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AN ANALYSIS OF SENSITIVITY IN ECONOMIC FORECASTING FOR PAVEMENT MANAGEMENT SYSTEMS

by

Antonio Fuentes

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Civil and Environmental Engineering

Approved:

Kevin Heaslip Major Professor	Ziqi Song Committee Member
Ryan Dupont Committee Member	Mark R. McLellan Vice President for Research and Dean of the School of Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

2015

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ABSTRACT

An Analysis of Sensitivity in Economic Forecasting for Pavement Management Systems

by

Antonio Fuentes, Master of Science

Utah State University, 2015

Major Professor: Dr. Kevin Heaslip
Department: Civil and Environmental Engineering

The research presented in this thesis investigates the effect the data collection process has on the results of the economic analysis in pavement management systems. The incorporation of pavement management systems into software packages has enabled local governments to easily implement and maintain an asset management plan. However a general standard has yet to be set, enabling local governments to select from several methods of data collection.

In this research, two pavement management system software packages with different data collection methods are analyzed on the common estimated recommended M&R cost provided by their respective economic analysis. The Transportation Asset Management Software (TAMS) software package developed by the Utah LTAP Center at Utah State University consists of a data collection process composed of nine asphalt pavement distress observations. The Micro PAVER™ software package developed by the Army Corps of Engineers consists of a data collection process composed of 20 asphalt pavement distress observations.

A Latin-hypercube sample set was input into each software package, as well as actual local government pavement condition data for the City of Smithfield, Utah and the City of Tremonton, Utah. This resulted in six total data sets for analysis, three entered and analyzed in TAMS and three entered and analyzed in Micro PAVER™. These sample sets were then statistically modeled to determine the effect each distress variable had on the response produced by the economic analysis of estimated recommended M&R costs.

Due to the different methodologies of pavement condition data collection, two different statistical approaches were utilized during the sensitivity analysis. The TAMS data sets consisted of a general linear regression model, while the Micro PAVER™ data sets consisted of an analysis of covariance model. It was determined that each data set had varying results in terms of sensitive pavement distresses; however the common sensitive distress in all of the data sets was that of alligator cracking/fatigue. This research also investigates the possibility of utilizing statistically produced models as a direct cost estimator given pavement condition data.

(143 pages)

PUBLIC ABSTRACT

An Analysis of Economic Forecasting Methods in Pavement Management

by

Antonio Fuentes, Master of Science

Utah State University, 2015

Major Professor: Dr. Kevin Heaslip
Department: Civil and Environmental Engineering

In the scope of transportation asset management, the maintenance and rehabilitation (M&R) performed on asphalt roads at the local government level requires careful planning and intelligent use of limited funding. For this reason, a Pavement Management System (PMS) is incorporated and used as a tool for local government leaders to make the best decision given their annual budget. The PMS process is a repeatable process which consists of determining present day pavement condition, evaluating future deterioration, performing an economic analysis of possible M&R treatments and finally implementing a proper M&R plan to keep the asphalt pavement network in good condition.

The PMS procedure has been incorporated into various software packages to facilitate the process and store historical records of asset management. Currently there is a wide range of methods and techniques utilized to successfully implement a PMS for local governments. The research presented in this thesis investigates the sensitivity of the

software package results to data collection procedures, and the effects data collection procedure has on the final economic analysis recommendations.

In this research, two PMS software packages were utilized for analysis: the TAMS software package developed by the Utah LTAP Center at Utah State University and the Micro PAVER™ software package developed by the Army Corps of Engineers. Statistical models were utilized to determine the effect that the nine condition distresses for TAMS and the 20 condition distresses for Micro PAVER™ had on the estimated recommended M&R cost provided by the software's economic analysis results, respectively. The results of this thesis illustrate the differences and similarities both PMS software packages have in terms of the data collection methodologies, and their respective influence on the software package's economic analysis. This research also investigates the possibility of utilizing statistically produced models as a direct cost estimator given pavement condition data.

The findings and methods of the conducted research will enable local governments to be aware of the types of distresses that are more sensitive to the estimated recommended M&R cost. This might provide incentive for careful consideration when recording certain distress observations that have a higher influence to the future results of the economic analysis than others.

Antonio Fuentes

DEDICATION

First of all I would like to thank God for the many blessings and opportunities throughout my life. This thesis is dedicated to my wife, Indhira Hasbun; for always encouraging me and helping me reach and exceed my academic potential, without her I wouldn't be in the position I am today. To my parents, Rosa and Ernesto Fuentes, for always believing in me and teaching how far a strong work ethic can take me. To my siblings, Neto, Valo and Edith, for always providing a good laugh and reminding me that they will always be there. And lastly to the memory of Cole Lovell, for sharing with me the pursuit of engineering and recommending Utah State University but more importantly for being my friend.

Antonio Fuentes

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I would like to especially thank Dr. Kevin Heaslip for allowing me the opportunity to pursue this research, while also providing guidance and encouragement. I would also like to thank Nick Jones and all at the Utah LTAP, for allowing my involvement in asset management as well as providing a source of data and resources. Special thanks to my committee members, Dr. Ziqi Song and Dr. Ryan Dupont, for providing guidance and recommendations in this research. Lastly special thanks to Dr. John Stevens from the statistics department and Dr. David Stevens from CEE for their willingness to answer my questions.

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CHAPTER 1

INTRODUCTION

Over the last few years economic hardships have resulted in a decrease in funding for cities and municipalities, forcing public agencies to take more consideration of the management of their expenses. With the significant investment the Moving Ahead for Progress in the 21st Century Act (MAP-21) has introduced, many local government agencies now have the opportunity to execute a plan in order to improve the overall assets of their transportation infrastructure and develop a management method to maintain these assets at the highest level of service possible.

Within the scope of assets in transportation infrastructure, pavement is one of the largest expenses to manage. Historically, the majority of pavement maintenance was addressed on a basis that repaired the worst streets first, the reason due to reaching the end of their service life. This method of maintenance and repair (M&R) can be unproductive and expensive; there can be significant differences in the cost of performing major M&R at the end of a pavements service life to that of providing routine and rehabilitative maintenance throughout its service life. Ultimately both the government agency and the road users are better off if a strategic plan is implemented and abided by for the maintenance of this critical aspect of our transportation system.

"In today's economic environment, as the pavement infrastructure has aged, a more systematic approach to determining M&R needs and priorities are necessary. Pavement networks must now be managed, not simply maintained" (Shahin, 2002). In

order to address pavement management needs, a pavement management system (PMS) can be developed to aid city engineers and decision makers in creating an M&R plan.

Currently PMSs are incorporated into computer software that are capable of performing a number of tasks to achieve the goal of managing pavement networks. Of available PMS software, the most well-known include Micro PAVER™ developed by the Army Corps of Engineers and the Highway Development & Management Model, Version 4 (HDM-4), developed by the World Bank. There are also many "in-house" or smaller scale asset management software packages specifically used by private companies, larger governments and state DOT's which strive to achieve similar goals.

The major functionalities of a PMS can be broken down into several key characteristics. These characteristics were adequately summarized by Ram B. Kulkarni and Richard W. Miller in their co-authored paper Pavement Management Systems: Past, Present, And Future (Kulkarni and Miller, 2003) and are listed below.

1. Functions
2. Data Collection and Management
3. Pavement Performance Prediction
4. Economic Analysis
5. Priority Evaluation
6. Optimization
7. Institutional Issues
8. Information Technology

The ultimate goal of a PMS is to equip city engineers and decision makers with the best possible tools to make informed decisions, enabling them to keep their pavement

networks at a high level of serviceability. This is accomplished by integrating the characteristics listed above into a repeatable process. The steps below discuss the needed measures to successfully implement a PMS, by applying the previously listed characteristics.

The first step is determining the functions and goals that the PMS will accomplish; these functions are usually a determination of the amount of time a PMS will be utilized before re-assessing pavement condition and re-starting the PMS procedure. The PMS procedure is most beneficial when on-going assessments of the pavement network are conducted; this also provides historical records that can be referred back to if needed. This step determines how the pavement network will be defined and what parameters are to be taken into consideration, such as determining road classification or road jurisdiction.

The second step involved is the data collection and data management process. Depending on the available resources, this could be stored and managed in something as simple as a spreadsheet, or a more robust approach could be used, such as a database within specialized software. The data collection procedure is an integral part of a PMS; it is during this step that current pavement condition can be estimated. Methods of collecting these data can be done in a variety of ways. Similarly a variety of measurement units are used to describe pavement condition. Some of the most recognized pavement condition indicators are listed below.

1. Present Serviceability Rating (PSR)
2. International Roughness Index (IRI)
3. Pavement Condition Index (PCI)

4. Pavement Condition Rating (PCR)
5. Remaining Service Life (RSL)

The PSR is used to represent the serviceability index (PSI) at the present time in pavements. The PSI is measured by a team of individuals that rate the condition on a scale from 0 to 5 based on ride (Mannering et al., 2009), where 0 is very poor pavement condition and 5 is very good (Pavement Interactive, 2007).

The IRI is a unit of measurement that is derived from ride quality, typically through the use of specialized equipment such as a profilometer or more recent laser technology products that produce a diagram of the road profile. The IRI is measured in units of vertical difference over horizontal distance such as in/mile or mm/km. When working with the IRI, the indication of a perfect pavement would have a measurement of 0.0 in/mile (mm/km). While there is no upper limit to the IRI (ACPA, 2002), higher IRI values are an indicator of poor pavement condition.

The PCI is a highly recognized pavement condition indicator within the United States. It is the current standard within the American Society of Testing and Materials (ASTM) for roads and parking lots (ASTM, 2007). The PCI is determined through visual inspection of pavement deterioration. By taking into account 20 surface distresses for flexible pavements (asphalt) and 20 surface distresses for rigid pavement (concrete), a condition index is calculated. The PCI ranges from 0 to 100, where a rating of 0 is a pavement in need of replacement or major rehabilitation, and 100 is a pavement in excellent condition.

The PCR is a method that is exclusively defined by state DOTs or private agencies. Measurements of the PCR include characteristics or parameters set by the

organization. Similar to the methods previously discussed, the goal of the PCR is to estimate the current condition of the pavement. The Ohio Department of Transportation (2004), Oregon Department of Transportation (2010) and Washington State Department of Transportation (Northwest Pavement Management Systems, 1992) all have specific procedures and requirements for collecting pavement condition data. This is important due to specific characteristics within each state that might have more influence in pavement deterioration than others. These characteristics could include weather, traffic volume or construction techniques.

The RSL is an estimate of the remaining years of service life for a specific pavement segment. The RSL can be obtained from the previously discussed methods such as the IRI or PCI, typically through the use of deterioration curves and lower limits (Utah Department of Transportation, 2009). Similar to the PCR, the RSL can also be adjusted to meet requirement set by agency experts. Typically the expected service life of a brand new pavement is estimated to have a 20-year upper limit. However, taking into account environmental and socioeconomic road characteristics, that limit can fluctuate.

Pavement performance prediction is also a very important factor in a PMS. Pavement performance prediction is usually approached stochastically, thus a significant amount of past pavement condition data, such as classification or annual average daily traffic (AADT), increases the probability of accurately modeling pavements with similar characteristics. Through the use of deterioration curves and linear regression models a good historical set of data can predict the future state of pavement condition to a high degree of accuracy. Another approach that is more simplistic in nature is assuming that after each year, the pavement loses one year of service life. This assumption is utilized in

some cases under the RSL methodology of condition rating. A constraint is set by assuming the maximum amount of service life is 20 years. Thus after each year, if there is no M&R conducted on a pavement segment, 1 year of service life will be lost.

The economic analysis portion of a PMS goes hand in hand with priority evaluation and optimization. Developing an effective economic plan with current budget constrains is the most valuable outcome of the PMS process. It utilizes all the previously collected information to implement an optimal plan for the pavement network. In the past, road segments were treated on a worst first basis. This process was discovered to impose a significantly higher cost than treating each road on a routine basis over time. The majority of M&R required for poor roads result in high cost rehabilitation and reconstruction, compared to implementing lower costs routine and preventative maintenance over the lifetime of the road. The PMS economic analysis provides a plan that takes into account current pavement network characteristics, and recommends adequate M&R treatments for the pavement network.

Priority evaluation and optimization come into the PMS process in the form of planning for future pavement network M&R. Priority is usually determined by the pavement condition as well as considering pavement attributes such as classification, surface type, AADT, and past M&R treatments. Optimization comes into play by applying the best M&R treatments to the pavement segments that require it at the time when funding is available. The ultimate goal of the economic analysis, priority evaluation and optimization is to develop a plan that will address all of the current pavement needs, and do so in a manner that will best utilize current budgets given constraints.

The last steps of a PMS are the institutional issues and information technology. These steps are composed of transferring the collected pavement condition data and analysis to the proper engineers and decision makers. The evaluation of the recommended results is then broken down and a plan of future M&R implementation is addressed. These results can be easily portrayed and delivered through database management and illustrated through GIS technology.

The research presented in this thesis is focused on the sections of economic analysis, priority evaluation and optimization. More robust software intended for large networks incorporate the benefit-cost ratio (B/C ratio) as an economic indicator for projects and decision making. This research will investigate the effect the data collection procedure of a PMS has on the results and recommendations of the economic analysis.

1.1 Research Question

The primary question this research plans to answer is "*What attributes of a PMS should local governments focus on to provide adequate economic analysis estimates for their pavement network?"* By examining the common differences and similarities between two different systems that have the same objectives, this research intends to determine what PMS data collection characteristics have the most significant impact when performing an economic evaluation. The PMS process provides the recommended M&R based on the pavement condition. The pavement condition however, is determined from the distresses that are observed and recorded by local governments. Therefore, in this research a step in the hierarchy intends to be skipped in order to determine which distresses the estimated M&R recommended costs from the economic analysis output are

the most sensitive to. In order to answer the main question, two subsequent questions were introduced.

1. What pavement distresses should local government technician's focus on in order to obtain a confident recommended M&R estimated cost?
2. Can a general statistical model be used to estimate a cost based solely on pavement distresses?

The first question will be addressed in Chapter 4 and the second in Chapter 5. After addressing these questions, the main question was discussed and summarized in Chapter 6. The hypothesis of this research was that certain pavement distresses would be common in all data sets examined. The comparison between Micro PAVER™ which required 20 total input distresses against TAMS which only requires nine input distresses was beneficial to determine how many of the considered distresses have on effect on the response. In a local government setting, this research can answer the question of what types of pavement distresses have a greater influence on the M&R cost estimation, and which should be observed with greater care.

1.2 Research Problem and General Approach

The research presented intends to address which factors have the most influence on economic analysis, priority evaluation and optimization and how these can be compared between different PMS approaches. A broad range of current economic analysis methods are available, thus the evaluation of various PMS software will help determine how current models work, their similarities and their differences. In addition to comparing current methods, a detailed literature review was conducted to identify new

publications offering improvements in the economic analysis, priority evaluation and optimization procedure of pavement management.

Often in a local government setting, the task of pavement condition collection is one that changes frequently with new personnel. One of the most common questions asked by new surveyors is how much data should be recorded. Different agencies and governments all have unique approaches and guidelines to answering this question but the major conflict is seen in the following two options.

1. Collection of only the dominant distress that is seen by the surveyor
2. Collection of every distress seen by the surveyor

The results from this thesis will answer how the outcome of the recorded distresses or combination of distresses can affect economic analysis output of the aforementioned PMS software packages and in a PMS in general. By determining the sensitivity of the estimated recommended M&R cost to each distress variable, the question can be answered of how much data should be collected to achieve a confident estimated M&R cost.

Data were obtained primarily from the Utah Local Technical Assistance Program (LTAP). The Utah LTAP center has conducted numerous pavement condition studies for local governments in the state of Utah. These were conducted through the guidelines specified by the "Distress Identification Manual for the Long-Term Pavement Performance Program" developed by the Federal Highway Administration (US Department of Transportation, 2003) and managed in their in-house developed software "Transportation Asset Management Software" (TAMS), which performs a unique method of economic analysis. The Utah LTAP also utilizes version 6.5.7 of the Micro PAVER™

software package with pavement condition data collected by the ASTM standard (ASTM, 2007) for Region 4 of the National Forest Service. Micro PAVER™ also utilizes a different approach to economic analysis to that of the TAMS software, enhancing the comparison capabilities of this thesis. Having these two PMS software packages available provides a base for initial comparison, and an additional economic analysis methodology to compare to is possible with the HDM-4 software by the World Bank.

1.3 Anticipated Contributions

The PMS process has already been implemented and proven to be successful. The anticipated contribution of this thesis will be to address how the economic analysis portion of the process can be improved through improvement in the previous steps of the PMS procedure, such as the data collection process. The key association was determining which of the condition attributes of a PMS have the most effect on the resulting economic analysis. This was done through statistical models that can distinguish the significance of distress variables on the estimated recommended cost of M&R. Overall this research will contribute by determining what pavement distresses are most influential to the estimated recommended M&R cost, providing city engineers and decision makers in local governments the best possible tool for M&R plan finalization.

By determining which characteristics influence the economic analysis, the steps of priority evaluation and optimization can be expected to improve as well. Overall, the economic analysis' goal is to provide the best alternatives to M&R implementation given current budget constraints.

1.4 Research Outline

The purpose of this thesis is to provide an evaluation of a PMS' economic analyses, priority evaluation and optimization methods to help local governments focus on major influences to the overall outcome of the analysis. Chapter 2 provides a literature review discussing the procedures, similarities, and differences of current commercial PMS programs as well as an introduction to the latest research that has contributed to the economic analysis topic. Chapter 3 introduces the data that were used and a discussion of how the data are attained. Chapter 4 integrates the data into different statistical models and compares the findings of significant pavement distresses that affect the outcome of recommended M&R costs. Chapter 5 discusses the possibilities of applying the given models directly into cost estimation given pavement surface distresses. Chapter 6 summarizes the findings and provides a conclusion of the research at hand as well as discusses future improvements and future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Purpose

The purpose of this literature review is to determine what the state of the art is in the economic analysis of pavement management. The use of current methods in PMS software is presented, as well as life cycle cost analysis approaches and additional proposed alternatives. Presenting what methods have been used as well as discussing recent contributions provides an accurate representation of where improvements may lie. This chapter is presented in four sections, discussing the economic analysis, priority evaluation and optimization of the PMS software listed below as well as discussing more recent contributions from journal publications.

1. Highway Development and Management Model: HDM-4
2. Micro PAVER™
3. Transportation Asset Management Software (TAMS)
4. PMS Economic Analysis Publications

2.2 Highway Development and Management Model: HDM-4

The HDM-4 software was initially developed as the Highway Cost Model (HCM) in 1968 by the World Bank Association (Kerali, 2000), and eventually evolved into the HDM-4 software after sponsorship by the Asian Development Bank (ADB), Department of International Development (DFID) in the UK and the Swedish National Road Administration (SNRA). The HDM-4 software is referred by Evdorides et. al. as “the de

facto world standard for road investment appraisal" (Evdorides et al., 2012). The use of HDM-4 appears to be more widespread in Europe and in developing countries than in the United States.

2.2.1 HDM-4 Condition and Deterioration Methodology

The HDM-4 Software utilizes the international roughness index (IRI) as the standard of determining current pavement conditions. It is also capable of integrating past pavement condition data from previous assessments if those data can be generalized into a good, fair, poor type of input. With the current IRI value of a pavement section, the HDM-4 software applies structured empirical models created from gathered data to predict future deterioration probabilities (Morosiuk et al., 2004). The HDM-4 model takes into account four different families or groups of pavements, they are bituminous, concrete, block and unsealed pavements. This addresses the fact that different types of roads deteriorate in different ways and even pavements within the same family experience unique factors that affect their deterioration rate.

Both the method of assessing condition and determining deterioration rates play a decisive role in the HDM-4 economic analysis. In the HDM-4 software "the basic unit of analysis is therefore the homogenous road section, to which several investment options can be assigned for analysis" (Morosiuk et al., 2004).

2.2.2 HDM-4 Economic Analysis Options

The HDM-4 methodology of economic analysis is very robust and flexible for the user. The HDM-4 software takes into account many variables when conducting life cycle costs analysis. These variables include road agency cost for maintenance and improvement, road user costs for vehicle operation, travel time and possible accident

damage as well as environmental effects from vehicle emission and energy consumption (Morosiuk et al., 2006). These environmental effects include hydrocarbon, carbon monoxide, nitrous oxide, sulfur dioxide, carbon dioxide, particulates and lead emissions. Future development of the environmental effects in HDM-4 are to be extended to include health effects, environmental damage costs and global warming impacts.

Required inputs however incorporate predicting maintenance and repair alternatives from pavement deterioration rates and the unit costs of implementing such efforts. Figure 2.1, an excerpt from The Highway and Management Series Collection (Morosiuk et al., 2006), illustrates the HDM-4 life-cycle analysis.

Different investment options and project strategies are easily created, altered and compared within the software in order to provide the user with economic rate of return (ERR) values, net present values (NPV) and net present value over cost ratio (NPV/C) which is similar to a benefit cost ratio (B/C) for decision making purposes. There are three key outputs produced by the economic analysis. They are economic efficiency indicators, multi-year works programs and strategic road maintenance and development plans (Morosiuk et al., 2006). The HDM-4 software package provides three types of economic analysis options for the user to examine. These economic analysis plans are listed below.

1. Project Analysis
2. Program Analysis
3. Strategy Analysis

Project analysis is primarily used when comparing M&R alternatives to fewer sections of pavements; used mainly for work that affects a small portion of the network.

