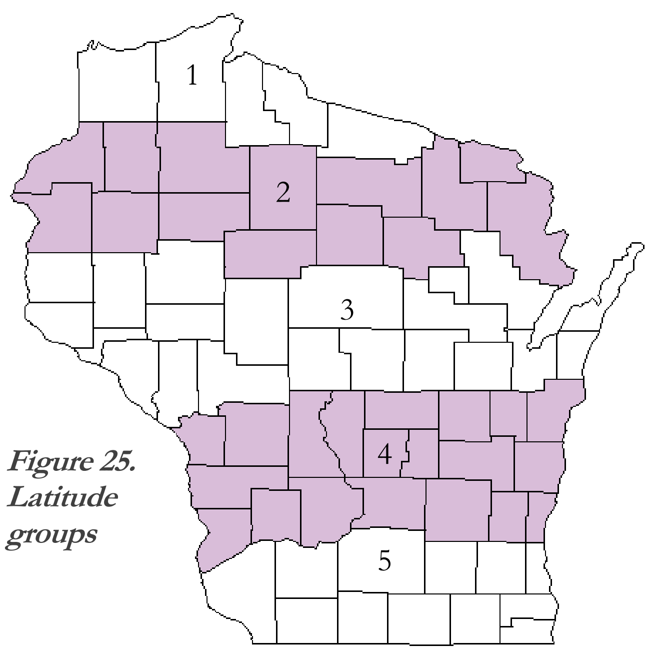


Figure 25. Latitude groups

Soil characteristics were included as variables in order to distinguish between counties on mowing, control of woody vegetation and noxious weeds, and maintenance of ditches. These characteristics include soil type (10), pH, potassium content, phosphorus content and organic matter content (11). The soil type was broken into five categories: 1-Silty, 2-Sandy, 3-Loamy, 4-Wetland, and 5-Sandstone.

Average age of pavement was a variable for the asphalt and concrete travel way models. This information was obtained from the agency's PIF (pavement information files). The age of pavement is the length of time, in years, between the year the condition was sampled and the last time the traveled way was resurfaced or reconstructed. It was hypothesized that older pavements have more deterioration and deteriorate more quickly than new pavements.

Truck vehicle miles traveled was provided by WisDOT's 2000 statewide travel demand model. The truck vehicle miles traveled were based on commodity freight estimates and forecasts and thus do not include urban type trucks (delivery trucks, cement trucks, etc.). Yet the data does capture the majority of trucks on the highways and is consistent with the scope of roadways of interest for the analysis. Truck vehicle miles traveled was used as a variable modeling cost versus condition of asphalt traveled way, concrete traveled way, paved shoulders, and unpaved shoulders.

The variables prior cost and prior %backlog are simply the previous year values for cost and %backlog used to calculate change in cost and change in backlog. For example, when calculating the change in %backlog from the years 2004 to 2005, the prior %backlog is the %backlog from the year 2004. These variables were used in the models that considered change in %backlog and change in cost to provide a base number for the change variables.

Centerline miles for each of the counties were provided by WisDOT and came from the STN Database. The variable total centerline miles was used for modeling mowing, litter pickup, woody vegetation, noxious weeds, and ditches because it measures the distance of roadway in each county. Counties with greater centerline miles may behave differently than counties with less centerline miles. The variables for centerline miles with unpaved and paved shoulders were used for the analysis of unpaved and paved shoulders, respectively. Centerline miles were not available for the year 2006 at the time of report so centerline miles from the year 2005 were used as data for 2006.

Finally, there is a strong negative correlation between winter severity index and latitude group. As mentioned earlier, the latitude groupings were numbered from 1 to 5, north to south. As the latitude group increases, and therefore is further south, it follows that the winter severity index would be lower because southern Wisconsin has less severe winter weather than northern Wisconsin.

The regression tree modeling algorithm, GUIDE (Generalized, Unbiased, Interaction, Detection and Estimation), was used to create equations that model the relationships between maintenance cost and condition. For each element, both fixed and marginal models were investigated. The exceptions are asphalt and concrete travel way which have only fixed models because condition observations are biennial rather than annual.

After finding the best fit models using GUIDE, the MINITAB statistical program was used to identify and remove outliers and then to refine the best fit model equations based on R^2. Models were compared using the adjusted R^2 because it accounts for the number of variables in the equation. Adjusted R^2 increases only if new variables improve the model more than would be expected by chance.