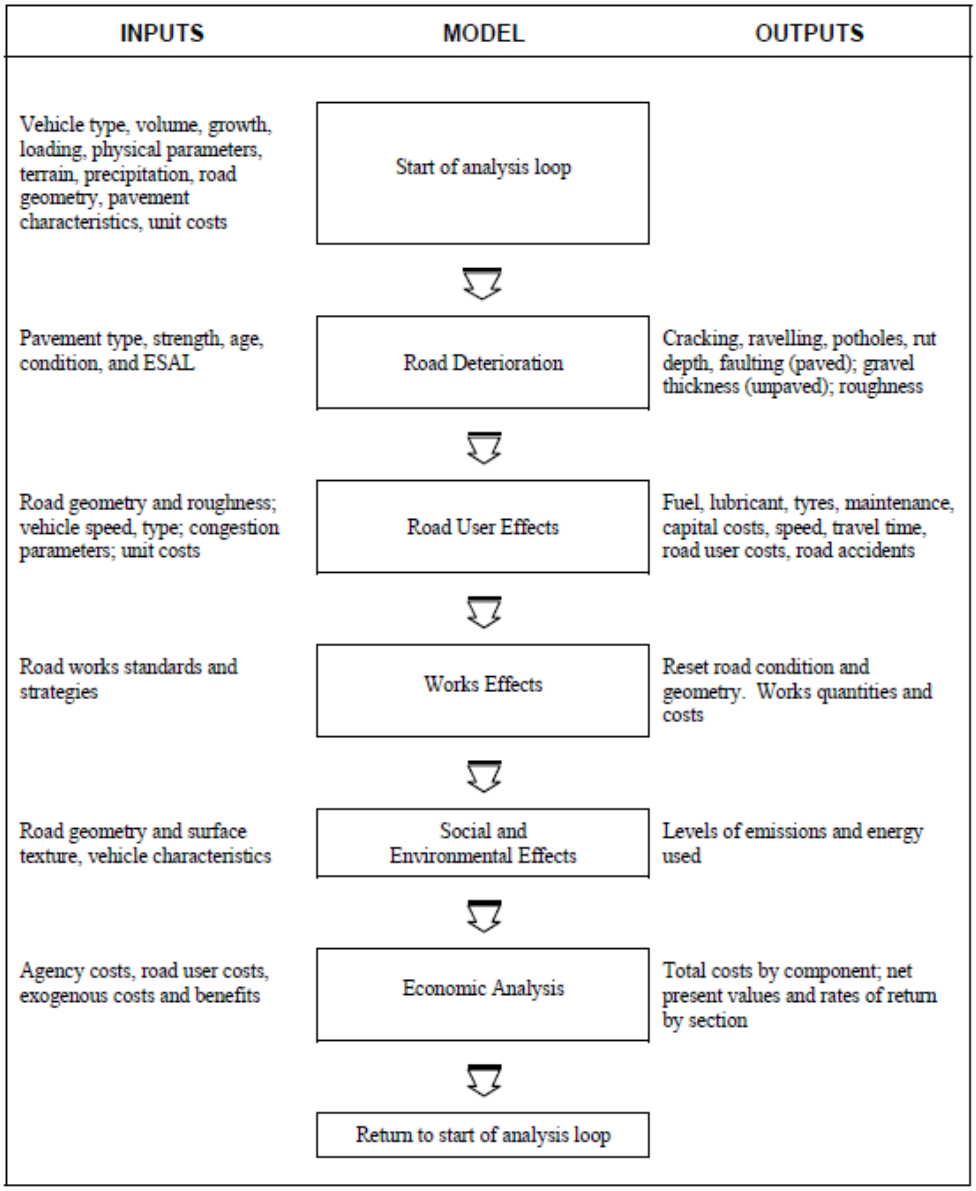


Figure 2.1 Life-Cycle Analysis in HDM-4 (Morosiuk et al., 2006)

When analyzing the application of project analysis M&R strategies to a section, the overall change in condition and deterioration rate at the time of implementation needs to be re-evaluated. The HDM-4 software performs this procedure as well as the economic analysis of the alternatives selected. Overall the benefit of having a project analysis option enables users to select the best M&R alternative to keep the roadway at a safe

level of service, doing so in a way that M&R alternatives can be compared against using economic indicators.

Program analysis is a method in which pavement segments are selected section by section in order to perform the economic analysis. This method is used for segments of pavement that can be specifically chosen or prioritized based on geographic similarities or overall necessity when conducting an economic plan. A multi-year plan can be created and evaluated for different alternatives and compared through economic indicators.

Strategy analysis is used to evaluate the economic alternatives and plan M&R strategies of a complete pavement network. This strategy allows for different parameters such as road classification, surface type or average annual daily traffic (AADT) to be prioritized when assigning M&R strategies.

The HDM-4 software also performs additional operations that increase the value of the economic analysis of a transportation network. These include a sensitivity analysis, a budget scenario analysis, a multi-criteria analysis, an estimation of social benefits and an asset valuation tool. The sensitivity analysis allows the user the input different values into key parameters to determine the sensitivity of the results, for example comparing the effects of high and low AADT in order to evaluate the difference in NPV. The budget scenario analysis is used to analyze and compare multiple budgets against each-other, such as a user defined base case or a do nothing scenario. The multi-criteria analysis (MCA) compares projects using conditions or features from which determining an economic monetary cost is difficult. These criteria include road user costs, comfort, congestion, safety and social benefits. The asset valuation tool enables the user to

determine the current value of transportation assets. These assets include earth works pavement layers, sidewalks, bridges, traffic facilities and signs.

2.2.3 HDM-4 Economic Analysis Methodology

For all of the analysis options discussed in the prior section, the methodology used to perform the economic analysis in the HDM-4 software requires a high level of comprehension and in-depth knowledge of network constraints from the user. Information such as present value unit costs of M&R treatments are required to perform an accurate analysis. Past treatment history, as well as the usual minimum treatment applied, play a role in accurately forecasting the condition treatment recommendations. The remainder of this section provides an in-depth description of each of the three analysis options introduced before.

The project analysis of the HDM-4 software is not restricted to any type of M&R treatments. That is, it is capable of evaluating treatments from routine works to higher impact projects such as road reconstruction, road widening and introduction of new road segments. Primary candidates for project analysis consist of M&R plans that will be implemented to fewer pavement sections; this type of analysis is primarily made available to address unexpected M&R, such as new construction within a city.

The project analysis can then be evaluated in two ways, either through analysis by section or analysis by project. Tables 2.1 and 2.2 are excerpts from The Highway and Management Series Collection (Morosiuk et al., 2006) which illustrate the capabilities of project analysis. The alternatives in the tables below are chosen and entered into the software by the user in terms of available resources.

Table 2.1 Analysis by Section (Morosiuk et al., 2006)

Road Section	Section Alternative				
	1 Base Alternative	2	3	4	5
Section A	Routine Maintenance	Resealing	Overlay		
Section B	Routine Maintenance	Overlay	Reconstruction	Widening	
Section C	Routine Maintenance	Resealing	Rehabilitation	Lane addition	Realignment
Section D	Grading 1 / year	Regravelling	Paving		

The program analysis is applicable when a budgetary constraint is present and a defined set of roads are prioritized for M&R treatment within a year or a multi-year program. As stated earlier, the program analysis is begun by selecting candidate road segments section by section.

Table 2.2 Analysis by Project (Morosiuk et al., 2006)

Road Section	Project Alternative			
	1 Base Alternative	2	3	4
Section A	Routine Maintenance	Resealing	Reconstruction	Realignment
Section B	Routine Maintenance	Overlay	Mill and replace	Widening
Section C	Routine Maintenance	Inlay	Reconstruction	Lane addition
Section D	Grading 1 / year	Regravelling	Widening	Upgrading
ΣProject NPV	0	ΣNPV	ΣNPV	ΣNPV

Usually the candidate roads are those that may require maintenance for safety issues or are in dire need of rehabilitation or reconstruction. There are two methods to execute the program analysis within the software, the life cycle cost analysis and the multi-year forward program, both of which add to the comparative power of the software in terms of economic analysis. For both cases the "prioritization method employs the

incremental NPV/cost ratio as the index, which provides an efficient and robust index for prioritization purposes" (Morosiuk et al., 2006).

The life cycle cost is applicable when current budgetary constraints are known between a year and 2 years in the future with high certainty, (typically for most local governments budgetary constraints are known on an annual basis). These constraints help prepare a detailed plan for each year and the ability to invest current budgets in pavement sections that may be in critical condition and address the removal of backlog. This analysis provides the results of implementing M&R treatments to road sections with a constrained budget. If the budget limit does not allow for M&R treatment it is pushed forward to the next year. Figure 2.2 illustrates an example of a life cycle analysis plan.

Section alternatives	Assignments	Year
Base Alternative	Minimum maintenance	from Year 1
Year 1 – Periodic maintenance	Periodic Maintenance	from Year 1
Year 2 – Periodic maintenance	Minimum maintenance	from Year 1
	Periodic maintenance	from Year 2
Year 3 – Periodic maintenance	Minimum maintenance	from Year 1
	Periodic maintenance	from Year 3
etc	etc	etc

Figure 2.2 Program Analysis - Life Cycle Analysis (Morosiuk et al., 2006)

The multi-year forward plan is designed for agencies that have a significant knowledge of what their budgetary restrictions are for future years. This allows the capability of applying substantial efforts of M&R to a pavement network until the year's budget is consumed, leaving pending work to roll into the next year. For this analysis "economic calculations are done by comparing investments made within the budget period against deferring the action to the first year after the budget period" (Morosiuk et al., 2006). Alternatives for the multi-year forward plan can be selected by the user in

terms of IRI condition, and be set to engage when a pavement section reaches a specific threshold. An example of this process is illustrated in Figure 2.3 and Table 2.3.

Reseal	when	3 < Roughness < 4 IRI
Overlay	when	4 < Roughness < 6 IRI
Reconstruct	when	Roughness > 6 IRI

Figure 2.3 Treatment Alternative Specification (Morosiuk et al., 2006)

For both of the life-cycle and multi-year forward program, the final step consists of budget optimization. The final optimization selects treatment options resulting in higher NPV/C ratio as the recommended treatments.

Table 2.3 Multi-Year Forward Program for Three Years (Morosiuk et al., 2006)

Section	Programme Period Alternative 1			Deferred Works Alternative 2
	Year 1	Year 2	Year 3	Year 4
S1	Reseal			Overlay
S2	Overlay			Reconstruct
S3		Reseal		Overlay
S4			Reseal	Reseal

Strategy analysis is conducted to evaluate the entire pavement network. The purpose of this type of analysis is to achieve either one of two goals. The first is to determine how much funding is required, or will be required to maintain the pavement network at an agency defined “good” level of service. The second goal is to determine how the network will perform with a set budgetary constraint already in place. This is conducted through three optimization models that are available within HDM-4. Figure 2.4 illustrates the constraints associated with each of the available optimization methods.

Objective Function	Constraint
Maximise benefits (NPV)	Financial agency costs
Maximise improvement in network condition (roughness)	Financial agency costs
Minimise agency costs	Target network condition (roughness)

Figure 2.4 Strategy Analysis - Optimization Methods (Morosiuk et al., 2006)

HDM-4 has the capability to run multiple budget scenarios at different time intervals in order to provide useful NPV/C ratios for the user. Significant reports created by the project analysis procedure include cost streams and economic evaluation, input data multi criteria analysis and asset valuation.

All of the economic analysis options take a large number of transportation network attributes into account when calculating costs. The costs can be broken down into the costs spent by the road administration, road user costs and environmental effects (Odoki and Kerali, 2006). The M&R costs fall directly under the road administration costs but must consider all of the additional factors to determine the benefits of implementation. The majority of these costs are calculated largely by user-defined values, such as unit costs of M&R treatments. These can be input as cost by square area, or cost per length, and depending on the area or length needed to be treated, are used to develop a base estimate cost.

The economic analysis within the HDM-4 software consists of developing a plan and comparing it against a base case, where each section is evaluated independently. The following equations represent the characteristics in which costs and savings are taken into account within the software. Equation 2.1 and Equation 2.2 illustrate the costs of

investment to the road agency. Equation 2.3 then illustrates the salvage value for the investment plan chosen by the agency.

$$\Delta C_{(m-n)i} = [\sum_s C_{mis} - \sum_s C_{nis}]] \qquad \text{(Eq. 2.1)}$$

where $\Delta C_{(m-n)i}$ is the difference in road administration cost of investment option *m* relative to option *n* for budget category *i*, and C_{jis} is the total costs to road administration incurred by investment option *j*, where *j = m or n* for budget category *i* for road section *s* (Odoki and Kerali, 2006).

$$\Delta RAC_{(m-n)} = \sum_i \Delta C_{(m-n)i} \qquad \text{(Eq. 2.2)}$$

where $\Delta RAC_{(m-n)}$ is the annual cost to the road administration of investment option *m* relative to base option *n* (Odoki and Kerali, 2006).

$$\Delta SALVA_{(m-n)} = [SALVA_m - SALVA_n] \qquad \text{(Eq. 2.3)}$$

where $\Delta SALVA_{(m-n)}$ is the difference in salvage value of investment option *m* relative to option *n*. $\Delta SALVA_j$ is the salvage value of the works performed under investment option *j*, where *j = m or n* (Odoki and Kerali, 2006). The salvage value is initially attained through Equation 2.4 below.

$$SALV = PCTSAV * CSTCON \qquad \text{(Eq. 2.4)}$$

where *SALV* is the salvage value, *PCTSAV* is the percent of total cost salvageable and *CSTCON* is the total cost of reconstruction (Odoki and Kerali, 2006).

Savings in road user costs come into the model with Equations 2.5 through 2.21. These cover savings in motorized vehicle operating costs, savings in travel time cost for

motorized vehicles, savings in non-motorized transportation time and operation costs, reduction in accident costs and the overall estimate of road user benefits. To begin, the savings in motorized vehicle operating costs are presented by first defining some of the characteristics which make up vehicle operating costs. Equations 2.5 through 2.7 illustrate these characteristics while Equation 2.8 summarizes the overall savings in vehicle operating costs.

$$VCN_{js} = \sum_k TN_{jsk} * UC_{jsk} \qquad \text{(Eq. 2.5)}$$

where VCN_{js} is the annual vehicle operation cost due to normal and diverted traffic over road section *s* with investment option *j*. TN_{jsk} is the normal and diverted traffic, in number of vehicles per year in both directions of road *s*, investment option *j*, for vehicle type *k* and UC_{jsk} is the annual average operating cost per vehicle-trip over road section *s*, for vehicle type *k* under investment option *j* (where *j = n or m)* (Odoki and Kerali, 2006).

$$\Delta VCN_{(m-n)} = [\sum_s VCN_{ns} - \sum_s VCN_{ms}] \qquad \text{(Eq. 2.6)}$$

where $\Delta VCN_{(m-n)}$ is the vehicle operating benefits due to normal and diverted traffic of investment option *m* relative to base option *n* (Odoki and Kerali, 2006).

$$\Delta VCG_{(m-n)} = [\sum_s \sum_k \{0.5 * [TG_{msk} + TG_{nsk}] * [UG_{nsk} - UC_{msk}]\}] \qquad \text{(Eq. 2.7)}$$

where $\Delta VCG_{(m-n)}$ is the annual vehicle operating cost due to generated traffic over road section *s* with investment option *j*, and TG_{msk} is the generated traffic in number of vehicles per year in both directions on road *s*, for vehicle type *k*, due to investment option *j* (Odoki and Kerali, 2006).

Equation 2.8 illustrates the overall savings in vehicle operating costs in terms of traffic as the summation of the previously defined components (Odoki and Kerali, 2006).

$$\Delta VOC_{(m-n)} = \left[\Delta VCN_{(m-n)} + \Delta VCG_{(m-n)}\right] \qquad \text{(Eq. 2.8)}$$

Similarly the savings in travel time costs for a motorized vehicle is taken into account by a series of defining characteristics from the transportation network users. Equations 2.9 through Equation 2.11 illustrate the components that make up the savings in travel time costs for motorized vehicles.

$$TCN_{js} = \sum_k TN_{jsk} * UC_{jsk} \qquad \text{(Eq. 2.9)}$$

where TCN_{js} is the annual vehicle travel time cost due to normal and diverted traffic over road section *s* with investment option *j*. TN_{jsk} is the normal and diverted traffic, in number of vehicles per year in both directions of road *s*, investment option *j*, for vehicle type *k* and UC_{jsk} is the annual average operating cost per vehicle-trip over road section *s*, for vehicle type *k* under investment option *j* (where *j = n or m)* (Odoki and Kerali, 2006).

$$\Delta TCN_{(m-n)} = [\sum_s TCN_{ns} - \sum_s TCN_{ms}] \qquad \text{(Eq. 2.10)}$$

where $\Delta TCN_{(m-n)}$ is the travel time benefits due to normal and diverted traffic of investment option *m* relative to base option *n* (Odoki and Kerali, 2006).

$$\Delta TCG_{(m-n)} = [\sum_s \sum_k \{0.5 * [TG_{msk} + TG_{nsk}] * [UG_{nsk} - UC_{msk}]\}] \qquad \text{(Eq. 2.11)}$$

where $\Delta TCG_{(m-n)}$ is the travel time benefits due to generated traffic over road section *s* with investment option *j*, and TG_{msk} is the generated traffic in number of vehicles per year

in both directions on road *s*, for vehicle type *k*, due to investment option *j* (Odoki and Kerali, 2006).

Equation 2.12 illustrates the overall savings in travel time costs in terms of traffic as the summation of the previously defined components (Odoki and Kerali, 2006).

$$\Delta TTC_{(m-n)} = \left[\Delta TCN_{(m-n)} + \Delta TCG_{(m-n)}\right] \qquad \text{(Eq. 2.12)}$$

Moving forward, the savings in travel time costs for non-motorized vehicle is taken into account by a series of defining characteristics composed of effects to the transportation network without motorized vehicles. Equations 2.13 through 2.16 illustrate the components that make up the annual savings in non-motorized time and operating costs.

$$TOCN_{js} = \sum_k TN_{jsk} * UTOC_{jsk} \qquad \text{(Eq. 2.13)}$$

where $TOCN_{js}$ is the annual non-motorized travel time and operating cost due to normal and diverted traffic over road section *s* with investment option *j*. TN_{jsk} is the non-motorized normal and diverted traffic, in number of vehicles per year in both directions of road *s*, investment option *j*, for vehicle type *k* and $UTOC_{jsk}$ is the annual average non-motorized time and operating cost per vehicle-trip over road section *s*, for vehicle type *k* under investment option *j* (where *j = n or m)* (Odoki and Kerali, 2006).

$$\Delta TOCN_{(m-n)} = [\sum_s TOCN_{ns} - \sum_s TOCN_{ms}] \qquad \text{(Eq. 2.14)}$$

where $\Delta TOCN_{(m-n)}$ is the non-motorized travel time and operating benefits due to normal and diverted traffic of investment option *m* relative to base option *n* (Odoki and Kerali, 2006).

$$\Delta TOCG_{(m-n)} = [\sum_s \sum_k \{0.5 * [TG_{msk} + TG_{nsk}] * [UTOC_{nsk} - UTOC_{msk}]\}] \quad \text{(Eq. 2.15)}$$

where $\Delta TOCG_{(m-n)}$ is annual non-motorized transport due to generated traffic over road section *s* with investment option *j*, and TG_{msk} is the non-motorized transport generated traffic in number of vehicles per year in both directions on road *s*, for non-motorized transport type *k*, due to investment option *j* (Odoki and Kerali, 2006).

Equation 2.16 illustrates the overall annual savings in non-motorized transport travel time and operating costs due to total traffic for investment option *m* relative to base option *n* (Odoki and Kerali, 2006).

$$\Delta NMTOC_{(m-n)} = \left[\Delta TOCN_{(m-n)} + \Delta TOCG_{(m-n)}\right] \quad \text{(Eq. 2.16)}$$

The HDM-4 software also takes into account the possible reduction in accident costs as part of the economic analysis; Equation 2.17 illustrates the formula used to account for accident reduction.

$$\Delta ACC_{(m-n)} = [AC_n - AC_m] \quad \text{(Eq. 2.17)}$$

where $\Delta ACC_{(m-n)}$ is the accident reduction benefits due to implementing investment option *m* relative to base option *n*, and AC_j are the total accident costs under investment option *j(where j = n or m)* (Odoki and Kerali, 2006).

Overall the road user benefits are portrayed as the summation of all the previously defined benefits of the transportation network as shown in Equation 2.18 (Odoki and Kerali, 2006).

$$\Delta RUC_{(m-n)} = \left[\Delta VOC_{(m-n)} + \Delta TTC_{(m-n)} + \Delta NMTOC_{(m-n)} + \Delta ACC_{(m-n)}\right] \quad \text{(Eq. 2.18)}$$

In order to account for other costs and benefits not included in the previously defined terms, a general equation is provided in Equation 2.19.

$$\Delta NEXB_{y(m-n)} = \left[EXB_{ym} - EXC_{ym} - EXB_{yn} + EXC_{yn}\right] \qquad \text{(Eq. 2.19)}$$

where EXB_{jy} are the exogenous benefits for investment option *j*, in year *y*, and EXC_{jy} are exogenous costs for investment option *j*, in year *y*, *(where j = n or m)* (Odoki and Kerali, 2006).

The annual net economic benefits are then presented as the overall combination of all previously defined characteristics. Two equations are used to illustrate this final step, Equation 2.20 illustrates the net annual benefit for each year that an investment plan is in place, while Equation 2.21 illustrates the net annual benefit for the last year in which the investment plan will be analyzed.

$$NB_{y(m-n)} = \left[\Delta RUC_{y(m-n)} + \Delta NEXB_{y(m-n)} - \Delta RAC_{y(m-n)}\right] \qquad \text{(Eq. 2.20)}$$

$$NB_{Y(m-n)} = \left[\Delta RUC_{Y(m-n)} + \Delta NEXB_{Y(m-n)} - \Delta RAC_{Y(m-n)} + \Delta SALV_{(m-n)}\right] \text{(Eq. 2.21)}$$

where $NB_{y(m-n)}$ is the net economic benefit of investment option *m* relative to base option *n* in year *y* (Odoki and Kerali, 2006).

In conclusion, the incorporation of all the previously defined economic terms are maximized by incorporating them into the economic indicator values produced by the HDM-4 software. Four economic indicators are provided in the form of the Net Present Value (NPV), Internal Rate of Return (IRR), Net Benefit/Cost Ratio (BCR) and First Year Benefits (FYB). These four economic indicators are illustrated in Equation 2.22 through Equation 2.26.

$$NPV_{(m-n)} = \sum_{y=1}^{Y} \frac{NB_{y(m-n)}}{[1+0.01*r]^{(y-1)}} \quad \text{(Eq. 2.22)}$$

where $NPV_{(m-n)}$ is the net economic benefit of investment option *m* relative to base option *n* in year y, *r* is the discount rate in terms of percentage and *y* is the analysis year (Odoki and Kerali, 2006). Ideally the higher NPV indicates a greater amount of benefits from the given investment option.

$$\sum_{y=1}^{Y} \frac{NB_{y(m-n)}}{\left[1+0.01*r^{\circ}\right]^{(y-1)}} = 0 \quad \text{(Eq. 2.23)}$$

where r^o is the internal rate of return (Odoki and Kerali, 2006), the overall equation is being solved for r^o when the NPV is equal to zero. The IRR is used as an economic indicator by comparing it to the discount rate used, if the IRR is larger than the discount rate the investment plan is considered a feasible option.

$$BCR_{(m-n)} = \frac{NPV_{(m-n)}}{C_m} + 1 \quad \text{(Eq. 2.24)}$$

where $BCR_{(m-n)}$ is the benefit cost ratio of investment option *m* relative to base option *n*, and C_m is the discounted total agency costs of implementing investment option *m*. The BCR ratio indicates the profitability of investment option *m* relative to base option *n* at a given discount rate (Odoki and Kerali, 2006). The BCR must be at equal to or greater than one in order to be considered economically acceptable.

$$FYB_{(m-n)} = \frac{100*NB_{y^{\circ}(m-n)}}{\Delta TCC_{(m-n)}} \quad \text{(Eq. 2.25)}$$

where $FYB_{(m-n)}$ are the first year benefits of investment option *m* relative to base option *n*, $NBy^o_{(m-n)}$ is the net economic benefit of investment option *m* relative to base option *n* in

year y^o, and y^o is the year immediately after the last year in which the capital cost for M&R is experienced in option *m* and $\Delta TCC_{(m-n)}$ is the difference in total capital cost of investment option *m* relative to base option *n* (Odoki and Kerali, 2006). The FYB is to be used as a guide to project timing; a justifiable investment would have a value of the FYB greater than the discount rate being used.

2.2.4 HDM-4 Application

The HDM-4 software was recently utilized in a study conducted by Evdorides et al. (Evdorides et al., 2012) in 2012 investigating strategies for clearing pavement M&R backlog for a network. Two strategies, along with two work plans were evaluated in order to achieve the goal. The first strategy consisted of maximizing the economic benefits of the network by maximizing the net present value (NPV) of the network. The NPV of the network in this study was based on the difference between project implementation costs and the benefits, which are presented in terms of the savings produced from "vehicle operating costs (VOC), reduced road user travel times, decrease in the number of accidents and environmental effects" (Evdorides et al., 2012). The second consisted of maximizing the overall pavement network condition, which entailed having an overall network condition average IRI value of 3.5 or less. The two work plans were assessed based on two time frames. The first consisted of an unconstrained budget for the first 5 years in order to remove the backlog with mainly rehabilitative and reconstructive treatments and some routine maintenance. The second consisted of a work plan implemented after the 5-year backlog removal that would focus on keeping the network at a steady state condition.

The analysis found that maximizing the NPV of the network would result in the less expensive alternative to implement over the 5-year period, while also achieving an overall network condition IRI value below the 3.5 goal. The unconstrained budget for the initial 5-year analysis resulted in $2,075 million and $2,590 million for maximizing the NPV and maximizing network condition, respectively. The backlog under these circumstances was removed in 3.6 years by maximizing the network NPV and in 1.6 years by maximizing the overall network condition.

Furthermore, an additional analysis was evaluated in which the unconstrained budgets from the previous analysis would now be constrained by 90%, 80%, 70%, 60% and 50% for each strategy, and the same criteria where to be met. The results of this analysis found that a 90% constrained NPV maximization and 70% constrained network condition maximization would meet the backlog clearing goals. The budgets for the constrained evaluation were $1,867 million and $1,813 million for maximizing the NPV and maximizing network condition, respectively. The backlog under these circumstances was removed in 4.6 years by maximizing the network NPV and in 4.5 years by maximizing the overall network condition. Thus, the results illustrate that focusing on bringing poor roads up to a higher condition initially can lead to flexibility in the amount required for road preservation in the future.

2.3 Micro PAVER™

The Micro PAVER™ software package, which is often recognized as “Paver,” was developed in the early 1970s by the Army Corp of Engineers. Its initial purpose was to manage pavements, parking lots and airports for the military. Throughout time its support, use and development has been by the US Air Force, the US Army,

the US Navy, the Federal Aviation Administration (FAA), Ohio Department of Transportation Aviation, the Federal Highway Administration (FHWA) and the American Public Works Association (APWA) (Shahin, 2002). The Micro PAVER™ software package is now commercially distributed and utilized by government and private agencies for pavement and airfield management purposes.

2.3.1 Micro PAVER™ Condition and Deterioration Methodology

The Micro PAVER™ software package requires that the American Society of Testing and Materials (ASTM) standard of determining PCI be used within the software. The PCI value is a numeric identifier of pavement condition in which 0 is the lowest possible value and signifies a severely deteriorated pavement and 100 is the highest possible value and signifies an excellent pavement or a brand new constructed pavement. PCI variables are collected non-destructively through visual inspection of pavement surfaces by examining the extent and severity of surface distresses and cracks found in specified sample areas. Calculation of the PCI is completed through the use of deduct values that are correlated to the type of surface distress or distresses observed (ASTM, 2007). The Micro PAVER™ software computes the PCI value in compliance to the ASTM standard. Within the ASTM standard there are 20 asphalt pavement distresses and 20 concrete pavement distresses that are used to calculate the final PCI value.

The deterioration prediction method used in the Micro PAVER™ software is referred to as the family model method. The family method is a unique method of statistically predicting PCI deterioration. This approach was developed by the Army Corps of Engineers for specific use in the Micro PAVER™ software. This type of model groups pavements with similar characteristics and classifications into families. A family

of pavements within the Micro PAVER™ software is expected to behave in a relatively similar manner throughout time, thus enabling the prediction of future PCI by referencing more data points assumed to be similar. This method requires a significant amount of data in order to increase the degree of accuracy needed to predict future PCI.

2.3.2 Micro PAVER™ Maintenance and Repair

Within the Micro PAVER™ software there are a number of available M&R options that can be evaluated for pavement improvement and economic analysis. The Micro PAVER™ software breaks down the treatments into four key categories. These categories are Localized Stopgap, Localized Preventative, Global Preventative and Major M&R (Odoki and Kerali, 2006). Localized Stopgap is described as the minimum treatment applied in order to keep the pavement at a safe level of service for the road user. Localized preventative are treatment alternatives whose functions are to slow the rate of deterioration. Global preventative treatments, similar to localized preventative are selected to slow the rate of deterioration; however the treatment is applied to an entire road segment rather than a localized area. Major M&R are treatments designated for structurally deficient pavements that require reconstruction.

2.3.3 Micro PAVER™ Economic Analysis

The Micro PAVER™ software offers a sophisticated approach to performing the economic analysis aspect of the PMS process. The types of M&R treatments recommended are selected by the user and activated based on PCI conditions that can also be modified by the user. The software default suggests what type of PCI conditions will activate certain M&R treatments. For example, segments with PCI lower than 60 should require major M&R if the budget permits or localized stopgap if the budget is

constrained. A PCI higher than 60 can be treated by either localized preventative or globalized preventative treatments. Similar to the family method of deterioration analysis, the Paver software performs its economic analysis taking into account the families previously defined. This enables Micro PAVER™ to analyze the complete network by breaking it down into smaller samples that are alike and easier to evaluate.

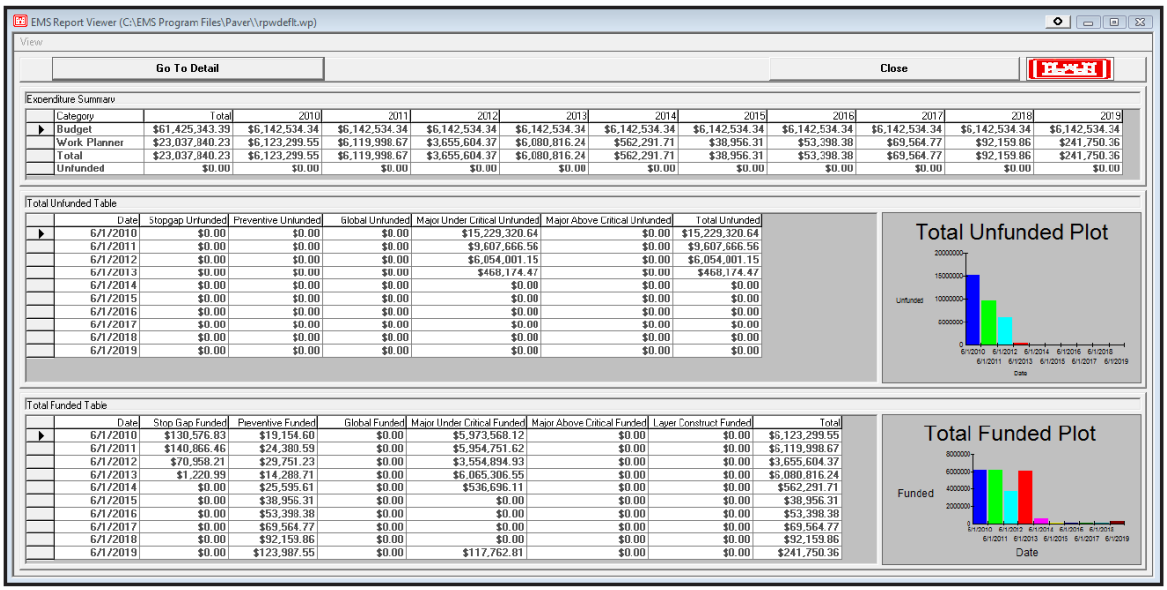
The Micro PAVER™ software package offers two types of economic analysis. The first is network-level pavement management and the second is project level analysis. The network-level management analysis is one that takes the complete network into account; while the project level analysis is a smaller scale evaluation for user defined sections receiving specific treatments.

Within the network-level analysis a variety of evaluation options are available simply by specifying the current PCI condition of a pavement network. Budget scenarios can be evaluated simultaneously in order to view the effects. The Micro PAVER™ software is also capable of predicting how much of the pavement network will remain unfunded based on the pavement segments that are funded for M&R. Figure 2.5 illustrates this in an excerpt from the Micro PAVER™ User manual.

The unfunded portion of pavement M&R is determined through a penalty cost whenever an M&R treatment is postponed. Equations 2.26 and 2.28 illustrate the penalty formula when delaying major M&R in the network level analysis and project level analysis, respectively.

$$Penalty\ \% = \left(\frac{C_F - C_S}{C_S}\right) x\ 100 \qquad \text{(Eq. 2.26)}$$

where C_S is the cost in original scheduled year, C_F is the future cost which is further defined in Equation 2.27 where i is inflation rate and n is time delay in years (Shahin, 2002).



Category	Total	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Budget	$61,425,343.39	$6,142,534.34	$6,142,534.34	$6,142,534.34	$6,142,534.34	$6,142,534.34	$6,142,534.34	$6,142,534.34	$6,142,534.34	$6,142,534.34	$6,142,534.34
Work Planner	$23,037,840.23	$6,123,299.55	$6,119,998.67	$3,655,604.37	$6,080,816.24	$562,291.71	$38,956.31	$53,398.38	$69,564.77	$92,159.86	$241,750.36
Total	$23,037,840.23	$6,123,299.55	$6,119,998.67	$3,655,604.37	$6,080,816.24	$562,291.71	$38,956.31	$53,398.38	$69,564.77	$92,159.86	$241,750.36
Unfunded	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00

Date	Stopgap Unfunded	Preventive Unfunded	Global Unfunded	Major Under Critical Unfunded	Major Above Critical Unfunded	Total Unfunded
6/1/2010	$0.00	$0.00	$0.00	$15,229,320.64	$0.00	$15,229,320.64
6/1/2011	$0.00	$0.00	$0.00	$9,607,666.56	$0.00	$9,607,666.56
6/1/2012	$0.00	$0.00	$0.00	$6,054,001.15	$0.00	$6,054,001.15
6/1/2013	$0.00	$0.00	$0.00	$468,174.47	$0.00	$468,174.47
6/1/2014	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
6/1/2015	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
6/1/2016	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
6/1/2017	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
6/1/2018	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
6/1/2019	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00

Date	Stop Gap Funded	Preventive Funded	Global Funded	Major Under Critical Funded	Major Above Critical Funded	Layer Construct Funded	Total
6/1/2010	$130,576.83	$19,154.60	$0.00	$5,973,568.12	$0.00	$0.00	$6,123,299.55
6/1/2011	$140,866.46	$24,380.59	$0.00	$5,954,751.62	$0.00	$0.00	$6,119,998.67
6/1/2012	$70,958.21	$29,751.23	$0.00	$3,554,894.93	$0.00	$0.00	$3,655,604.37
6/1/2013	$1,220.99	$14,288.71	$0.00	$6,065,306.55	$0.00	$0.00	$6,080,816.24
6/1/2014	$0.00	$25,595.61	$0.00	$536,696.11	$0.00	$0.00	$562,291.71
6/1/2015	$0.00	$38,956.31	$0.00	$0.00	$0.00	$0.00	$38,956.31
6/1/2016	$0.00	$53,398.38	$0.00	$0.00	$0.00	$0.00	$53,398.38
6/1/2017	$0.00	$69,564.77	$0.00	$0.00	$0.00	$0.00	$69,564.77
6/1/2018	$0.00	$92,159.86	$0.00	$0.00	$0.00	$0.00	$92,159.86
6/1/2019	$0.00	$123,987.55	$0.00	$117,762.81	$0.00	$0.00	$241,750.36

Figure 2.5 Funded and Unfunded Network Analysis (US Army Corps of Engineers, 2010)

$$C_F = [Major\ M\&R\ Cost\ for\ projected\ PCI * ((1+i)^n)] + Localized\ Safety\ M\&R\ Cost\ over\ dealy\ period$$

(Eq. 2.27)

The project level analysis provides a delay penalty only for the pavement segments that will be included in the specific project as shown in Equation 2.28.

$$Major\ M\&R\ Delay\ Penalty\ \% = \frac{\sum_{i=1}^{n} C_i P_i}{\sum_{i=1}^{n} C_i} \qquad \text{(Eq. 2.28)}$$

where C_i is the area of section *i* scheduled to receive major M&R as part of the project, *Pi* is the penalty cost in % for major M&R delay for section *i*, and *n* are the number of sections in the project receiving major M&R (Shahin, 2002).

The strongest programming function performed by the software's economic analysis is known as the "Dynamic Programming Procedure" (Shahin, 2002) that takes place under network level management. This procedure is used to perform multiple year M&R assignments to the pavement network through a process more commonly known as the Markovian technique. Throughout this process, there are five key constraints that are continuously being evaluated and re-evaluated as the analysis progresses. These constraints are states, stages, decision variables, transformations and returns. The state is referred to as the present condition of a given section; because condition is measured in PCI the states are broken down into ten PCI groups each ranging in intervals of ten PCI condition values (State 1: PCI = 100-90, etc.). The stage is referred to the year in which the analysis is being conducted. Decision variables are the specific M&R treatment decisions that are made based on the segment stage, state and pavement family. The transformation refers to the pavement segments moving from one stage to the next and is where the Markovian technique influences the procedure. The Markovian technique procedure is completed through probability transition matrixes. These transition matrixes are broken down into the previously described condition states, and later each pavement segment is individually assessed for the probability of it staying in its current state or dropping to the preceding state below. Finally, the return is the expected cost of the final M&R decision made based on the state, stage and pavement family of the pavement segments (US Army Corps of Engineers, 2010).

Once the dynamic programming procedure is begun, the first cost is estimated for the optimum repair strategy. This strategy separates segments favored for routine maintenance. Segments that are candidates for routine maintenance will have a PCI value larger than the minimum critical PCI value specified by the user. Equation 2.29 illustrates the formula used to calculate the optimum repair strategy.

$$C^*_{ij,N} = MIN\left[C_{ij1,N}, C_{ijk,N}\right] for\ all\ i,j \qquad \text{(Eq. 2.29)}$$

where $C^*_{ij,N}$ is the optimum cost for state i, family j, in year N. $C_{ij1,N}$ is the cost of applying routine maintenance in year N. $C_{ijk,N}$ is the cost of applying treatment k to family j in state i during year N. The optimal strategy for this case would be the minimum cost alternative (Shahin, 2002).

For segments in which routine maintenance is not feasible, the present worth of the M&R alternatives is then calculated through Equation 2.30.

$$C_{ij1,N-n} = C_{ij1} + \left[P_{ij}C^*_{ij,N-n-1} + (1 - P_{ij})C^*_{i-1,j,N-n-1}\right] * (1 + f)/(1 + r) \qquad \text{(Eq. 2.30)}$$

where $C_{ij1,N-n}$ is the present worth cost of applying routine maintenance, P_{ij} is the Markovian transformation probability for each state i and family j, f is the inflation rate and r is the interest rate (Shahin, 2002).

The cost for feasible major M&R alternatives that treat pavements below the critical PCI are calculated in a similar manner through the equation illustrated in Equation 2.31. The key difference between Equation 2.30 and 2.31 is that after applying major M&R, the condition state of the pavement segment is returned a value of 1 (PCI 100) (Shahin, 2002).

$$C_{ij1,N-n} = C_{ijk} + \left[P_{ij}C^{*}_{ij..N-n-1} + (1 - P_{ij})C^{*}_{2j..,N-n-1}\right] * (1 + f)/(1 + r) \quad \text{(Eq. 2.31)}$$

The project level analysis is presented as a life cycle cost analysis; the analysis is presented as a four step process using basic engineering economic principles. The first step is determining the initial cost of the designated M&R treatments. The second step consists of determining the present value of such M&R treatments if they are to be applied at a future date by applying Equitation 2.32.

$$PV = C_l + \sum_{t=1}^{N} C_m \frac{(1+r)^t}{(1+i)^t} \quad \text{(Eq. 2.32)}$$

where PV is the present value, C_l is the initial cost of the M&R treatment, N is the number of years in the analysis, C_m is the cost of the M&R alternative in present value, r is the annual inflation rate, i is the interest rate and t is the time in future years (Shahin, 2002).

The third step requires the user to calculate the equivalent uniform annual cost (EUAC) by multiplying the present value by a capital recovery factor (CRF), Equation 2.33 and Equation 2.34 illustrate both the EUAC and the CRF, respectively.

$$EUAC = CRF * PV \quad \text{(Eq. 2.33)}$$

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \quad \text{(Eq. 2.34)}$$

The fourth and final step is determining the EUAC in terms of square area of pavement, which is simply done by dividing the EUAC by the surface area of the pavement segment (Shahin, 2002). By following the above four steps, multiple project

alternatives can be conducted, compared and evaluated in order to select the most economic and cost-effective alternative.

An additional advantage in the Paver software is its GIS capabilities which are incorporated into the economic analysis. With GIS features adapted into the software, users can easily see what treatments are needed throughout time based on the Paver results. Figure 2.6 illustrates a GIS screenshot in an excerpt from the Paver User manual. Layes can be developed by years and color coded by the user in order to visually see current pavement performance of a given pavement network. With these capabilities, city leaders and technicians can easily plan out pavement treatments throughout time, see anticipated deterioration of pavement and adequately plan ahead with available funding programs. These developed databases can also be further integrated into professional GIS software to more carefully evaluate data and illustrate funding results and anticipated benefits.

2.3.4 Micro PAVER™ Economic Application

Upon installation of the Micro PAVER™ software, various pre-collected databases are available to use for training purposes. In reference to the Micro PAVER™ user's manual (US Army Corps of Engineers, 2010), two training workshops are presented to illustrate the procedure of applying the economic analysis. These workshops are intended to train city personnel for the actual use and implementation procedures of the PMS methodology. Thus, the steps taken for this study are the same steps taken by city governments during the implementation of a PMS for a given pavement network. The first workshop outlines three procedures and the steps of execution taken by the user upon the collection of pavement network condition data.

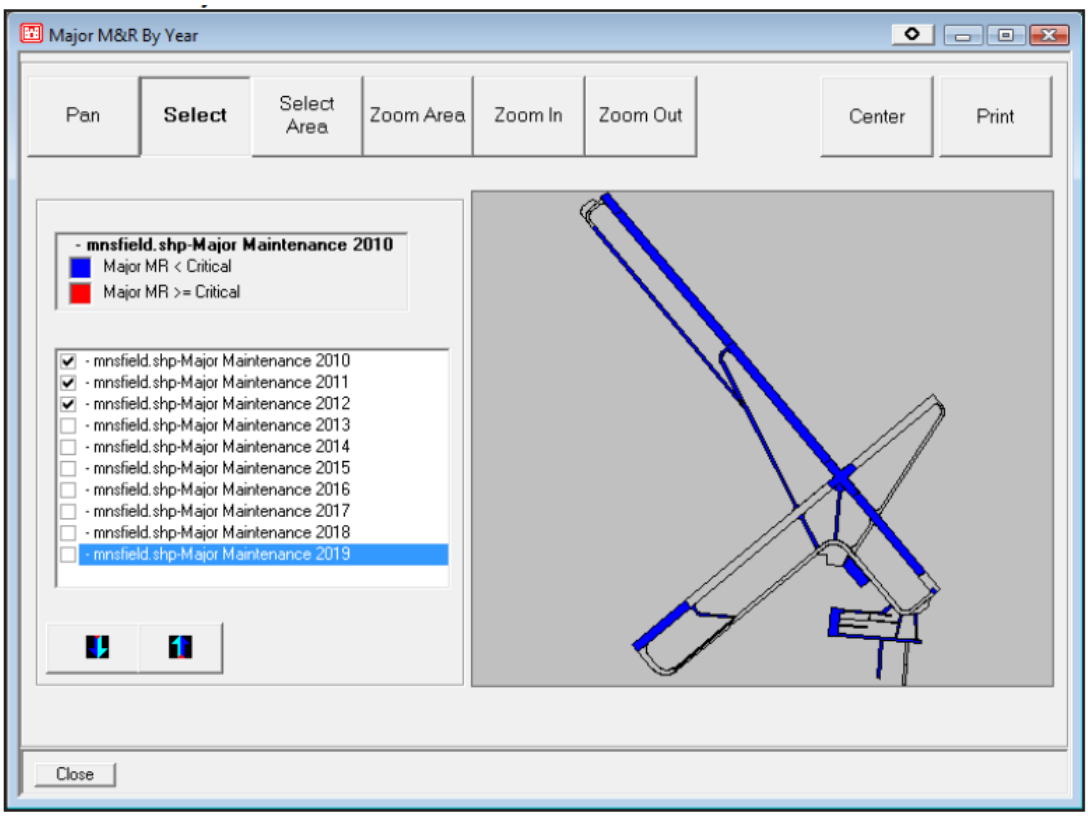


Figure 2.6 Economic Recommendations using the GIS Feature (US Army Corps of Engineers, 2010)

The first procedure consists of using a constrained budget of $300,000 per year for a period of 5 years. The second consists of iterating a budget that will maintain the current network condition at a constant state for 5 years. And the third is a plan that will eliminate the backlog of the pavement network within 5 years. All of the studies are done assuming an inflation rate of 3%, and a critical PCI value of 55. The critical PCI value comes into play because of the M&R categories being used for the study. Localized stopgap M&R is applied when pavements are below the critical PCI and localized preventative M&R is applied when pavements are greater than or equal to the critical PCI.