The regression tree approach did not produce statistically valid relationships between backlog and expenditures for paved or unpaved shoulders, noxious weeds and ditches. In the following subsections, we present the results of our analysis of several elements.

5.4.3 Regression Tree Models

CONCRETE TRAVEL WAY

A scatter plot of county-level %backlog on concrete travel ways versus expenditures per million vehicle miles traveled does not show a relationship between expenditures and backlog. Alternatively, the regression tree for the best fit model is shown in Figure 26. The model splits the data by average pavement age. %Backlog for counties with average pavement age less than 16 years is modeled by the equation associated with node 2. The average %backlog for this group is 15.43%. The %backlog for all other counties is estimated with the equations associated with nodes 6 or 7 depending on whether the county's VMT is greater than or less than 1332 million. Counties with no concrete pavements were removed because keeping them in would cause the model to force a zero intercept. The overall R^2 for the model is 75%.

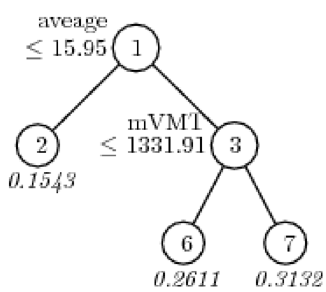


Figure 26. Regression tree for maintenance backlog of concrete pavements

The model equation for node 2 expresses %backlog as a dependent variable of cost. A graph of the observed versus fitted values of %backlog for the model is shown in Figure 27.

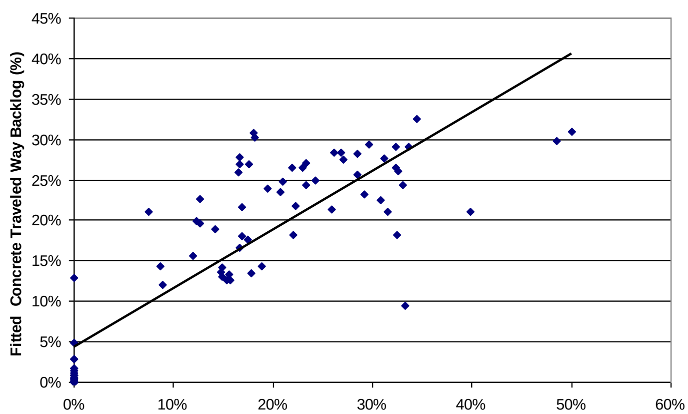


Figure 27. Observed versus fitted backlog for concrete traveled ways

For counties having concrete pavements with average age ≤ 16 years (node 2),

$$\%\boldsymbol{Backlog} = -\,0.00018 - 0.00000014\,\boldsymbol{Cost} + 0.0189\,\boldsymbol{AveAge}_{\boldsymbol{Concrete}} + 0.000043\,\boldsymbol{LM}_{\boldsymbol{Concrete}}$$

with average age > 16 years and VMT ≤ 1332 million (node 6),

$$\%\boldsymbol{Backlog} = -0.0374 - 0.000168\,\boldsymbol{mVMT} + 0.0199\,\boldsymbol{AveAge}_{\boldsymbol{Concrete}}$$

with average age > 16 years and > VMT 1332 million.

$$\%\boldsymbol{Backlog} = 31\%$$

ASPHALT TRAVEL WAY

Similarly the scatter plot of %backlog versus maintenance expenditures on asphalt travel ways does not reveal relationships between backlog and expenditure. By considering other parameters and using regression analysis, the best fit model equation that relates %backlog to cost per lane mile of asphalt pavement has an R^2 of 87%. For all counties:

$$\%Backlog = -0.00484 + 0.0000014\ CostperLM_{Asphalt} + 0.00107\ AveAge_{Asphalt} + 0.04\ mTruckVMT$$