The first plan, which consisted of $300,000 per year, is found to have little positive effect on the network. The majority of the network is below the critical PCI, thus all of the treatments applied are localized stop gap M&R treatments which only provide minimum safety measures and do not extend the life of the network. Over the 5 year analysis period, a total of $1.5 million is allocated to the network and the failed pavements (0<PCI<10) increased from 4% to 16%, while there was 2% in the satisfactory category (70<PCI<85) a 0% in the good pavement category (85<PCI<100).

The second plan, which consisted of stabilizing the network at the current condition level, was also found to be unbeneficial. The condition stabilization is completed through iterative procedures within the software in order to determine budget requirements. In this case the condition was already in a poor state, with an average network PCI of 44. Thus the stabilization procedure was found to be ineffective. Over the 5 year analysis period, a total of $7.96 million is allocated to the network and the failed pavements increased from 4% to 31%, while 15% of the pavements deteriorated to the satisfactory and good categories (70<PCI<100).

The third plan consisted of finding a budget that would eliminate the overall pavement network backlog. Similar to the network stabilization process, an iterative procedure within the software calculates the required pavement budget to remove all network backlog. Over the 5 year analysis period, a total of $33.94 million is allocated to the network and the failed pavements decreased from 4% to 0% with 78% of the pavements in the satisfactory and good categories. This result, further confirms that attending to poor roads first can be result in high spending while the remaining roads falter to a poor state as well.

2.4 Transportation Asset Management Software (TAMS)

The TAMS software was developed by the Utah LTAP center in cooperation with Utah State University around 1999. TAMS is a simple PMS software package with basic models and data collection strategies. The TAMS software has been mainly used in Utah, Idaho and some areas of Colorado. It has useful GIS integration which enables the user to be visually involved through both the data collection and M&R work assignment process.

2.4.1 TAMS Condition and Deterioration Methodology

Within the TAMS software the condition of the pavement is referenced in Remaining Service Life (RSL). It is assumed that a pavement has a total service life of 20 years, thus a brand new pavement will have an RSL of 20 and a pavement in critical condition will have an RSL between 3 - 0 years. The TAMS condition rating method is conducted using non-destructive visual inspections following the "Distress Identification Manual for the Long-Term Pavement Performance Program" (US Department of Transportation, 2003). The condition is determined by inspecting nine of 15 distresses for asphalt pavement and nine of 16 distresses for concrete pavement. Depending on the type of distress, and its extent and severity within a pavement segment, an RSL value is calculated for each segment.

The deterioration of a pavement is evaluated through linear methodology in reference to the RSL, within the TAMS approach if a pavement segment does not receive any M&R treatment in a given year the segment will lose 1 year of service life.

2.4.2 TAMS M&R Alternatives

The TAMS software allows the user to determine what type of M&R alternatives can be evaluated and analyzed. The software has approximately 20 treatment alternatives

as a default. These treatment options are presented in four categories; routine maintenance, preventative maintenance, rehabilitative maintenance and reconstruction. Each of these M&R categories has an optimal execution period depending on the current pavement condition. Table 2.4 is often referenced by the Utah LTAP to illustrate how a certain M&R treatment will affect the RSL in TAMS. From the Table 2.4, the yellow band illustrates the type of treatment that should be applied to a segment based on the current RSL. For example, if a pavement has an RSL of 16, the most cost effective M&R treatment to be applied would be to crack seal. Or if a pavement has an RSL value of 13, an evaluation of routine maintenance or preventative maintenance (seal coats) would need to be conducted. The number associated to treatment is the value of RSL that will be added once the M&R treatment is applied. For example, if crack seal is applied to the segment with a value of RSL 16, 3 years of service life will be added and the new RSL after application will be 20. However, if crack seal is applied to a segment with an RSL value of 10, 1 RSL will be added according to the current table because the application of crack seal will be insufficient to account for the needs.

All of the values and treatments within the TAMS software can be changed to match the user's assumptions or needs. This means that although the TAMS software has the values in Table 2.4 set as a default, the user is capable of adding, deleting or changing M&R treatments as well as unit costs and the RSL improvement. This capability allows users to better adapt to their current environment. Different cities and municipalities may have different costs associated to the type of treatment required for a road based on their geographic location. For example, larger cities may have an in-house treatments available that would not be necessary to reflect as an additional cost within the TAMS software.

Table 2.4 TAMS Maintenance Performance Chart (Utah LTAP, 2010)

Treatment Type	Maintenance Category	Cost (SqYd)	Remaining Service Life Categories (years)							
			0	1-3	4-6	7-9'	10-12	13-15	16-18	19-21
Crack Seal	Routine	$0.30	0	0	0	0	1	2	3	2
Digout and Hot Patch (R&R)	Routine	$0.45	0	0	0	0	0	0	0	0
Fog Coat	Routine	$0.45	0	0	0	1	1	2	2	2
High Mineral Asphalt Emulsion	Seal Coats	$1.20	0	0	0	1	2	3	5	5
Sand Seal	Seal Coats	$0.65	0	0	0	1	2	2	2	2
Scrub Seal	Seal Coats	$1.00	0	1	3	4	5	5	5	5
Single Chip Seal	Seal Coats	$1.30	0	1	3	4	5	5	5	5
Slurry Seal	Seal Coats	$1.75	0	1	3	4	5	5	5	5
Microsurfacing	Seal Coats	$2.40	0	2	3	4	7	7	7	7
Bonded Wearing Course	Rehabilitation	$6.00	0	3	4	5	7	7	7	7
Cold In-place Recycling (2 in with chip seal)	Rehabilitation	$5.00	0	3	4	5	6	7	7	7
Thin Hot Mix Overlay (<2 in)	Rehabilitation	$6.75	0	4	6	7	7	7	7	7
HMA (leveling) & Overlay (<2 in.)	Rehabilitation	$7.50	0	4	6	8	8	8	8	8
Hot Surface Recycling	Rehabilitation	$5.00	0	3	5	7	8	8	8	8
Rotomill & Overlay (<2 in)	Rehabilitation	$8.40	0	4	7	8	8	8	8	8
Cold In-place Recycling (2/2 in.)	Reconstruction	$10.30	15	15	15	15	15	15	15	15
Thick Overlay (3 in.)	Reconstruction	$10.00	12	12	12	12	12	12	12	12
Rotomill & Thick Overlay (3 in.)	Reconstruction	$11.00	12	12	12	12	12	12	12	12
Base Repair\Pavement Replacement	Reconstruction	$12.00	16	16	16	16	16	16	16	16
Cold Recycling & Overlay (3/3 in.)	Reconstruction	$11.15	14	14	14	14	14	14	14	14
Full Depth Reclamation& Overlay (3/3 in.)	Reconstruction	$13.25	20	20	20	20	20	20	20	20
Base/Pavement Replacement (3/3/6 in.)	Reconstruction	$19.00	20	20	20	20	20	20	20	20

2.4.3 TAMS Economic Analysis

The economic analysis within TAMS is relatively simple. It has capabilities to perform project planning analysis as well as complete network analysis. The project planning aspect takes into account M&R treatments that have been applied since the last date of inspection. This means that users can enter M&R treatments that have been implemented and the RSL value will be updated within the TAMS software and database.

The complete network analysis requires a more iterative approach. The TAMS economic analysis begins by determining the total area of the pavement network. This area is then broken down in terms of percentages to represent RSL of the present year and the RSL of future years. Similarly, the treatment is specified as a percentage of to complete pavement network surface area. Additional treatments may be added and altered within the software to more closely illustrate the constraints and costs of pavement treatments by local governments. Figure 2.7 is an excerpt from the TAMS software illustrating the economic analysis window.

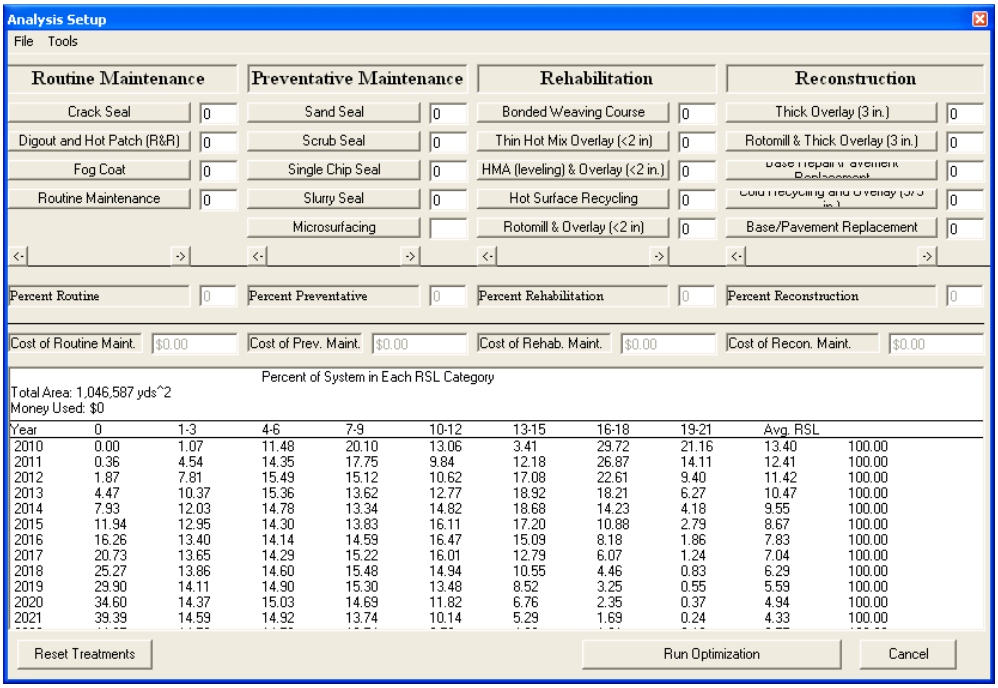


Figure 2.7 TAMS Economic Analysis Window

As previously mentioned, if a pavement segment does not receive any treatment in a given year one RSL value will be lost. In the economic analysis portion, the segments are approached in terms of percent area. Eight categories are used ranging from 0 to 21 as shown in Figure 2.7. These categories are composed of the surface area of pavements that fall under their respective RSLs. The economic analysis accounts for the 1 year of service loss by subtracting one-third of the area for each category and moving it down to the preceding category until all of the surface area is in the RSL of zero if no M&R treatments are applied over time.

Selecting treatments to evaluate in the TAMS software is also done in terms of the percentage of area that will be treated. Thus, detailed treatments to pavement segments cannot be specified in this analysis. The cost for each M&R treatment is calculated based on surface area and summed up based on category. Figure 2.8 illustrates a network in

which 3% of the area is treated with crack seal, 3% of the area is treated with slurry seal, 3% of the area is treated with a thin overlay, and 3% of the area is treated with a thick overlay. The final amount estimated is summed up by each M&R category as well as for the complete network.

2.4.4 TAMS Application

The majority of the TAMS economic analyses are implemented upon the request of a city's desire to perform the TAMS study and implement a PMS. The current method of practice used at the Utah LTAP when performing the economic analysis consists of evaluating three alternatives.

The first is to provide a "do nothing" analysis, in which no M&R treatments are applied to the network over 10 years. This analysis provides the worst case scenario of the network as the pavement deteriorates without prevention over 10 years. The second analysis provides a 10 year evaluation with the local government's budget limitations for pavement M&R. The 10 year analysis is broken down into two sections in terms of years (years 1-5 and years 5-10) in order to provide flexibility to change the M&R treatment recommendations for the 5 year plans. Two parameters are attempted to be met during this process, the first is to have less than 3.5% of the network in the 0 RSL category and the second is to have an average RSL of 10 or greater for the overall network. These parameters are set by the Utah LTAP and are represent a pavement network in good condition. They are however difficult to address when the pavement network contains a large area of pavement surface, and thus can provide over conservative results. In situations such as these, the recommended budget and treatment is addressed on an annual basis.

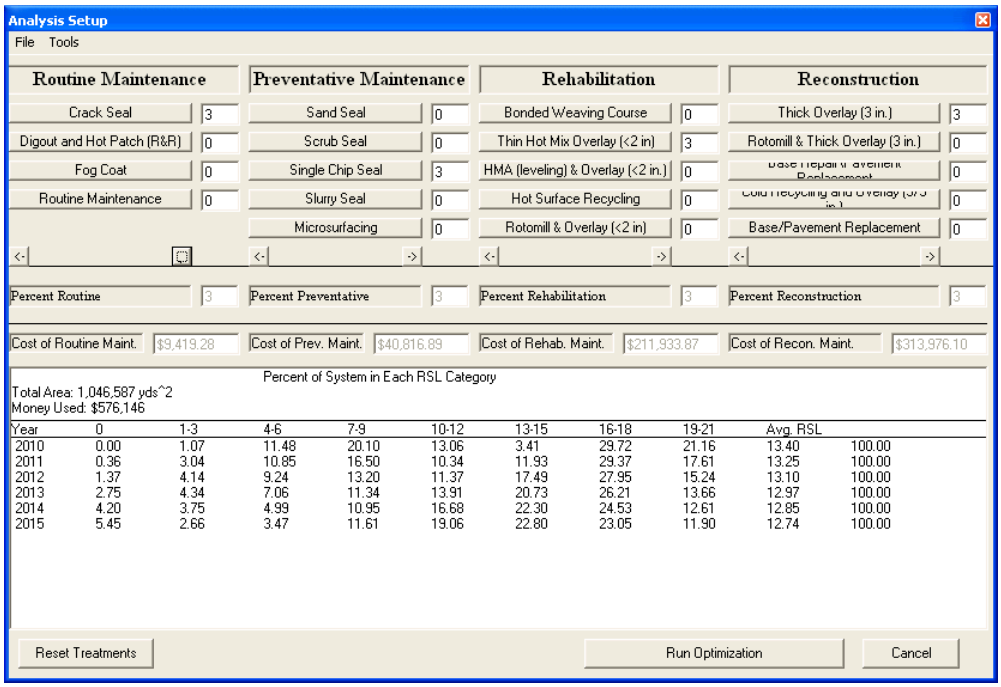


Figure 2.8 TAMS M&R Economic Evaluation

The final analysis is presented by optimizing the pavement network M&R while trying to meet the same parameters mentioned before. These parameters are difficult to meet depending on the size of the pavement network. The majority of the time the parameters cannot be met with a city's given budgetary constraints. Thus, the optimization of the pavement network M&R is presented as an unconstrained budget that represents what a city should be spending in their pavement M&R plans.

2.5 PMS Economic Analysis Publications

This section consists of publications that have reported on evaluation of the economic analysis aspects of a PMS. Although some of the publications in this section discuss the analysis strategies used by the previously discussed software, there are important characteristics of possible improvement, unique alternatives for enhancement

and in-depth examination of some of the previously discussed methodologies that can be evaluated.

To begin, one of the methods currently being used to evaluate engineering economic decisions is the life cycle cost (LCC) analysis. The LCC is a method that can be applied to all projects and considers not only the costs of implementation but all costs associated with the "manufacturer, user and society" (Asiedu and Gu, 1998). In pavements specifically, the LCC includes the initial design process, implementation, consideration of future M&R, user costs and also the retirement costs. The LCC analysis can take into account significantly more factors than the ones previously discussed. Some DOTs provide their own guidelines about what is and what is not to be included in a LCC analysis. Thus each DOT approaches the LCC differently in accordance to their state policies. One important aspect to note is that the LCC analysis is different than the benefit-cost (BC) analysis approach. Douglas. and Lee define the LCC analysis as a "restricted form of BCA that can be applied in situations where benefits are assumed to be equal for all alternatives" (Douglass and Lee, 2002).

In a published article by Shahin, a mathematical algorithm is presented to address economic analysis in pavements (Shahin et al., 1985). The presented procedure is identified as the incremental benefit-cost (IBC) technique. It is a mathematical algorithm that requires five pavement network characteristics in order to be successfully executed. The five items are listed below.

1. Total budget available for M&R treatments
2. M&R treatment alternative identifier
3. M&R Equivalent Uniform Annual Cost (EUAC)

4. Annual benefit
5. Initial cost of M&R treatment alternatives

The first requirement, which is the available budget, is unique and dependent on a specific agency's resources and limitations. Similarly, the M&R treatment alternative is a unique identifier that an agency uses to label or refer to specific M&R treatments. The EUAC is determined through a series of steps; the authors specify that elected officials making M&R plans and decisions "must have some way to compare the time value of cash flow" (Shahin et al., 1985). For this reason the anticipated future costs of M&R implementation treatments must be converted to present value costs, and the EUAC is then calculated from the present value cost. Equations 2.35 and 2.36 illustrate the present value formula and the EUAC formulas, respectively, from the proceedings (Shahin et al., 1985). The EUAC in pavement M&R is usually presented in terms of unit area or the cost associated per treating a square unit area of pavement.

$$PV = C_i + \sum_{t=1}^{N} C_m \left(\frac{1+r}{1+i}\right)^t \qquad \text{(Eq. 2.35)}$$

$$EUAC = PV * \frac{i\,(1+i)^N}{(1+i)^N - 1} \qquad \text{(Eq. 2.36)}$$

where C_i is initial cost, C_m is the cost acquired in the tth year, r is the annual inflation rate, i is annual interest rate, t is the year of the analysis period and N is the analysis period in years (Shahin et al., 1985).

Determining the annual benefit consists of assigning a monetary value to the improvement of a pavement. This process is accomplished by first knowing what type of improvements and M&R treatment can provide in terms of PCI, and graphing each M&R treatment line against time (years). The next step involves evaluating the performance, in

which the performance consists of the area under the M&R treatment line plotted against service life (years). This approach provides the possibility that some M&R treatment plots might have very similar, if not identical performance areas. For this reason a utility value is introduced. The utility is a value between 0 and 1 used to modify the performance area based on PCI, assuming that it is less expensive to perform M&R to a better pavement (PCI=>60) than a poorer pavement (PCI<60). The utility is not a linear but rather a curve for specific types of pavements. A utility of 1 would represent a PCI of 100 and 0 would represent a PCI of 0. A final modifier is introduced to determine the weight or importance a specific pavement has on the street network. This modifier is referred to as a relative weight modifier and is also based on a value between 0 and 1, where a lower value signifies a road with lesser importance such as a parking lot or residential road, and a 1 signifies a high importance road such as an arterial road, collector road or highway. Multiplying the performance area by the utility and relative weight produces the relative utility-weighted performance value which is the key to determining the overall benefit of a particular M&R treatment. Two methods are proposed for benefit evaluation; the first is by dividing the relative utility-weighted performance value by the time (years) needed to reach a designated minimum PCI condition. The second is to multiply the relative utility-weighted performance value by a capital recovery factor (CRD). This later approach is done when the benefits are assumed to “be proportional in value to the monetary units” (Shahin et al., 1985).

The IBC algorithm is then executed; the algorithm can be subject to single budget evaluation or multiple budget evaluation. The alternatives are to be plotted by annual

benefit against EUAC by unit area based on increasing order of EUAC. Figure 2.9 illustrates a single budget evaluation with four alternatives.

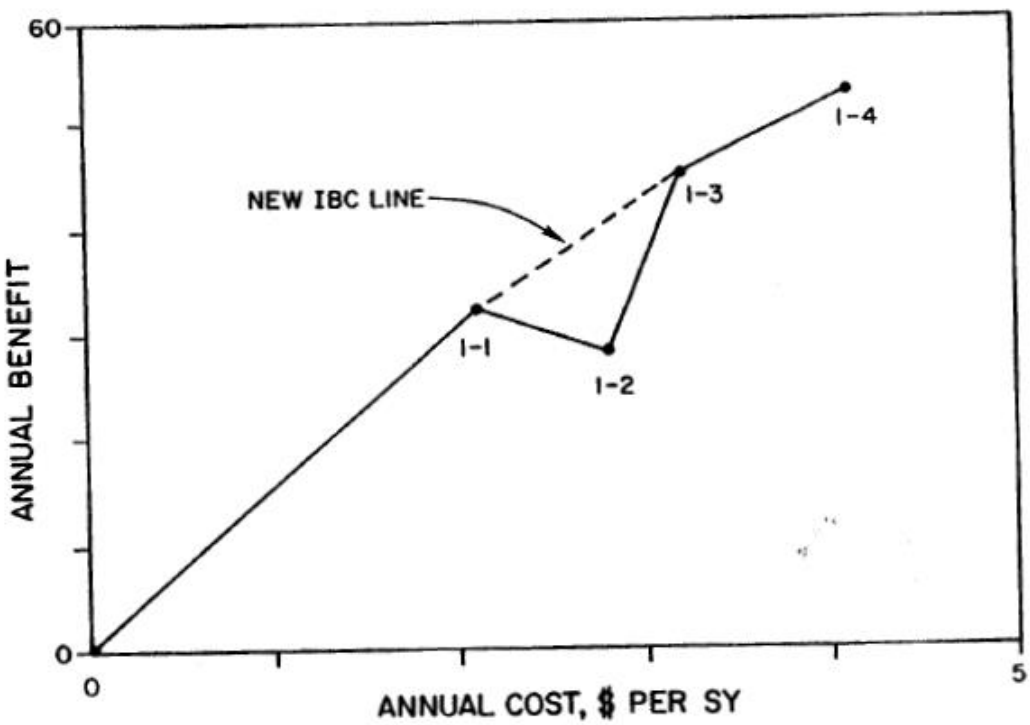


Figure 2.9 Annual Benefits Vs EUAC per Unit Area (Shahin et al., 1985)

As illustrated in the figure if an M&R alternative has an increase in both benefit and EUAC then it is viable alternative, however if there is an increase in EUAC and a decrease in benefit the M&R alternative should not be considered. Referring back to Figure 2.9, the alternative labeled 1-2 would not be considered for implementation.

A similar process is done for a multiple budget evaluation. The final results consist of a table with the results in descending order of the IBC ratio as shown in Table 2.5. Plotting the results in the same manner as the single budget evaluation will determine which M&R treatments can be considered for implementation in terms of the IBC ratio and available budget.

Table 2.5 IBC Algorithm Results (Shahin et al., 1985)

Total number of features in M&R Program = 5

Feature Number	M&R Alternative Number	Annual Cost, Dollars per Square Yard	Annual Benefit	Initial Cost, Dollars
1	1-1	2.10	32	24,000
1	1-2	2.80	28	32,000
1	1-3	3.20	45	37,000
1	1-4	4.10	53	47,000
2	2-1	3.50	43	43,000
2	2-2	3.40	35	43,000
2	2-3	2.80	29	35,000
3	3-1	4.20	38	46,000
3	3-2	2.70	28	29,000
3	3-3	5.70	58	62,000
4	4-1	4.00	54	41,000
4	4-2	3.60	45	37,000
4	4-3	2.90	36	30,000
5	5-1	4.60	44	48,000
5	5-2	3.40	36	36,000
5	5-3	2.50	32	26,000
5	5-4	3.80	42	40,000

In a separate article authored by Abaza, a new method of M&R planning is proposed through the use of a pavement life-cycle model (Abaza, 2002). This is a LCC analysis based rehabilitative treatments applied to a flexible pavement, rather than a LCC taking into account all possible factors. The major concept that is introduced is the “life-cycle disutility” value, which is the life-cycle cost over the life-cycle performance of a pavement. In summary, the procedure of the life-cycle disutility is advantageous after evaluating multiple alternatives of rehabilitative treatments, determining their respective life-cycle disutility, and recommending the M&R alternative with the lowest life-cycle disutility.

The process presented is based on the most cost-efficient time to perform rehabilitative treatments to pavements. In the literature, there are two decision policies proposed based on time (years). The first decision policy is one in which a treatment is applied at a fixed number of years; the second decision policy is one in

which a treatment is applied at a variable number of years. Thus the costs are acquired through engineering economic equations taking into account the time of the designated decision policy. The first decision policy evaluates the cost in present value, while the second decision policy evaluates the cost in equivalent annual value. The performance is determined through the area under the life cycle performance curve of the pavement. The performance curve can be determined by either past data or through the American Association of State Highway and Transportation Officials (AASHTO) design method (AASHTO, 1993).

The recommend present value and equivalent annual value equations to use for this procedure are presented in Equations 2.37 to 2.41. First the present value equation is presented in Equation 2.37, while Equations 2.38 and 2.39 illustrate functions that compose the present value Equation.

$$P_{LC} = C_c + M_c \times f\left(\frac{P}{A}, r, T_{m+1}\right) + \sum_{j=1}^{m} R_j \times f\left(\frac{P}{F}, r, T_j\right) \qquad \text{(Eq. 2.37)}$$

where P_{LC} is the pavement life-cycle present worth cost for a given M&R plan, C_C is the initial construction cost of pavement, M_C is the annual routine maintenance and user cost, R_j is the future rehabilitation cost, m is the number of major rehabilitation cycles in the analysis period and j is the analysis cycle in terms of years and r is the interest rate and T is the length of the life cycle in years (Abaza, 2002).

$$f\left(\frac{P}{A}, r, T_{m+1}\right) = \left[\frac{(1+r)^{T_{m+1}}-1}{r(1+r)^{T_{m+1}}}\right] \qquad \text{(Eq. 2.38)}$$

$$f\left(\frac{P}{F}, r, T_j\right) = \frac{1}{(1+r)^{T_j}} \qquad \text{(Eq. 2.39)}$$

$$EA_{LC} = P_{LC} \times f\left(\frac{A}{P}, r, T_{m+1}\right) \quad \text{(Eq. 2.40)}$$

where EA_{LC} is the pavement life cycle equivalent annual cost, P_{LC} is the pavement life-cycle present worth, r is the interest rate and T is the time periods (Abaza, 2002).

$$f\left(\frac{A}{P}, r, T_{m+1}\right) = \left[\frac{r(1+r)^{T_{m+1}}}{(1+r)^{T_{m+1}}-1}\right] \quad \text{(Eq. 2.41)}$$

After determining the present worth for the first decision policy through a fixed year analysis or the equivalent annual value for the second decision policy through a variable year analysis, the life-cycle disutility is determined for each through the following equations. Equations 2.42 and 2.43 illustrate the first decision policy and the second decision policy disutility calculations, respectively. The deciding factor would be the lowest utility value between the tested M&R alternatives.

$$U_{LC} = \frac{P_{LC}}{A_{LC}} \quad \text{(Eq. 2.42)}$$

where U_{LC} is the disutility value, P_{LC} is the pavement life cycle present value and A_{LC} is the area under the pavement life cycle curve (Abaza, 2002).

$$U_{LC} = \frac{EA_{LC}}{(A_{LC}/T_{m+1})} \quad \text{(Eq. 2.43)}$$

where U_{LC} is the disutility value, EA_{LC} is pavement life-cycle equivalent annual value, A_{LC} is the area under the pavement life cycle curve and T_{m+1} is the pavement life cycle analysis period of a specific M&R plan (Abaza, 2002).

In a separate publication by Abaza. and Ashur, the authors investigate the application of a new pavement management approach focusing on “microscopic” segments. The term microscopic in the literature refers to the “identification, inspection and rating of each pavement section” (Abaza and Ashur, 2009), macroscopic segments are defined as evaluating a representative portion based on pavement class.

The pavement management methodology in this process is referred to as a constrained integer linear programming model; it is a method proposed for pavement M&R optimization that is subject to budget and improvement requirement constraints. Two models are discussed in the literature, the first is focused on optimizing the condition of the pavement, which in the article is the pavement condition rating (PCR), and thus the optimum result is an increase in the PCR condition value. The second consists of optimizing the age of the pavement, therefore the output results as increased years of service life or “age-gain.”

The following equations illustrate the application of the previously discussed models. Equation 2.44 is the PCR optimization model and Equation 2.45 is the age-gain optimization model.

$$RG_S = \sum_{i=1}^{n} \sum_{j=1}^{m} \left[(PCR_0)_{ij} - (\overline{PCR_t})_j \right] \times I_{ij} \qquad \text{(Eq. 2.44)}$$

where RG_S is the net PCR-gain to a pavement resulting from M&R implementation, n is the number of pavement classes, m is the number of M&R actions, i is an index for pavement class, j is an index for M&R action, PCR_0 is the expected PCR after M&R implementation, $\overline{PCR_t}$ is the average terminal PCR of an untreated pavement in the ith class and I_{ij} represents an integer of the M&R applied to a number of pavement sections

in the ith class with j^{th} M&R treatment (Abaza and Ashur, 2009). This model is subjected five constraints, two that are mandatory and three that are optional for the user. The first and second are the upper and lower limits of the M&R variables. These constraints are mandatory and state that there must be greater than zero treatments applied but less than the number of available pavement sections. The following third constraint is optional and is one that places a budgetary constraint on the amount of M&R applied. Of the remaining two constraints, only one can be applied at a time. The fourth constraint would be one that emphasizes that all the pavements in a certain class be improved proportionally. The final constraint is one that specifies a target value for PCR-gain.

$$AG_S = \sum_{i=1}^{n} \sum_{j=1}^{m} EA_{ij} \times I_{ij} \qquad \text{(Eq. 2.45)}$$

where AG_S is the net pavement-gain in years to a pavement resulting from M&R implementation, n is the number of pavement classes, m is the number of M&R actions, i is an index for pavement class, j is an index for M&R action, PCR_0 is the expected PCR after M&R implementation, EA_{ij} is the average terminal PCR of an untreated pavement in the ith class and I_{ij} represents an integer of the M&R applied to a number of pavement sections in the ith class with j^{th} M&R treatment (Abaza and Ashur, 2009). The same constraints discussed in the previous model are available here; however the final constraint is altered to a target value for age-gain.

In addition to the models provided, an M&R cost minimization model is presented for each of the PCR and age-gain models. This model is illustrated in Equation 2.46 and can be used for either model. The same constraints previously discussed can be applied to the respective model, however the governing constraint will be the budgetary limit.

$$C_S = \sum_{i=1}^{n} \sum_{j=1}^{m} A \times \overline{C_{ij}} \times I_{ij} \qquad \text{(Eq. 2.46)}$$

Where C_S is the cost minimization output, A is the surface area of a pavement section, $\overline{C_{ij}}$ is the average cost per unit area (Abaza and Ashur, 2009).

This M&R cost model is designed to take into account applying an M&R treatment to pavement segments that require the same treatment at different physical locations throughout the network. Thus, it provides cost estimation for the "scatter" of the pavements requiring similar treatments. One of the factors to consider with this approach is the grouping of different pavement classes. A pavement class is defined as pavements that have the same condition and would thus require the same M&R treatment. The M&R cost for pavement classes that are similar and are in close proximity to each other within a network would produce a lower M&R cost. The breakdown of pavement classes ultimately determines the M&R treatment analysis. By knowing what condition a certain group is in, a specific M&R treatment can be applied to those pavement classes and the associated cost is then determined.

The microscopic approach presented in this literature provides a number of different results that are ultimately based on the model constraints initially set. The benefits are that estimates can be produced at a microscopic level in order to determine budgeting for the M&R that needs to be completed.

2.6 Summary and Conclusion

In conclusion, there are many methods available to perform economic analysis procedures as well as many factors to consider. Methods include the benefit-cost ratio, life-cycle cost and present value estimates. Factors that are especially important are the

pavement condition, definition of benefits and costs, interest rates and financial indicators. The pavement condition is a significant factor when determining what M&R treatments will be recommended as well as determining future M&R needs through pavement deterioration models. It is through these methods that present day M&R decisions are made, thus making the economic analysis a critical element of the process.

Benefits are sometimes difficult to determine. There are many suggestions and assumptions made as to what the benefits of pavement M&R implementation really are. The HDM-4 software uses a unique definition and methodology for M&R benefits, while others may define it as the area under the pavement performance curve.

Interest rates are also a factor to take into consideration. Research by Ozbay et al. (2004) illustrated a high degree of variation between the interest rates used by state DOTs between 1984 and 2001. The study also suggests that agencies are using periods of analysis longer than a year for their pavement projects, and the interest and inflation rates used can be anticipated to have a significant impact in the final estimates.

Financial indicators are a factor that could be implemented more in PMS and the overall economic analyses. Currently the more well-known indicators are the benefit cost ratio and the life cycle cost analysis. However, new methods can be introduced and evaluated such as the life cycle disutility value.

In conclusion, the PMS process is one that progresses from the initial data collection process through final treatment recommendations. The common methodology among all of the previously discussed methods is that a present condition must be known from which a M&R recommendation can be made. The economic analysis is then based on treatment cost and future investment alternatives.

CHAPTER 3

DATA COLLECTION AND METHODOLOGY

3.1 Introduction

In order to provide a proper assessment of the factors with greatest effect on sensitivity the economic analysis of a PMS systems in local governments, statistical models were used to determine the significance and sensitivity of PMS economic analysis outcomes to distress attributes. A previous study conducted by Mrawira et al. (1999) titled Sensitivity Analysis of Computer Models: World Bank HDM-III Model addressed a similar question by performing a sensitivity analysis of input factors in the HDM-III software where the Net Present Value (NPV) was the response variable. This study was performed in the previous version of the HDM-4 PMS software discussed in Chapter 2.

The concept performed in the study by Mrawira et al. (1999) was implemented in this thesis as well. In the original study, a Latin-Hypercube sample (LHS) was used to obtain a sample set which accounts for a range of all probable combinations of input factors. The sample data set was then statistically modeled by using software input factors and significant combinations as predictor variables. The same data set was then modeled by two methods, the first method is a first-order linear regression approximation, and the second is a Gaussian stochastic process model. The purpose of the study was to determine which input factors the outcome of NPV was most sensitive to in the HDM-III PMS software package.

For the data in this thesis two statistical models were considered, the first was a general linear regression and the second an Analysis of Covariance (ANCOVA). The

analysis was conducted by using two out of the three PMS software packages discussed in Chapter 2. Micro PAVER™ and TAMS were each used for analysis, HDM-4 was not considered as the software is unavailable for use and analysis. The estimated cost for the recommended M&R was the response variable, while the distress input values served as the predictor variables. Table 3.1 illustrates an outline of the statistical models used to analyze the sensitivity of each PMS software package.

Table 3.1 Software Packages Considered for Data

PMS Software Package	Considered	Statistical Model
HDM-4	No	None
Micro PAVER™	Yes	ANCOVA
TAMS	Yes	General Linear Regression

A total of six sample sets of data were used for data analysis, the first two being a Latin-Hypercube sample of each software package considered. The remaining were data collected from two local governments, and each local government was subjected to assessment in the Micro PAVER™ and TAMS software packages.

The Latin-Hypercube sampling procedure assures “that each of the input variables X, has all portions of its distribution represented by the input values” (Mckay et al., 1979). Thus the Latin-Hypercube sampling was first used as a theoretical data set to consider the outcome of a scenario where all input factors are accounted for. Following the Latin-Hypercube sampling analysis, current local government pavement condition data were collected and entered into each PMS software package. The City of Smithfield, Utah as well as the City of Tremonton, Utah were the sources of the pavement condition data samples. The latter two samples served as a more direct comparison between the two PMS software packages in a local government setting than the synthesized data set. Table

3.2 summarizes the data sets that were obtained and analyzed for each PMS software package.

Table 3.2 Data Sets Used for Analysis

Data Sample Set	Statistical Model
LHS Micro PAVER™	ANCOVA
Smithfield by Micro PAVER™	ANCOVA
Tremonton by Micro PAVER™	ANCOVA
LHS TAMS	General Linear Regression
Smithfield by TAMS	General Linear Regression
Tremonton by TAMS	General Linear Regression

3.2 Research Question

The focus of this research was to answer the question "*What attributes of a PMS should local governments focus on to provide adequate economic analysis estimates for their pavement network?"* In order to answer this question, the two available PMS software packages of TAMS and Micro PAVER™ were used to calculate a recommended M&R cost based off of pavement condition data. Through statistical modeling, the response variable of estimated recommended M&R cost from each software package was analyzed for its sensitivity to the distress input variables.

3.3 Data Collection

This section defines the specific input factor variables of the two PMS software packages that were used for statistical analysis. In addition, the pavement networks used for this study are also presented and described. The city networks for which data was collected consist of the City of Smithfield, Utah and the City of Tremonton, Utah. Both are good examples of the type of centerline mileage and distresses that can be observed in a Utah local government setting.

3.3.1 Micro PAVER™ Input Factors

As described in Chapter 2, the Micro PAVER™ data collection process is based on the American Society of Testing and Materials (ASTM) standard (ASTM, 2007) to determine a PCI. The ASTM method is based on non-destructive visual inspections. There are 20 flexible asphalt condition ratings to take into consideration when applying the ASTM standard. Segment characteristics will also be taken into consideration. The ASTM standard requires two levels of input for the Micro PAVER™ software package to determine pavement condition. The first input level is the amount of surface distress present in terms of unit length or unit area, while the second level of input variable is used to specify the severity of given surface distress. Table 3.1 illustrates the two input factor levels that must be taken into consideration through assessment by the Micro PAVER™ software.

The severity levels are only applicable to the surface distresses, where L, M, H stands for Low Severity, Medium Severity and High Severity, respectively. The input factor of rank can be specified by the user, Table 3.1 illustrates typical inputs, whether initials of primary, secondary and tertiary roads (P, S, T) or importance in ascending alphabetical order. Within the ASTM standard and the Micro PAVER™ software package, the hierarchy of a pavement network is broken down in the following way.

1. Network: Complete pavement network of city, municipality or township
2. Branches: Street corridors, collectors, arterials, residential streets
3. Sections: Breakdown of branches (between intersections, specified length of corridor)
4. Sample: Sample of condition of pavement (Usually 10%)

Table 3.3 Micro PAVER™ Input Factors

Input Factor	Factor Name	Description	Measurement	Severity Level
1	Rank	Jurisdictional Characteristic	P, S, T (A, B, C)	N/A
2	Length	Segment Characteristic	Unit Length	N/A
3	Width	Segment Characteristic	Unit Length	N/A
4	Alligator Cracking	Surface Distress	Unit Area	L, M, H
5	Bleeding	Surface Distress	Unit Area	L, M, H
6	Block Cracking	Surface Distress	Unit Area	L, M, H
7	Bumps/Sags	Surface Distress	Unit Length	L, M, H
8	Corrugation	Surface Distress	Unit Area	L, M, H
9	Depression	Surface Distress	Unit Area	L, M, H
10	Edge	Surface Distress	Unit Length	L, M, H
11	Joint Reflection Cracking	Surface Distress	Unit Length	L, M, H
12	Lane Shoulder Drop-off	Surface Distress	Unit Length	N/A
13	Longitudinal/Transverse Cracking	Surface Distress	Unit Length	L, M, H
14	Patching/Utility Cuts	Surface Distress	Unit Area	L, M, H
15	Polished Aggregate	Surface Distress	Unit Area	L, M, H
16	Potholes	Surface Distress	Count of Potholes	L, M, H
17	Railroad Crossing/ Cattle Guard	Surface Distress	Unit Area	L, M, H
18	Rutting	Surface Distress	Unit Area	L, M, H
19	Shoving	Surface Distress	Unit Area	L, M, H
20	Slippage Cracking	Surface Distress	Unit Area	L, M, H
21	Swell	Surface Distress	Unit Area	L, M, H
22	Raveling: Coarse Aggregate	Surface Distress	Unit Area	M, H
23	Weathering: Fine Aggregate	Surface Distress	Unit Area	L, M, H

Pavement distresses are not usually monitored for 100% of the actual pavement area in the ASTM methodology. The Micro PAVER™ software and the ASTM standard suggest only collecting a portion of surface distresses from a sample area that is

representative of the entire pavement section. As cited in the ASTM methodology, for a network having "over 20 sample units" (ASTM, 2007), a 10% survey is recommended.

By sampling only 10% of the total centerline miles, a sample of 132 feet long per section or per mile can be the reference point for a 10% survey assuming the width of the road stays constant. Thus, in a mile long branch, four sections were assigned and each was surveyed for a 132 ft sample. The sum of these four samples per mile account for 528 ft, which accounts for 10% of a centerline mile. Figure 3.1 illustrates the hierarchy methodology.

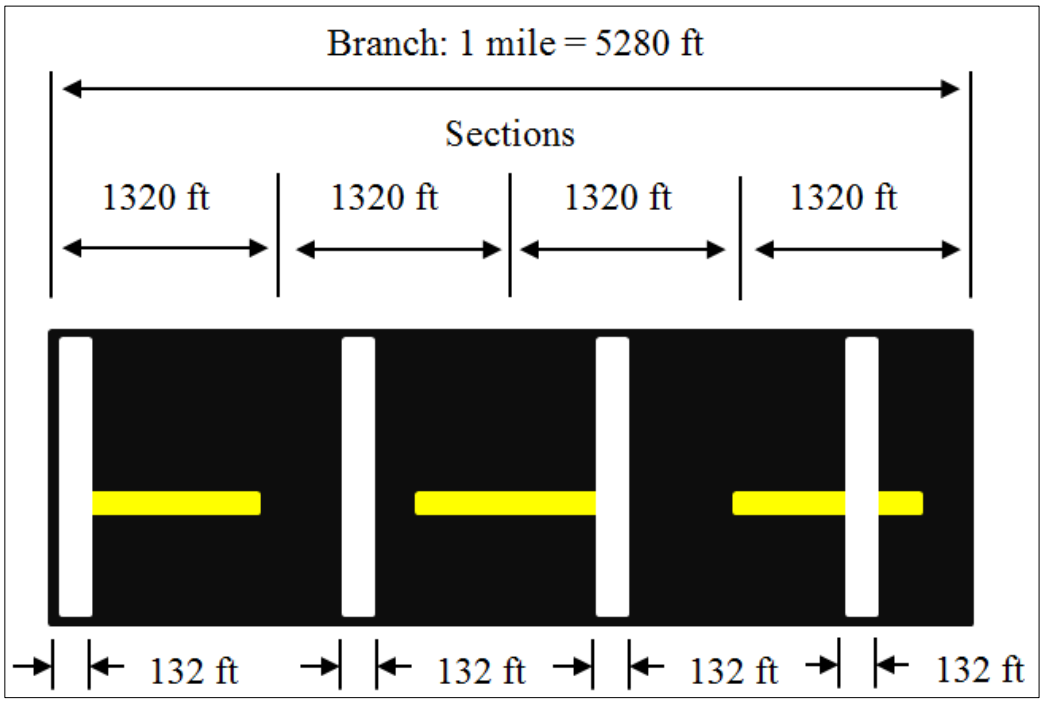


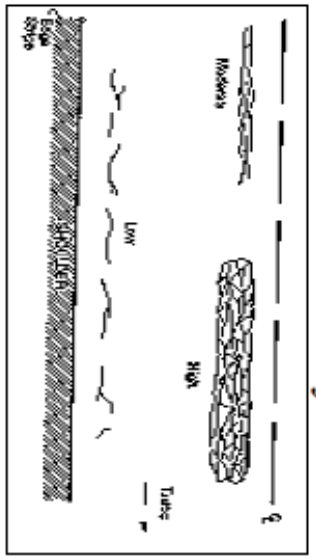
Figure 3.1 Micro PAVER^{TM} Hierarchy Methodology

3.3.2 TAMS Input Factors

The TAMS Software requires fewer input factors when conducting the data collection procedure. The TAMS condition rating method is conducted using non-

destructive visual inspections following the “Distress Identification Manual for the Long-Term Pavement Performance Program” (US Department of Transportation, 2003).