MOWING

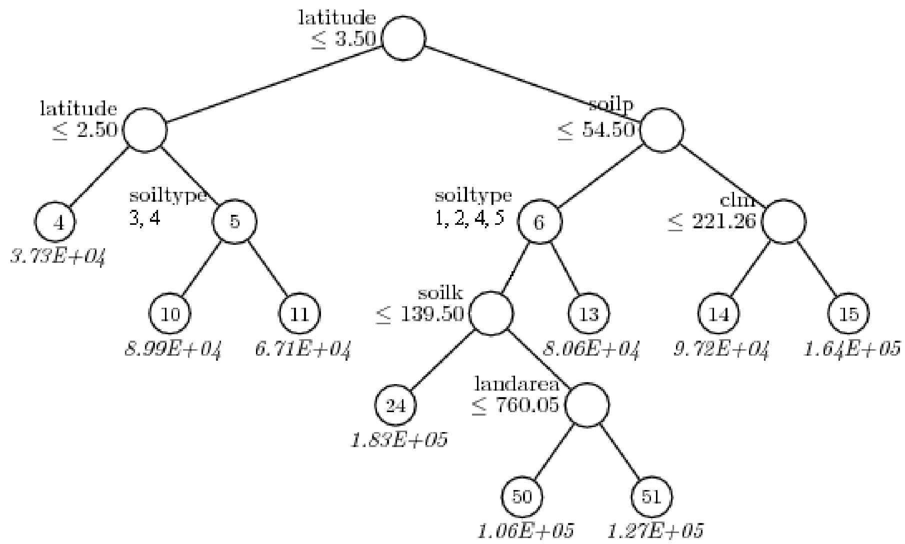


Figure 28. Regression tree for mowing maintenance expenditures

The scatter plot of %backlog versus expenditures per million VMT for mowing maintenance did not reveal any relationships. The regression tree for mowing maintenance expenditures in Figure 28 provided a model that relates %backlog and expenditure. Node 13 applies to counties in latitude groups 4 and 5, with soil phosphorous content less than or equal to 54.50, and soil type 3. The equation for annual cost has an R^2 value of 99%.

$$Cost = -71{,}079 + 21{,}202\ \%Backlog + 1{,}001\ CLM$$

This equation was derived from 9 data points for three adjacent counties (Calumet, Manitowoc, and Winnebago) and each of the three years. The equation is an excellent tool to estimate mowing cost in this area of the state.

LITTER PICKUP

The scatter plot of %backlog versus expenditures for litter pickup shows no relationship. The regression tree analysis found models but with unsatisfactory fit.

Alternatively, a best subsets analysis used %backlog, million VMT, lane miles, and centerline miles as the predictor variables for cost. Table 37 lists the subset of variables that produced the best fit regression equation along with the Mallows C-p and R^2 goodness of fit measures. All of the models include %backlog as a predictor variable. The Mallows C-p is 5.0, which is close

Table 37. Best Subsets Regression for Litter Pickup Cost

Vars	R-Sq	R-Sq(adj)	Mallows C-p	S	Mvmt	lm	CLM
1	73.7	73.5	17.7	134993	X		
1	46.7	46.2	251.8	192250		X	
2	75.4	75.0	5.7	131080	X	X	
2	75.1	74.7	8.1	131820	X		X
3	75.7	75.2	5.0	130559	X	X	X

to the number of predictor variables, and the adjusted R^2 is 75.2%. After removing outliers, R^2 for the model equation is 86%. For all counties:

$$Cost = 56{,}516 + 1{,}972\ \%Backlog + 274\ mVMT - 282\ \mathrm{LM} - 234\ CLM$$

WOODY VEGETATION

The scatter plot of %backlog versus expenditure per million VMT for litter pickup shows considerable dispersion and a wide range of expenditure. The regression tree for expenditures for managing woody vegetation, shown in Figure 29, splits the data by latitude group.

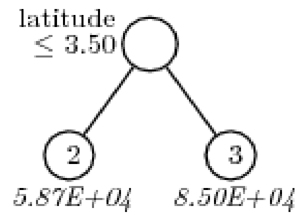


Figure 29. Regression tree for managing woody vegetation

The model at node 3 is for counties in latitude groups 4 and 5. The model predicts expenditures as a function of %backlog, centerline miles, and soil properties including pH, potassium content, and phosphorus content. The model is based on 96 data points and has an R^2 of 65%.

For counties in latitude groupings 4 and 5:

$$Cost = 787{,}891 - 280{,}584\ \%Backlog + 13.9\ mVMT - 83{,}790\ Soil_{pH} - 894\ Soil_K - 1{,}798\ Soil_P + 339\ CL$$

5.4.4 Discussion

The most influential parameter for fitting and splitting the asphalt and concrete traveled way regression tree models is average pavement age. This indicates that age of the pavement is a critical parameter for estimating the backlog and maintenance budget pavements. Nodes for model with high average pavement age have average backlogs that are larger than nodes with low values for average pavement age.