The measurement of pavement surface distresses is done through a matrix style approach in which only severity and extent are used to determine the condition of a specific distress. The TAMS procedure assesses the complete pavement segment, which in most cases is the complete intersection to intersection street section. Thus, in this manner 100% of the asphalt pavement network surface distresses are inspected. Figure 3.2 illustrates an example of the fatigue distress assessment under the TAMS approach. The Appendix contains the complete distress matrices for all of the input factors for the TAMS factors.



Severity	Extent: Low	Extent: Medium	Extent: High
0 None	1 Crack WP or 1' off C&G Length	2 Crack WP or 1'-2' off C&G Length	>30% of Surface Area or Length
Low Cracks < 1/4"	1	2	3
Medium Cracks 1/4"to 3/4"	4	5	6
High Cracks > 3/4"	7	8	9

Figure 3.2 TAMS Fatigue Condition Rating Matrix

The input factors that were examined for this thesis are listed in Table 3.4. The functional classification input in TAMS is similar to Micro PAVER^{TM}’s rank, in TAMS the road classification is presented in three options collectors, arterials and residential.

Table 3.4 TAMS Input Factors

Input Factor	Factor Name	Description	Measurement
1	Road Width	Segment Characteristic	Unit Length
2	Segment Length	Segment Characteristic	Unit Length
3	Functional Classification	Jurisdictional Characteristic	String Input
4	Fatigue	Surface Distress	Severity and Extent
5	Longitudinal	Surface Distress	Severity and Extent
6	Transverse	Surface Distress	Severity and Extent
7	Block	Surface Distress	Severity and Extent
8	Patching/Potholes/ Utility Cuts	Surface Distress	Severity and Extent
9	Edge	Surface Distress	Severity and Extent
10	Rutting	Surface Distress	Excellent/Good/Fair/Poor
11	Roughness	Surface Distress	Excellent/Good/Fair/Poor
12	Drainage	Surface Distress	Excellent/Good/Fair/Poor

3.3.3 Similarities in Input Factors

The input distresses taken into account for each software package originate from the same PMS methodology. Thus, the fundamental methods of observation for the pavement distresses have similar inventory procedures. Take for example the fatigue distress in TAMS and the alligator cracking in Micro PAVER^{TM}. These two distresses, although labeled differently in the software packages, are a measurement of the same observations. In Micro PAVER^{TM}, the description of alligator cracking is “after repeated traffic loading, the cracks connect, forming many sided, sharp-angled pieces that develop a pattern resembling chicken wire or the skin of an alligator” (ASTM, 2007) while in the TAMS methodology, fatigue is described as occurring “in areas subjected to repeated traffic loadings (wheel paths). Can be a series of interconnected cracks in the early stages of development. Develops into many-sided, sharp-angled pieces, usually less than 0.3 meters (m) on the longest side, characteristically with a chicken wire/alligator patter in

later stages" (US Department of Transportation, 2003). Similarly, block cracking, edge cracking and rutting are common distresses that are similarly defined in both software packages.

The distresses of transverse cracking and longitudinal cracking in TAMS are addressed as one single distress in Micro PAVER™. Similarly TAMS considers patching, utility cuts and potholes as one distress, while Micro PAVER™ considers patching and utility cuts as one distress but segregates potholes as an individual distress. The remaining distresses of roughness and drainage in TAMS can be more closely associated with bumps/sags, shoving and depression in Micro PAVER™, although in TAMS the results of roughness and drainage observations are side effects of bumps/sags, shoving and depression.

Therefore, all of the TAMS pavement distresses are accounted for in the Micro PAVER™ software package. Those unique to Micro PAVER™ include bleeding, corrugation, joint reflection cracking, lane shoulder drop-off, polished aggregate, railroad crossing/cattle guard, shoving, swell, raveling and weathering.

3.3.4 Pavement Networks

The main focus of this research is to determine which input factors of different PMS software are most sensitive to the economic analysis of local governments. Two local governments with different pavement network sizes were the sources of sample data.

The first pavement network evaluated was the city of Smithfield, Utah. Smithfield is located in northern Utah and is responsible for maintaining approximately 56 miles of centerline pavement. This accumulates to 260 segments of pavement under the

jurisdiction of Smithfield City that does not include state routes or private property. Figure 3.3 illustrates the boundaries of Smithfield city along with their centerline mileage.

Figure 3.3 Smithfield City Pavement Network

The second pavement network evaluated was the City of Tremonton, Utah. Tremonton City is located in northern Utah and is responsible for maintaining approximately 39 miles of centerline pavement. This accumulates to 224 segments of

asphalt pavement under the jurisdiction of Tremonton City. Figure 3.3 illustrates the boundaries of Tremonton city along with their centerline mileage.

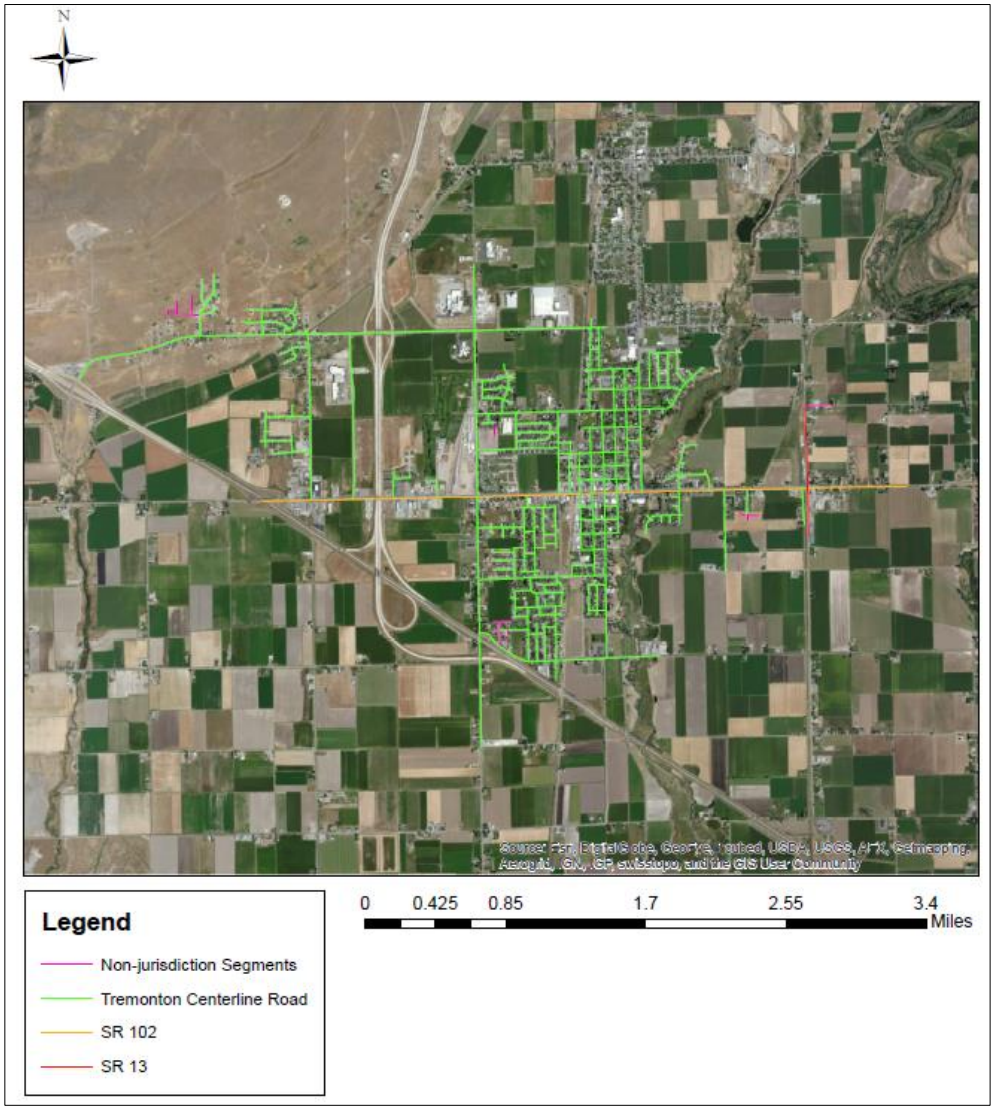


Figure 3.4 Tremonton City Pavement Network

3.4 Methodology

This section further discusses the statistical models that were used for this research. The experiment consisted of a Latin-Hypercube sampling (LHS) set for both the Micro PAVER^{TM} software and TAMS software that determined the input factors that the

economic analysis' estimated recommended M&R costs were most sensitive to. Once the LHS was obtained, the Micro PAVER™ data sets were modeled under the Analysis of Covariance (ANCOVA) and the TAMS software data sets were modeled using linear regression. Through these statistical approaches, input factors that the economic analysis procedure was sensitive to could be determined.

3.4.1 Latin-Hypercube Sampling

The Latin-Hypercube sampling (LHS) procedure produces a sample set of data that will ensure "that each of the input variables X, has all portions of its distribution represented by the input values" (Mckay et al., 1979). Thus this process produces a range of input factors that will make sure each input factor is represented. When undertaking this task, parameters of the input factors must be identified beforehand in order to receive accurate input factors from the Latin-Hypercube sampling procedure.

The input factor parameters were derived from previous project data for both Smithfield City and Tremonton City. This allowed the LHS to represent local government road characteristics. These local governments were subject to evaluation by the Utah LTAP Center with the TAMS software in 2010 and 2011, respectively. The data parameters used to determine the range of input factors are illustrated in Tables 3.5 and 3.6, while Table 3.7 shows the average input factors for the two local governments.

Table 3.5 Smithfield 2010 Segment Characteristic Summary

	Width (ft)	**Length (ft)**
Average	32.96	546.07
Minimum	12.00	51.64
Maximum	64.00	3237.32
Standard Deviation	8.89	422.41

Table 3.6 Tremonton 2011 Segment Characteristic Summary

	Width (ft)	**Length (ft)**
Average	34.76	511.42
Minimum	14.00	48.91
Maximum	60.00	4318.46
Standard Deviation	6.78	517.11

Table 3.7 Average Segment Characteristic Data for the Two Local Governments

	Width (ft)	**Length (ft)**
Average	33.86	528.74
Minimum	13.00	50.27
Maximum	62.00	3777.89
Standard Deviation	7.83	469.76

Therefore, input ranges for the Latin-Hypercube sample were selected by considering the information illustrated in Table 3.7.

For the Micro PAVER™ software package, distresses that are measured in units of length were assumed to have a range spanning only the average length of the sample area, which as discussed earlier is 132 feet. For distresses measured in units of area, the same length of 132 feet were multiplied by a 34 foot width to produce a 4,488 square foot sample area range. Table 3.8 illustrates the two levels of input factor ranges that were considered for the Micro PAVER™ software. Similarly, a LHS sample set for the distress severity levels were acquired for observations where a distress is present. The TAMS software accounts for surface distresses for the matrix illustrated earlier and in Appendix A. Therefore, the input factors are based on a scale of 0 – 9, and 0 – 3. The same assumption that the average pavement segment width is 34 feet were made, however there is no real constraint on the length of a segment. Thus the upper limit maximum of 3,780 feet were used for the TAMS software. Table 3.9 illustrates the input ranges for the TAMS software.

Table 3.8 Micro PAVER™ Input Factor Ranges

Input Factor	Factor Name	Severity Level	Measurement
1	Rank	N/A	P, S, T (A, B, C)
2	Length	N/A	50 - 3780 ft
3	Width	N/A	13 - 34 ft
4	Alligator Cracking	L, M, H	0 - 4488 ft^2
5	Bleeding	L, M, H	0 - 4488 ft^2
6	Block Cracking	L, M, H	0 - 4488 ft^2
7	Bumps/Sags	L, M, H	0 -132 ft
8	Corrugation	L, M, H	0 - 4488 ft^2
9	Depression	L, M, H	0 - 4488 ft^2
10	Edge	L, M, H	0 -132 ft
11	Joint Reflection Cracking	L, M, H	0 -132 ft
12	Lane Shoulder Drop-off	L, M, H	0 -132 ft
13	Longitudinal/Transverse Cracking	L, M, H	0 -132 ft
14	Patching/Utility Cuts	L, M, H	0 - 4488 ft^2
15	Polished Aggregate	N/A	0 - 4488 ft^2
16	Potholes	L, M, H	0 - 10
17	Railroad Crossing/ Cattle Guard	L, M, H	0 - 4488 ft^2
18	Rutting	L, M, H	0 - 4488 ft^2
19	Shoving	L, M, H	0 - 4488 ft^2
20	Slippage Cracking	L, M, H	0 - 4488 ft^2
21	Swell	L, M, H	0 - 4488 ft^2
22	Raveling: Coarse Aggregate	M, H	0 - 4488 ft^2
23	Weathering: Fine Aggregate	L, M, H	0 - 4488 ft^2

Successful completion of the Latin-Hypercube sampling procedure will provide a data set with values that cover the range of input factors listed above. The produced input factors will then be input into their respective software to determine the results of the economic analysis. Finally, the economic analysis output of estimated cost of recommended M&R was used as the response variable and regressed against the input factors to assess their significance and their effect on the estimated cost of M&R.

Table 3.9 TAMS Input Factor Ranges

Input Factor	Factor Name	Range
1	Road Width	13 - 34 ft
2	Segment Length	50 - 3780 ft
3	Functional Classification	C, A, R
4	Fatigue	0 - 9
5	Longitudinal	0 - 9
6	Transverse	0 - 9
7	Block	0 - 9
8	Patching/Potholes	0 - 9
9	Edge	0 - 9
10	Rutting	0 - 3
11	Roughness	0 - 3
12	Drainage	0 - 3

With the TAMS software, one special interaction that was observed was the interaction of longitudinal cracking and transverse cracking. The reason this interaction is of special interest is because the Micro PAVER™ software accounts for longitudinal and transverse cracking as the one distress, while TAMS accounts for it separately.

3.4.2 Analysis of Covariance

The Analysis of Covariance (ANCOVA) is a general linear model similar to the analysis of variance (ANOVA). The ANCOVA assumes the same model assumptions, but also includes "independence of the covariate treatment effect and homogeneity of regression slopes" (Fied, 2012). This test is well suited for the Micro PAVER™ software due to the two levels of input required for the distress variables. Each distress input variable that is observed requires a severity level, which is defined as its covariate. As defined by Howell, "covariance is a measure of how much two variables change together and how strong the relationship is between them" (Howell, 2009). In this study, the

interest was in the relationship of both the distress and severity to the response variable of estimated recommended M&R cost. The ANCOVA model can be defined as illustrated in Equation 3.1.

$$Y_i = GM_y + \tau + \left[B_i\left(C_i - M_{ij}\right) + \cdots\right] + \varepsilon \qquad \text{(Eq. 3.1)}$$

where *Yi* is the response variable, *GMy* is the grand mean of the response variable, τ is the treatment effect, *Bi* is the regression coefficient for the *ith* covariate, *Ci, M* is the mean of the *ith* covariate and is ε the error (Clark, 2014). The three data sets modeled under the ANCOVA are listed below.

1. Latin-Hypercube data set for the Micro PAVER™ software
2. Tremonton local government data set with Micro PAVER™ software
3. Smithfield local government data set with Micro PAVER™ software

The response variable for the above models was the estimated cost of M&R from the economic analysis. The results produced by the ANCOVA procedure were tables of Type I Sum of Squares (SS) and a Type III SS in which the input factor and its covariate of severity level were analyzed for significance. For this thesis the results referenced were that of a Type III SS. This enabled a more direct analysis of the sensitivity of the M&R cost outcomes to the severity input factors. A Type III SS "includes interactions with A but not the main effect of A" (Oehlert, 2010) where A is the main effect of distress.

3.4.3 General Linear Regression

The general linear regression model that assumes independence, symmetric normal distribution and constant variance from the possible error terms was used to

model the three data sets. The general linear regression model can be defined as illustrated in Equation 3.2.

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \cdots + \beta_{p-1} X_{i,p-1} + \varepsilon_i \qquad \text{(Eq. 3.2)}$$

where Y_i is the response variable, β_k is the partial regression coefficient, X_{ij} is the input factor, p is the number of predictor variables X and ε is the error in the model. The three data sets modeled under the general linear regression are listed below.

1. Latin-Hypercube data set for the TAMS software
2. Tremonton local government data set with TAMS software
3. Smithfield local government data set with TAMS software

The response variable for the above models was the estimated cost of recommended M&R from the economic analysis.

3.4.4 Statistical Software

All data collected in this thesis were modeled and analyzed in the SAS statistical software package. Within each model, the effect of the input variables to the estimated recommended M&R cost was determined by the significance explained by the variable p-value and a 95% confidence interval.

CHAPTER 4

SENSITIVITY ANALYSIS OF ECONOMIC MODEL TO DISTRESSES

4.1 Introduction

This chapter presents the results acquired from the previously discussed data sets and statistical models. A total of six data sets were acquired for input from three sources. Two of the data sets were composed of a Latin-Hypercube sample set, two where collected from the local government of Smithfield City, Utah and the remaining two where collected form the local government of Tremonton City, Utah. Table 4.1 illustrates a summary of the six data sets and the respective PMS software package used for evaluation.

Table 4.1 Summary of Datasets and Software Used for Evaluation

Data Source	PMS Software Package
Latin-Hypercube Sample	Micro PAVER™
	TAMS
Local Government Sample City of Tremonton, Utah	Micro PAVER™
	TAMS
Local Government Sample City of Smithfield, Utah	Micro PAVER™
	TAMS

The economic analysis for each PMS software package was then executed under the respective data set. The output of focus was the estimated recommended M&R cost given the condition of each pavement section. Thus, when the data were evaluated under the statistical models, the response variable was the estimated cost of M&R, a variable that is common for both PMS software packages. The predictor variables for the PMS software packages are unique, differentiating in various ways from the number of

distresses available for observation, the method of inputting distress and the different levels of input for each distress.

4.2 Data Analysis

This section discusses the data sets and analyses used to determine the sensitivity of the response of estimated recommended M&R cost to each distress input variable. Each data set was modeled using the SAS statistical software package.

The purpose of the ANCOVA approach and the research of this thesis in respect to the Micro PAVER^{TM} data set and the TAMS data set, was to determine the effect each distress variable had on the response produced by the economic analysis of estimated M&R costs and in turn determining which variables the economic analysis was sensitive to.

Under the ANCOVA analysis, in order to adequately determine the significant effects of the distress variables, two constraints had to be met. The first consisted of the statistical model analyzed having a significant p-value and the second consisted of the distress variables of interest having a significant p-value. The model p-value evaluates the significance of the entire model, and thus must be significant in order to conclude the effect of the variables on the response. In the following sections, the ANCOVA results presented denote the results after each individual distress and its respective covariate of severity were modeled individually for their effect on the response variable of estimated recommended M&R cost. In order to conclude an effect, the model p-value as well as the distress variable of interest required a p-value significant to a 95% confidence interval.

Under the linear regression analysis, in order to adequately determine the significant effects of the distress variables, three model assumptions had to be met in

order to conclude any inference on the statistical results. These model assumptions are that the error terms have a normal distribution, constant variance, and have linearity. The model assumptions are determined through graphical diagnostics produced by the SAS statistical software package. If the graphical diagnostics do not appear to meet model assumptions, then a transformation is made to the model and the model assumptions are re-evaluated. A transformation to the model requires defining a new response variable, which typically is a change to the original response variable. It is determined through a statistical method called the box-cox approach and is implemented in the form of a logarithmic or an exponential change to the original response variable. If a transformation was required to meet the model assumptions, it is referred to as applying remedial measures to the data set.

Lastly, for each data set considered it must be noted, that higher influential variables such as the condition index (PCI and RSL) and the total surface area of a segment were not included in the model. The reasoning behind their exclusion is derived from the fact that they were an influential observation, and would thus shadow any possible investigation of the effect the individual distresses the economic analysis was sensitive to.

4.2.1 Latin-Hypercube Data Set for Micro PAVER™

The results from the previously discussed LHS data set that was input into the Micro PAVER™ software and statistically modeled through the Analysis of Covariance (ANCOVA) are illustrated in Table 4.2. In Table 4.2, the significant model p-values are highlighted in blue, while the significant variables of interest (pavement distress, severity and pavement distress and severity interaction) are highlighted in green.

As illustrated in Table 4.2 above, each row indicates the ANCOVA results for the distress variable, its respective severity and the interaction effect of both distress and severity on the response of variable of estimated recommended M&R cost. The model p-values that are significant to a 95% confidence interval are alligator cracking, block cracking, edge cracking, shoving, slippage cracking, swell and raveling. However, these results only allowed the consideration of the distress as significant. The next phase of consisted of evaluating the significance of the distress variable, distress severity and the distress/severity interaction, respectively.

Table 4.3 summarizes the input distresses, severity and interaction effects that were found to be the most sensitive to the estimated recommended M&R cost. The distresses of alligator cracking, block cracking, shoving, slippage cracking and raveling were all significant to the effect they had on the recommended M&R cost. The severity was only found significant in alligator cracking, block cracking and shoving. Lastly the interaction of distress and severity was found significant block cracking, shoving and raveling.