The parameter that is most influential for splitting in the mowing and woody vegetation regression trees is latitude group. This indicates that northern counties behave differently than southern counties when estimating the backlog and budget for mowing and woody vegetation activities. Counties in the southern latitude groups (4 and 5) have higher costs than counties in the northern latitude groups (1, 2, and 3). This finding is independent of the labor rates, because labor rates were adjusted prior to running the models.

Other influential parameters for fitting the models for mowing, litter pickup, and woody vegetation are million vehicle miles traveled and centerline miles. In all cases the parameters budget and backlog were used as variables in the equations. These parameters are important for predicting the backlog and budget for these elements. Large values for million vehicle miles traveled and centerline miles result in large costs.

A relationship between median household income and cost occurred for two elements: concrete traveled way and mowing. In both cases median household income was a splitter variable – not in the models. The node with higher median household income resulted in a higher average cost. This could indicate that counties with higher median household incomes have larger budgets for highway maintenance. Again, this finding occurs after labor costs were adjusted for location.

Chapter 6. Conclusions

Maintenance cost and condition are difficult to relate and study. This research explored the ability to predict maintenance condition given cost trends and to predict cost given the desired condition level. Equations that predict condition could be used to determine the effects on condition of increased or decreased funding. Equations that estimate cost could be used to determine the required cost to achieve certain levels of condition. In this project, neither of these modeling efforts was particularly successful.

Among the salient results of this research are a set of probabilistic distribution functions for annual maintenance costs for a wide range of maintenance activities. Confidence intervals can be constructed around the average using the chosen level of confidence (i.e., 95%). The functions are useful for sensitivity and simulation analyses.

The GUIDE regression tree analysis found few models for relating condition to costs. This could occur because budget allocations are based on previous allocations not on condition. Counties in Ohio, Michigan and Wisconsin receive a fixed amount based on variables such as vehicle miles traveled and centerline miles which is adjusted according to available funds rather than current maintenance conditions.

The research identified some important parameters for estimating and relating condition and cost:

- The most important parameter for estimating the backlog and the required maintenance budget for asphalt and concrete traveled ways is average pavement age. The regression tree nodes with high average pavement age also had high average backlogs and higher estimated costs than nodes with low values for average pavement age. This finding is statistically significant.
- In Wisconsin, the most influential parameter for estimating mowing and woody vegetation maintenance costs and condition is latitude group. Counties in the southern latitude groups (4 and 5) have higher costs than counties in the northern latitude groups (1, 2, and 3). This finding is independent of the labor rates, because labor rates were adjusted prior to running the models.
- Other influential parameters for mowing, litter pickup, and woody vegetation are million vehicle miles traveled and centerline miles. Normalized costs are higher for counties with large values of million vehicle miles traveled and centerline miles.

Lack of significant findings could be attributed to the data. First, to see trends overtime, three years of data may not be enough. With biennial state budgets, three years is only one and one-half budget cycles. The analysis showed little change over the three year period. Furthermore, even with budget cuts, noticeable deterioration in condition, deficiencies, or maintenance backlog may take longer than three years.

Second, cost and condition data are often collected and managed to support different business processes by separate units of the agency. Consequently, the analysis of this research depended on assumptions to aggregate condition data or cost data so that they can be related. Similarly assumptions about the activities associated with the cost data were necessary to assign costs as being spent for maintenance of specific elements. When examining the impact of this mapping, the many-to-many and one-to-many mappings performed best. One possible explanation is that for the one-to-one mapping of cost to condition, the costs did not accurately apply for the elements and conditions to which they were mapped.

Trends and relationships between cost and condition are washed out by the lack of precision and accuracy of the maintenance activities and associated costs. For these, the condition data is complete, not sampled. The best results were for asphalt and concrete pavements. The available cost and condition data are aggregated and generalized over large areas for many highway miles. Maintenance management and cost records generally do not include the precise highway location where maintenance was performance, the specific activities that were performed, nor the precise cost and timing of those activities. To overcome this problem, maintenance activities and costs must be more clearly tied to specific maintenance elements and the condition of those elements.

More accurate models could help maintenance programmers justify budgets and show accountability. A follow up study should use data covering a longer time period. The study should focus on maintenance features for which the maintenance expenditures and condition data can be clearly related.

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