Again, the distresses the distresses that resulted in a significant model p-value but were not considered were edge cracking and swell. This is due to the variables of interest having p-values not significant to a 95% confidence interval.

Table 4.2 LHS ANCOVA Results

Distress Definition	Severity Levels	Model p-Value	R^2	Type III SS		
				Distress p-value	Severity p-value	Interaction p-value
Alligator Cracking	L, M, H	0.0317	0.0458	0.0052	0.0472	0.9232
Bleeding	L, M, H	0.7869	0.0107	0.9247	0.5612	0.6422
Block Cracking	L, M, H	0.0007	0.0761	0.0081	0.0428	0.0071
Bumps/Sags	L, M, H	0.1420	0.0321	0.0718	0.3646	0.7482
Corrugation	L, M, H	0.2685	0.0255	0.0787	0.4575	0.8419
Depression	L, M, H	0.0542	0.0411	0.0192	0.2514	0.1063
Edge	L, M, H	0.0227	0.0486	0.1839	0.6021	0.2447
Joint Reflection Cracking	L, M, H	0.3088	0.0239	0.0909	0.8179	0.5311
Lane Shoulder Drop-off	L, M, H	0.1087	0.0347	0.004	0.3254	0.8639
Longitudinal/Transverse Cracking	L, M, H	0.3222	0.0234	0.0342	0.4128	0.8088
Patching/Utility Cuts	L, M, H	0.2117	0.0280	0.2999	0.072	0.6943
Polished Aggregate	N/A	0.0507	0.0128	0.0507	N/A	N/A
Potholes	L, M, H	0.1966	0.0288	0.9973	0.7521	0.7688
Railroad Crossing/Cattle Guard	L, M, H	0.1596	0.0309	0.057	0.4278	0.783
Rutting	L, M, H	0.8293	0.0096	0.417	0.6328	0.7034
Shoving	L, M, H	<.0001	0.1763	<.0001	0.0053	0.001
Slippage Cracking	L, M, H	0.0044	0.0619	0.0024	0.2113	0.0794
Swell	L, M, H	0.0216	0.0490		0.7694	0.291
Raveling	M,H	0.0018	0.0562	0.0041	0.203	0.0029
Weathering	L, M, H	0.0600	0.0402	0.2756	0.0222	0.053

`

Table 4.3 Summary of Sensitivity in LHS ANCOVA

Input Variable	Model p-value	Distress	Severity	Interaction
Alligator Cracking	0.0317	Significant	Significant	Non-Significant
Block Cracking	0.0007	Significant	Significant	Significant
Shoving	<.0001	Significant	Significant	Significant
Slippage Cracking	0.0044	Significant	Non-Significant	Non-Significant
Raveling	0.0018	Significant	Non-Significant	Significant

4.2.2 Smithfield Data Set for Micro PAVER™

The data set developed from the City of Smithfield pavement network consisted of 260 observations that were input into the Micro PAVER™ software package. The economic analysis was conducted within the Micro PAVER™ software package, and the results of estimated recommended M&R cost were modeled as the response variables while the input distresses and their respective severity were the predictor variables.

The ANCOVA results presented denote the results after each individual distress, and its respective covariate of severity were tested for their effect on the response variable of estimated recommended M&R cost individually. Similarly to the LHS data set, in order to conclude a significant effect the model p-value as well as the variables of interest required a significant p-value 95% confidence interval.

The ANCOVA results are shown in Table 4.4. The Smithfield sample set differs from the LHS in that not all distress variables were observed, and thus not all 20 were available for analysis. The distresses of alligator cracking was found to be the only significant distress in the sample set. The severity was found to have the highest effect on the recommended M&R cost, as neither the distress nor interaction where found to be significant.

Table 4.4 Smithfield ANCOVA Results

Distress Definition	Severity Levels	Model P-Value	R-Square	Type III SS		
				Distress p-value	Severity p-value	Interaction p-value
Alligator Cracking	L, M, H	<.0001	0.1860	0.6964	<.0001	0.8910
Bleeding	L, M, H	0.6201	0.0173	0.0887	0.6288	0.2255
Block Cracking	L, M, H	0.9318	0.0052	0.9914	0.5564	0.9505
Bumps/Sags	L, M, H	-	-	-	-	-
Corrugation	L, M, H	-	-	-	-	-
Depression	L, M, H	0.9895	0.0022	0.7486	0.8343	0.7141
Edge	L, M, H	0.0778	0.0437	0.4536	0.1409	0.3214
Joint Reflection Cracking	L, M, H	0.8200	0.0015	0.9666	0.7161	N/A
Lane Shoulder Drop-off	L, M, H	-	-	-	-	-
Longitudinal/Transverse Cracking	L, M, H	0.3776	0.0250	0.9903	0.1092	0.9915
Patching/Utility Cuts	L, M, H	0.7427	0.0137	0.9915	0.3459	0.9970
Polished Aggregate	N/A	-	-	-	-	-
Potholes	L, M, H	0.9512	0.0004	0.9917	0.8776	-
Railroad Crossing/Cattle Guard	L, M, H	-	-	-	-	-
Rutting	L, M, H	0.9808	0.0007	0.9857	0.8072	-
Shoving	L, M, H	-	-	-	-	-
Slippage Cracking	L, M, H	-	-	-	-	-
Swell	L, M, H	-	-	-	-	-
Raveling	M,H	0.9400	0.0005	0.9997	0.9386	-
Weathering	L, M, H	0.4935	0.0210	0.6001	0.9900	0.9475

In Table 4.4, the significant model p-values are highlighted in blue, while the significant variables of interest (pavement distress, severity and pavement distress and severity interaction) are highlighted in green. As shown from results in Table 4.4, in the Smithfield sample set, the only significant distress that the estimated recommended M&R cost was sensitive to at the 95% confidence interval was the alligator severity. This result is summarized in Table 4.5.

Table 4.5 Summary of Sensitivity in Smithfield ANCOVA

Input Variable	Model P-value	Distress	Severity	Interaction
Alligator Cracking	<.0001	Non-Significant	Significant	Non-Significant

4.2.3 Tremonton Data Set for Micro PAVER™

The data set generated from the City of Tremonton pavement network consisted of 224 observations that were input into the Micro PAVER™ software package. The economic analysis was conducted within the Micro PAVER™ software package, and the results of estimated recommended M&R cost were modeled as the response variables while the input distresses and their respective severity where the predictor variables.

The ANCOVA results that were presented denote the results after each individual distress and its respective covariate of severity was tested for its effect on the response variable of estimated recommended M&R cost. The ANCOVA results are shown in Table 4.6. The Tremonton sample set, similar to the Smithfield sample set differs from the LHS in that not all distress variables were observed, and thus not all 20 were available for sensitivity analysis.

Table 4.6 Tremonton ANCOVA Results

Distress Definition	Severity Levels	Model P-Value	R-Square	Type III SS		
				Distress p-value	Severity p-value	Interaction p-value
Alligator Cracking	L, M, H	<.0001	0.5604	<.0001	0.0849	0.2953
Bleeding	L, M, H	<.0001	0.1977	<.0001	0.1316	<.0001
Block Cracking	L, M, H	-	-	-	-	-
Bumps/Sags	L, M, H	-	-	-	-	-
Corrugation	L, M, H	-	-	-	-	-
Depression	L, M, H	0.9447	0.0017	1.0000	0.7503	-
Edge	L, M, H	0.1220	0.0321	0.6014	0.5646	0.2896
Joint Reflection Cracking	L, M, H	-	-	-	-	-
Lane Shoulder Drop-off	L, M, H	-	-	-	-	-
Longitudinal/Transverse Cracking	L, M, H	0.0095	0.0735	0.1092	0.7817	0.1583
Patching/Utility Cuts	L, M, H	0.4357	0.0262	0.2329	0.2727	0.1313
Polished Aggregate	N/A	-	-	-	-	-
Potholes	L, M, H	-	-	-	-	-
Railroad Crossing/Cattle Guard	L, M, H	-	-	-	-	-
Rutting	L, M, H	-	-	-	-	-
Shoving	L, M, H	-	-	-	-	-
Slippage Cracking	L, M, H	-	-	-	-	-
Swell	L, M, H	-	-	-	-	-
Raveling	M,H	-	-	-	-	-
Weathering	L, M, H	0.0248	0.0631	0.8646	0.8486	0.8891

In Table 4.6, the significant model p-values are highlighted in blue, while the significant variables of interest (pavement distress, severity and pavement distress and severity interaction) are highlighted in green. Based on results shown in Table 4.6 for the Tremonton sample set, the significant distresses that were the most sensitive to the estimated recommended M&R cost at the 95% confidence interval were alligator and bleeding. These results are summarized in Table 4.7.

Table 4.7 Summary of Sensitivity in Tremonton ANCOVA

Input Variable	Model p-value	Distress	Severity	Interaction
Alligator Cracking	<.0001	Significant	Non-Significant	Non-Significant
Bleeding	<.0001	Significant	Non-Significant	Significant

Again, the distresses the distresses that resulted in a significant model p-value but were not considered were Longitudinal/Transverse cracking, and weathering. This is due to the variables of interest having p-values not significant to a 95% confidence interval.

4.2.4 Micro PAVER™ Software Results Summary and Conclusions

The ANCOVA results of the pavement condition data input into the Micro PAVER™ software package resulted in varying responses. Table 4.8 summarizes the results of the models used to determine the sensitivity the economic analysis had on the distress variables. In Table 4.8, the illustrated variables of interest are summarized based on the significant p-value of each variable after meeting the previous constraint of having a significant model p-value. Thus, if a variable p-value was found to be significant but the model p-value was not significant, it was not considered as sensitive and thus, was not considered to have an effect on the results of the estimated M&R cost.

Table 4.8 Summary of Sensitive Distresses for Micro PAVER™ Sample Sets

LHS Sample Set			Smithfield Sample Set			Tremonton Sample Set		
Distress	**Severity**	**Interaction**	**Distress**	**Severity**	**Interaction**	**Distress**	**Severity**	**Interaction**
Alligator Cracking	L, M, H	D1 X S1	Alligator Cracking	L, M, H	D1 X S1	Alligator Cracking	L, M, H	D1 X S1
Bleeding	L, M, H	D2 X S2	Bleeding	L, M, H	D2 X S2	Bleeding	L, M, H	D2 X S2
Block Cracking	L, M, H	D3 X S3	Block Cracking	L, M, H	D3 X S3	Block Cracking	L, M, H	D3 X S3
Bumps/Sags	L, M, H	D4 X S4	Bumps/Sags	L, M, H	D4 X S4	Bumps/Sags	L, M, H	D4 X S4
Corrugation	L, M, H	D5 X S5	Corrugation	L, M, H	D5 X S5	Corrugation	L, M, H	D5 X S5
Depression	L, M, H	D6 X S6	Depression	L, M, H	D6 X S6	Depression	L, M, H	D6 X S6
Edge	L, M, H	D7 X S7	Edge	L, M, H	D7 X S7	Edge	L, M, H	D7 X S7
Joint Reflection Cracking	L, M, H	D8 X S8	Joint Reflection Cracking	L, M, H	D8 X S8	Joint Reflection Cracking	L, M, H	D8 X S8
Lane Shoulder Drop-off	L, M, H	D9 X S9	Lane Shoulder Drop-off	L, M, H	D9 X S9	Lane Shoulder Drop-off	L, M, H	D9 X S9
Longitudinal/Transverse Cracking	L, M, H	D10 X S10	Longitudinal/Transverse Cracking	L, M, H	D10 X S10	Longitudinal/Transverse Cracking	L, M, H	D10 X S10
Patching/Utility Cuts	L, M, H	D11 X S11	Patching/Utility Cuts	L, M, H	D11 X S11	Patching/Utility Cuts	L, M, H	D11 X S11
Polished Aggregate	N/A	D12 X S12	Polished Aggregate	N/A	D12 X S12	Polished Aggregate	N/A	D12 X S12
Potholes	L, M, H	D13 X S13	Potholes	L, M, H	D13 X S13	Potholes	L, M, H	D13 X S13
Railroad Crossing/Cattle Guard	L, M, H	D14 X S14	Railroad Crossing/Cattle Guard	L, M, H	D14 X S14	Railroad Crossing/Cattle Guard	L, M, H	D14 X S14
Rutting	L, M, H	D15 X S15	Rutting	L, M, H	D15 X S15	Rutting	L, M, H	D15 X S15
Shoving	L, M, H	D16 X S16	Shoving	L, M, H	D16 X S16	Shoving	L, M, H	D16 X S16
Slippage Cracking	L, M, H	D17 X S17	Slippage Cracking	L, M, H	D17 X S17	Slippage Cracking	L, M, H	D17 X S17
Swell	L, M, H	D18 X S18	Swell	L, M, H	D18 X S18	Swell	L, M, H	D18 X S18
Raveling	M,H	D19 X S19	Raveling	M,H	D19 X S19	Raveling	M,H	D19 X S19
Weathering	L, M, H	D20 X S20	Weathering	L, M, H	D20 X S20	Weathering	L, M, H	D20 X S20

The LHS sample set showed that the most sensitive input variables were the alligator cracking along with its severity level. All levels of bleeding and shoving were found to be have an effect on the recommended M&R cost. The distress of slippage cracking was significant as well as raveling and the interaction of raveling and its severity level. For the City of Smithfield sample set, only the severity level of alligator cracking was found to significantly affect the M&R economic estimate. Finally, for the City of Tremonton, the severity level of alligator cracking as well as bleeding and the interaction of bleeding and its severity level had an effect on the recommended M&R cost, thus the economic analysis can be determined to be sensitive to the aforementioned distresses.

The amount of variation explained by each sensitive distress considered in the table above is illustrated in Table 4.9 below. The distresses shown are the distresses that met both constraints of having a significant model p-value and variables of interest with significant p-values. The R-Square value is the variation explained by the considered variables in the previously analyzed models. Thus, the R-square illustrates how much influence the individual variables of interest have on the software's economic analysis.

Table 4.9 Summary of R-Square Values for Individual Distresses to Which the Economic Analysis Is Sensitive

LHS Sample Set		**Smithfield Sample Set**		**Tremonton Sample Set**	
Distress	**R-Square**	**Distress**	**R-Square**	**Distress**	**R-Square**
Alligator Cracking	0.0458	Alligator Cracking	0.1860	Alligator Cracking	0.5604
Bleeding	0.0107			Bleeding	0.1977
Shoving	0.1763				
Slippage Cracking	0.0619				
Raveling	0.0562				

4.2.5 Latin-Hypercube Data Set for TAMS

The LHS data set consisted of 300 observations. The results of the TAMS economic analysis was modeled in the SAS statistical software package as a general linear regression model. Figure 4.1 illustrates the model diagnostics after applying remedial measures, as discussed in section 4.2 Data Analysis. In Figure 4.1, the three graphical diagnostics of interest are normal distribution, constant variance, and linearity which are located in the left-hand column. Tables 4.10 and 4.11 illustrate the model results and the sensitivity of the economic M&R results to the nine TAMS input variables as well as one additional interaction of longitudinal and transverse cracking. This interaction was added in order to further investigate its effect, as the Micro PAVER^{TM} software package considers these two distresses as only one input variable.

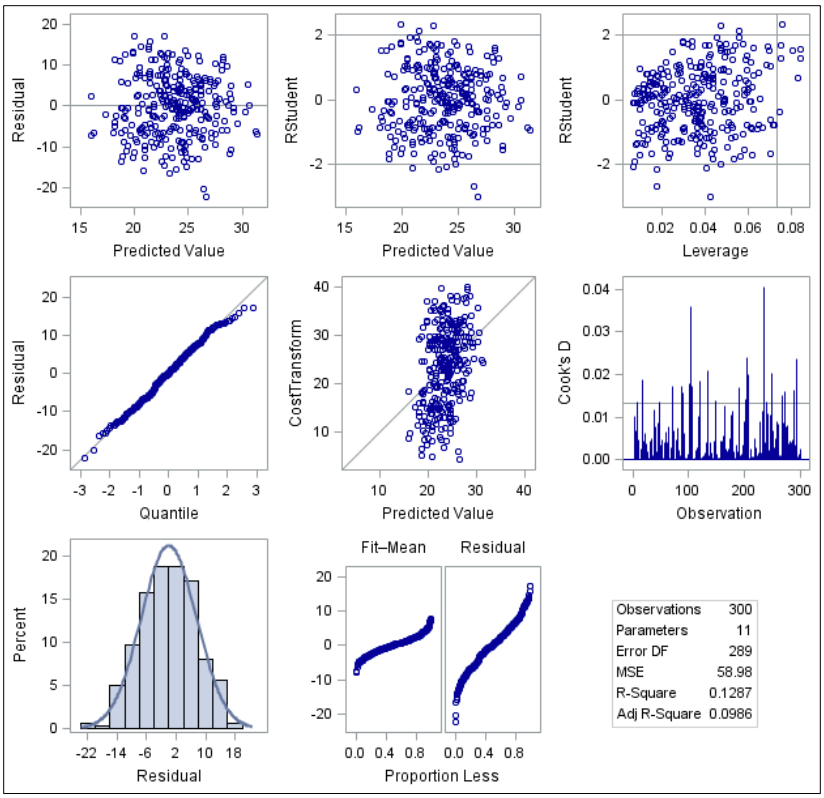


Figure 4.1 Model Diagnostics for LHS-TAMS Regression

Table 4.10 Model Results for LHS-TAMS Regression

Model F-Value	Model P-Value	Adj R-Square	R-Square
4.27	<.0001	0.0986	0.1287

Table 4.11 Parameter Estimates for LHS-TAMS Regression

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	13.07785	2.59135	5.05	<.0001
Fatigue	1	0.75177	0.16852	4.46	<.0001
Longitudinal	1	0.17757	0.30850	0.58	0.5653
Transverse	1	0.09989	0.31790	0.31	0.7536
Block	1	0.58725	0.16886	3.48	0.0006
Patching/Potholes	1	0.07429	0.16916	0.44	0.6609
Edge	1	0.18642	0.16972	1.10	0.2729
Rutting	1	0.81649	0.46476	1.76	0.0800
Roughness	1	1.01289	0.46647	2.17	0.0307
Drainage	1	-0.0942	0.46483	-0.20	0.8395
Longitudinal X Transverse	1	-0.02192	0.05935	-0.37	0.7122

The model diagnostics in Figure 4.1 illustrate that model assumptions appear to be met, the plots in the left hand column from top to bottom illustrate acceptable constant variance, acceptable linearity, and acceptable normal distribution. The R-square value in Table 4.10 denotes that about 12.87% of the variation in the model is explained when all of the input variables are present. As Table 4.11 illustrates, the input factors of greater significance are the ones that the estimated M&R recommended cost is the most sensitive to. In the LHS TAMS regression, fatigue cracking, block cracking and roughness where the most sensitive to estimated M&R recommended cost.

4.2.6 Smithfield Data Set for TAMS

The data set generated from the City of Smithfield pavement network consisted of 260 observations. The results of the TAMS economic analysis was modeled in the SAS statistical software package as a general linear regression model. Figure 4.2 illustrates the model diagnostics after applying remedial measures, as discussed in section 4.2 Data Analysis. In Figure 4.2, the three graphical diagnostics of interest are normal distribution, constant variance, and linearity which are located in the left-hand column. Tables 4.12 to 4.13 illustrate the model results and the sensitivity of the economic M&R results to the nine TAMS input variables as well as one additional interaction of longitudinal and transverse cracking. This interaction was added in order to further investigate its effect, as the Micro PAVER^{TM} software package considers these two distresses as one input.

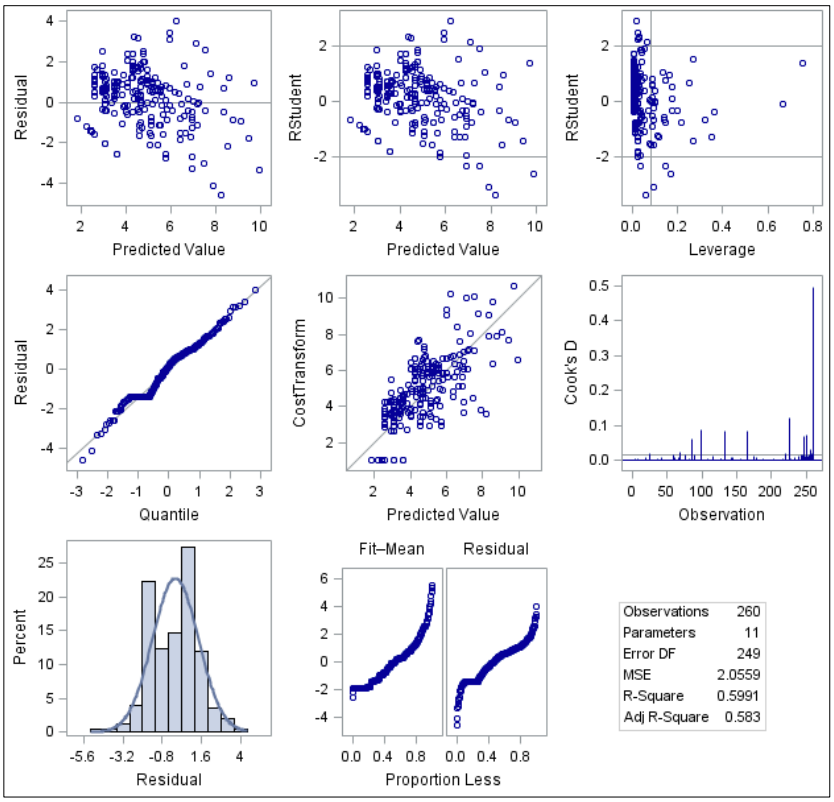


Figure 4.2 Model Diagnostics for Smithfield-TAMS Regression

Table 4.12 Model Results for Smithfield-TAMS Regression

Model F-Value	Model P-Value	Adj R-Square	R-Square
37.21	<.0001	0.583	0.5991

Table 4.13 Parameter Estimates for Smithfield-TAMS Regression

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	2.41537	0.14601	16.54	<.0001
Fatigue	1	0.64630	0.07531	8.58	<.0001
Longitudinal	1	0.62017	0.10901	5.69	<.0001
Transverse	1	0.53406	0.05438	9.82	<.0001
Block	1	0.79511	0.19668	4.04	<.0001
Patching/Potholes	1	0.13362	0.06484	2.06	0.0404
Edge	1	0.01218	0.10719	0.11	0.9096
Rutting	1	1.86012	0.41727	4.46	<.0001
Roughness	1	0.61983	0.19381	3.20	0.0016
Drainage	1	-0.20790	0.27138	-0.77	0.4444
Longitudinal X Transverse	1	-0.12458	0.02184	-5.70	<.0001

The model diagnostics in Figure 4.2 illustrate that model assumptions appear to be roughly met, the plots in the left hand column from top to bottom illustrate satisfactory constant variance, satisfactory linearity, and satisfactory normal distribution. These results are expected, given the nature of the data for a local government which does not guarantee every distress will be observed. On the other hand the LHS sample set is designed to account for every distress variable. The R-square value in Table 4.16 denotes that about 60% of the variation in the model is explained when all of the input variables are included. The input factors of greatest significance are the ones that have the most impact on predicting the estimated M&R recommended cost. In the Smithfield TAMS regression, Table 4.13 indicates that all of the distress except Edge Cracking, and Drainage were found to significantly impact the estimated M&R recommended cost.

For the Smithfield sample set for the TAMS software, the input variables that most affected the estimated recommended M&R cost at the 95% confidence interval are fatigue cracking, longitudinal cracking, transverse cracking, block cracking, rutting, and the interaction of longitudinal and transverse cracking. The distress of Patching/Potholes and Roughness were also found to be significant, but not to the degree of the previously listed distresses based on the p-values for their model parameters estimates.

4.2.7 Tremonton Data Set for TAMS

The sample set developed from the City of Tremonton pavement condition data consisted of 224 observations. The results of the TAMS economic analysis was modeled in the SAS statistical software package as a general linear regression model. Figure 4.3 illustrates the model diagnostics after applying remedial measures, as discussed in section 4.2 Data Analysis. In Figure 4.3, the three graphical diagnostics of interest are normal distribution, constant variance, and linearity which are located in the left-hand column. Tables 4.14 to 4.15 illustrate the model results and the sensitivity of the economic M&R results to the nine TAMS input variables as well as one additional interaction of longitudinal cracking and transverse cracking. This interaction was added in order to further investigate its effect, as the Micro PAVER™ software package considers these two distresses as only one input variable.

The Tremonton City sample set was unique because it was composed of data from a significantly smaller local government, and one that may be similar to many local governments throughout the United States. The issue was seen in the distress samples collected that did not represent the entire available distresses observations. And thus, prevented additional analysis to be performed simply due to the lack of data.

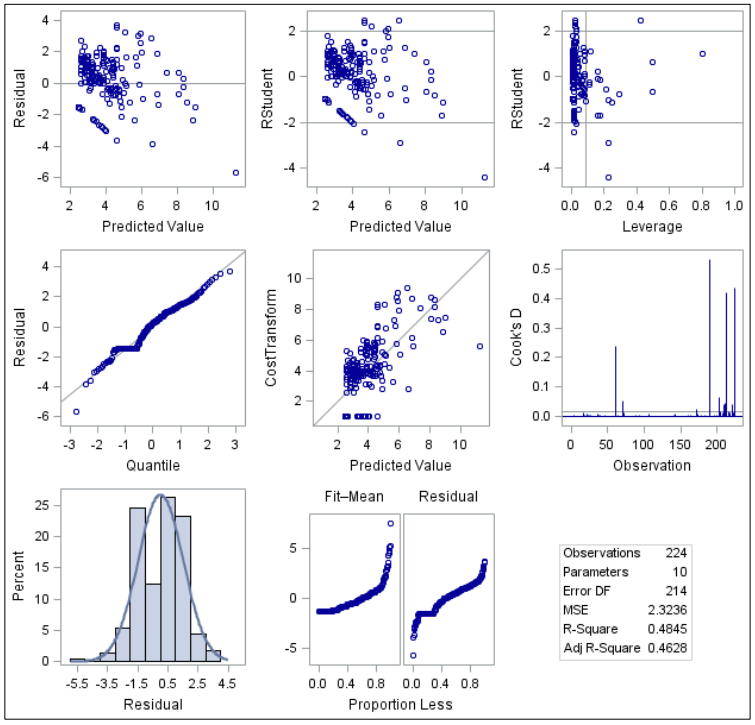


Figure 4.3 Model Diagnostics for Tremonton-TAMS Regression

Table 4.14 Model Results for Tremonton-TAMS Regression

Model F-Value	Model P-Value	Adj R-Square	R-Square
22.35	<.0001	0.4628	0.4845

Table 4.15 Parameter Estimates for Tremonton-TAMS Regression

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	2.48327	0.15465	16.06	<.0001
Fatigue	1	0.71122	0.07265	9.79	<.0001
Longitudinal	1	0.44622	0.10942	4.08	<.0001
Transverse	1	0.34165	0.07215	4.74	<.0001
Patching/Potholes	1	0.10119	0.08788	1.15	0.2508
Edge	1	0.09120	0.14454	0.63	0.5287
Rutting	1	-0.57297	1.54980	-0.37	0.712
Roughness	1	2.79928	0.54445	5.14	<.0001
Drainage	1	0.46632	0.71294	0.65	0.5138
Longitudinal X Transverse	1	-0.08641	0.02484	-3.48	0.0006

The model diagnostics in Figure 4.3 illustrate that model assumptions appear to be roughly met, the plots in the left hand column from top to bottom illustrate satisfactory constant variance, satisfactory linearity, and satisfactory normal distribution. These results are expected, given the nature of the data for a local government which does not guarantee every distress will be observed. On the other hand the LHS sample set is designed to account for every distress variable. The R-square value in Table 4.14 denotes that about 48% of the variation in the model is explained when all of the input variables are included in the regression model. From Table 4.15 it is seen that in the Tremonton TAMS regression, Fatigue, Longitudinal, Transverse, Roughness and the interaction of Longitudinal and Transverse were found to be the variables that the estimated M&R recommended cost was most sensitive to. The distress of block cracking, was not analyzed because no block cracking distresses where observed in the city of Tremonton.

For the Tremonton sample set for the TAMS software, the input variables that were the estimated recommended M&R cost was most sensitive to at the 95% confidence interval are fatigue cracking, longitudinal cracking, transverse cracking, roughness and the interaction of longitudinal and transverse cracking.

4.2.8 TAMS Software Results Summary

The general linear regression model of the pavement condition data input into the TAMS software package resulted in varying responses. Table 4.16 summarizes the input distress factors per data set that the response of estimated recommended treatment cost were sensitive to at the 95% confidence interval. In Table 4.16, all of the considered distresses are listed while the sensitive distress is highlighted in blue.

Table 4.16 Summary of Sensitive Distresses for TAMS Sample Sets

LHS Sample Set	Smithfield Sample Set	Tremonton Sample Set
Fatigue	Fatigue	Fatigue
Longitudinal	Longitudinal	Longitudinal
Transverse	Transverse	Transverse
Block	Block	Block
Patching/Potholes	Patching/Potholes	Patching/Potholes
Edge	Edge	Edge
Rutting	Rutting	Rutting
Roughness	Roughness	Roughness
Drainage	Drainage	Drainage
Longitudinal X Transverse	Longitudinal X Transverse	Longitudinal X Transverse

As illustrated in Table 4.16, fatigue cracking is a sensitive input factor in all three data sets. Longitudinal and transverse cracking as well as their interaction are only sensitive in the Smithfield and Tremonton sample sets. Block cracking is sensitive in the LHS and the Smithfield sample sets. Rutting is only sensitive in the Smithfield sample set, while roughness is sensitive in both the LHS and the Tremonton sample sets. The interaction of fatigue, block and roughness was only found to be sensitive in the LHS sample set.

The variation of results produced by the data sets can be attributed to the composition of the data sets. The LHS sample set, is a hypothetical data set that considered each available distress equally and thus provided the significant distresses the economic analysis sensitive to. On the other hand, the Tremonton and Smithfield data sets had a composition of actual observed distresses in a local government setting, an outcome which is more likely to be observed in real data sets for city governments. Distresses that effect the structural durability of a pavement are fatigue cracking and block cracking, while roughness is an influential measurement based on ride that is less likely to be observed due to the nature of the data collection procedure (slow driving

conditions to observe visible pavements distresses). The local government sample sets acknowledged fatigue as a significant distress the economic analysis was sensitive to. The difference in significant distresses can be derived from the data collection procedure and visible distresses of each pavement segment. If there were not enough observations of a certain distress, the statistical procedure would be unable to identify a significant distress to which the economic analysis was significant.

Table 4.17 summarizes the R-square value for each of the evaluated regression models. In the table below, the percentage of variation explained is reported by all of the distresses that were considered significant.

Table 4.17 Summary of R-Square Values for Linear Regression Models

	R-Square of LHS Sample Set	**R-Square of Smithfield Sample Set**	**R-Square of Tremonton Sample Set**
All Variables	0.1287	0.5991	0.4845

4.3 Discussion of Sensitivity Analysis

Using the ANCOVA and the general linear regression statistical methods, each of the input distresses for the PMS software packages of Micro PAVER™ and TAMS were tested for model output sensitivity. Each data set resulted in identifying varying pavement distresses to which the response variable of estimated recommended M&R cost was sensitive.

A common distress that was found to significantly affect the response variable in all of the data sets was some degree of alligator cracking in the Micro PAVER™ software package and similarly the fatigue distress in TAMS. This similarity can be explained by the typical causes of alligator cracking/fatigue, which include continuous heavy loading

and possible sub-surface failure. Essentially, this type of distress is observed due to a damaged or weak pavement structure. High observations of severe alligator cracking or fatigue are an indication of needed rehabilitative or reconstructive maintenance, which results in a higher cost of M&R.

In the LHS sample sets for TAMS and Micro PAVER™, block cracking was also found to be a highly significant distress. Similar to the distress of fatigue, block cracking is addressed through rehabilitative or reconstructive maintenance and is present in the entire pavement segment when observed, resulting in higher costs of M&R. The effect of roughness in TAMS and shoving in Micro PAVER™ relate as they are both observed and assessed based on ride quality. This observation suggests a possible indicator that both software packages may have a lower estimated recommended M&R costs output if the pavement surface is smooth. Slippage cracking and raveling were significant distresses in Micro PAVER™ that TAMS does not account for, however the presence of slippage cracking under the TAMS methodology could be a sign of early alligator cracking and be observed as such. Raveling, much like weathering, is a distress that accounts for "wearing away of the pavement surface due to a loss of asphalt or tar binder" (ASTM, 2007), although unaccounted for in TAMS, its presence could be beneficial to the economic analysis in the TAMS software package as the pavement surface wears even if no distresses are visible.

The LHS sample set was considered as a theoretical data set to observe the sensitivity of all available distress variables. Meaning that the sample was composed of equal observations of each distress in order to properly evaluate their significance. This provided information about the economic analysis' sensitivity to every available distress.

However in a typical local government assessment, obtaining a data set in which all distresses are present is not a common result. Thus, the data sets composed of the City of Smithfield and the City of Tremonton are a direct representation of a local government setting.

The common sensitive distress within both of the evaluated local governments' was that of alligator cracking/fatigue. The TAMS software package resulted in significant effects for observations of longitudinal cracking and transverse cracking, as well as their interaction. The distress of longitudinal and transverse cracking for the Micro PAVER™ data sets did not affect the response of estimated recommended treatment M&R cost.

In conclusion, in a local government setting the dominant distress that most affects the estimated recommended treatment M&R cost is alligator cracking/fatigue. Alligator cracking/fatigue is a distress that is taken into account in both PMS software packages, and is more closely associated with pavements that see continuous loading and possible sub-surface failure. Other distresses may be found to affect predicted M&R costs, as shown in the previous data sets, but their influence may depend on the structure of the additional distresses present in the local government sample set.

4.4 Summary and Recommendation

To address the proposed research question of, "what pavement distresses should local government technician's focus on in order to obtain a confident estimated recommended M&R cost?", it was determined that the response of estimated recommended M&R cost is the most sensitive to alligator cracking/fatigue cracking distress. Thus, it is recommended that local government technicians pay special attention to the distress of alligator cracking/fatigue as this distress variable has the greatest impact

on the outcome of the economic analysis portion of the PMS software packages of TAMS and Micro PAVER™.

The sensitivity analysis of both PMS software packages also allowed the comparison of the TAMS software package nine distress data collection approach to that of Micro PAVER™ software package 20 distress data collection approach. In terms of the response variable of estimated recommended treatment cost, the TAMS software package resulted in similar results for the dominant sensitive distress of alligator cracking/fatigue. While each data set resulted in varying sensitivity results, it is recommended that whatever PMS software package is used, in addition of paying close attention to alligator cracking/fatigue that each distress is also accounted for. Accounting for every input distress will increase the probability of obtaining results that resemble the LHS data set discussed earlier, allowing for future sensitivity analyses to possibly match the results of the LHS data set due to more distresses being accounted for.

CHAPTER 5

STATISTICAL MODELS FOR ECONOMIC ANALYSIS

5.1 Introduction

The previous chapter discussed the statistical results performed on the economic analysis output of two different PMS software packages. The TAMS software package and the Micro PAVER^{TM} software package were analyzed for the effect each distress variable had on the response of estimated recommended M&R cost. The sensitivity analysis for TAMS and Micro PAVER^{TM} was conducted through statistical methods of general linear regression and an analysis of covariance (ANCOVA), respectively. This chapter addresses the generated models from Chapter 4, focusing on significant distresses and discusses the feasibility of implementing such models in a local government data collection setting.

5.2 Research Question

As discussed in Chapter 4, the main research question this thesis answers is "*What attributes of a PMS should local governments focus on to provide adequate economic analysis estimates for their pavement network?"* This section discusses the subsequent question, "can a general statistical model be used to estimate a cost based solely on pavement distresses?" This section provides support to the main question that is addressed in Chapter 6.

5.3 Background to Research Question

Providing a general model to the response of estimated recommended M&R cost based on observed pavement distresses can be beneficial for engineering technicians collecting local government pavement distress data. The benefit can arise from comparing questionable observations during the pavement distress inventory process.

This section is intended to benefit engineering technicians responsible for observing and collecting pavement surface distress data. Often during the data collection process, one governing distress may be considered sufficient and is the only surface distress recorded. Conflicts arise when considering how additional distresses that are present, (but not the extent of others) may affect the economic analysis when either recorded or exempt.

The inclusion of additional distresses may not be considered as necessary by an engineering technician if it is assumed that a governing distress will control the pavement treatment recommendation and in turn, the cost estimate from the economic analysis. In situations where distresses or distress severities are in question, two conflicts may arise in the decision making process of an engineering technician. The first conflict lies in whether or not all distresses present should be recorded and the second is deciding between two borderline severities (L or M/ M or H). The decisions made during the data collection process directly influence the economic analysis' final estimates and recommendations. Therefore, an additional tool in the form of a regression model is presented to aid engineering technicians in making judgment calls in the field during the data collection process.

A regression model will first provide an outline of distresses that the economic analysis is sensitive to for a given local government, this will allow engineering technicians to know which pavement distresses have a higher influence in the pavement network and which they should take more care in evaluating. The model will also aid in assuring proper distress severities are called if an engineering technician is conflicted. By inputting the two values and identifying the difference, an engineering technician can then use personal judgment to conclude if the results of estimated M&R cost provided by the model represent what is being observed. By providing more tools and resources to the engineering technician. The initial steps of the PMS procedure can be expected to increase in quality, confidence and be representative of actual surface conditions which will in turn result in accurate economic analysis results.

The purpose of providing such models is to aid engineering technicians in making critical decisions during the data collection process. A quick input of distresses serves as a reference that can aid an engineering technician into determining if what the estimated result represents what is being observed on the actual pavement. For example, often times a brand new pavement may have negligible surface cracks that do not represent the entire pavement section, if these minimal distresses are recorded, the recommended M&R and estimated cost may not be representative or adequate for the overall analysis of the pavement network. The overall final judgment still rests on the engineering technician, however a predetermined model may serve as a tool to conclude a final decision of excluding a present minimal distress, or deciding between two severity levels.

5.4 Data Analysis

The data analysis presented here focuses on the TAMS software package data sets, as the objective is to simplify the observed pavement distresses. The goal of this analysis is to provide a model capable of estimating M&R cost solely based on observed distresses and distress severity. This analysis enhances the previously discussed data sets and the development of models with nonlinear variables. The SAS statistical software package was utilized to illustrate the proposed models.

Similar to the linear regression models used in the previous chapter the same approach will be used to develop models of the available data sets of LHS, Smithfield City and Tremonton City using the TAMS software package distress data and results. Thus, the same statistical model assumptions must be met in order to adequately determine the significant variables that are to be included in the final proposed model. These model assumptions are that the error terms have a normal distribution, constant variance, and have linearity. The model assumptions are determined through graphical diagnostics produced by the SAS statistical software package. If the graphical diagnostics do not appear to meet model assumptions, then a transformation is made to the model and the model assumptions are re-evaluated. A transformation to the model requires defining a new response variable, which typically is a change to the original response variable. It is determined through a statistical method called the box-cox approach and is implemented in the form of a logarithmic or an exponential change to the original response variable. If a transformation was required to meet the model assumptions, it is referred to as applying remedial measures to the data set.

For the following data sets, additional measures were taken in order to provide a model with nonlinear properties, and focus on significant pavement distresses. These measures allowed a model to be generated that included only the interaction of significant distresses as the predictor variables, narrowing down the distress observations to those the economic analysis was sensitive to.

5.4.1 Latin-Hypercube Data Set for TAMS

The LHS data set used in Chapter 4 was further analyzed for the model's sensitivity to the significant variables. A model consisting of only the input variables of fatigue cracking, block cracking, roughness and their interaction was examined. Figure 5.1 illustrates model diagnostics after applying remedial measures to the response variable of estimated M&R cost, as discussed in Section 5.4. Tables 5.1 and 5.2 illustrate the model results given the subset of significant input variables.

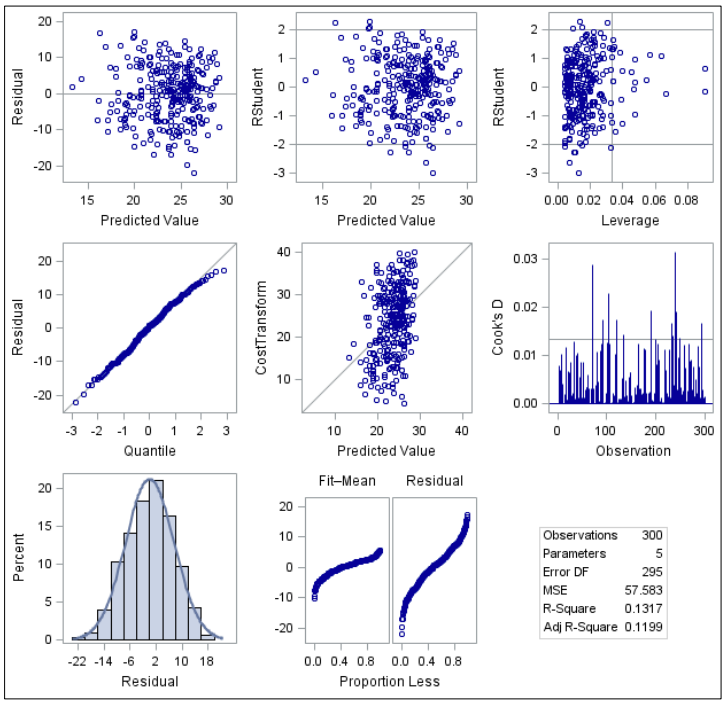


Figure 5.1 Model Diagnostics for LHS-TAMS Regression of Significant Variables

Table 5.1 Model Results for LHS-TAMS Regression of Significant Variables

Model F-Value	Model P-Value	Adj R-Square	R-Square
11.19	<.0001	0.1199	0.1317

Table 5.2 Parameter Estimates for LHS-TAMS Regression of Significant Variables

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	13.23153	1.77539	7.45	<.0001
Fatigue	1	1.07218	0.21273	5.04	<.0001
Block	1	0.91929	0.21577	4.26	<.0001
Roughness	1	1.9867	0.60664	3.27	0.0012
Fatigue X Block X Roughness	1	-0.04784	0.0195	-2.45	0.0147

The model diagnostics in the left hand column of Figure 5.1 illustrate that model assumptions appear to be met, the plots in the left hand column from top to bottom illustrate acceptable constant variance, acceptable linearity, and acceptable normal distribution. The R-square value in Table 5.1 denotes that about 13% of the variation in the model is explained when only the significant input variables and their interaction are present.

A general linear model composed of the considered pavement distresses with the included interaction and remedial measures is illustrated in Equation 5.1, as discussed previously remedial measures implies that a transformation was applied to the response variable in order to meet statistical model assumptions. In this case, the response variable of estimated recommended M&R cost was transformed by raising it to the 0.3 power.

$$Y'^{0.3} = 13.231 + 1.072(\text{Fatigue}) + 0.919(\text{Block}) + 1.987(\text{Roughness}) - 0.048(\text{FatigueXBlockXRoughness})$$

(Eq. 5.1)

In order to further analyze and simplify the model, the introduction of a nonlinear variable was introduced only taking into account the significant interaction of significant variables. The purpose of this model is to simplify the number of input variables and account for any possible nonlinearity in the existing data set.

Similarly through methods of linear regression, a new model was introduced which contained a nonlinear variable. This was done in order to view the fit of the model compared against actual data points from the LHS data set. Figure 5.2 illustrates the model diagnostics for the interaction of fatigue cracking, block cracking and roughness as well as the interaction of fatigue cracking, block cracking and roughness raised to the power of -2. Tables 5.3 to 5.4 illustrate the model results and parameter estimates, respectively.

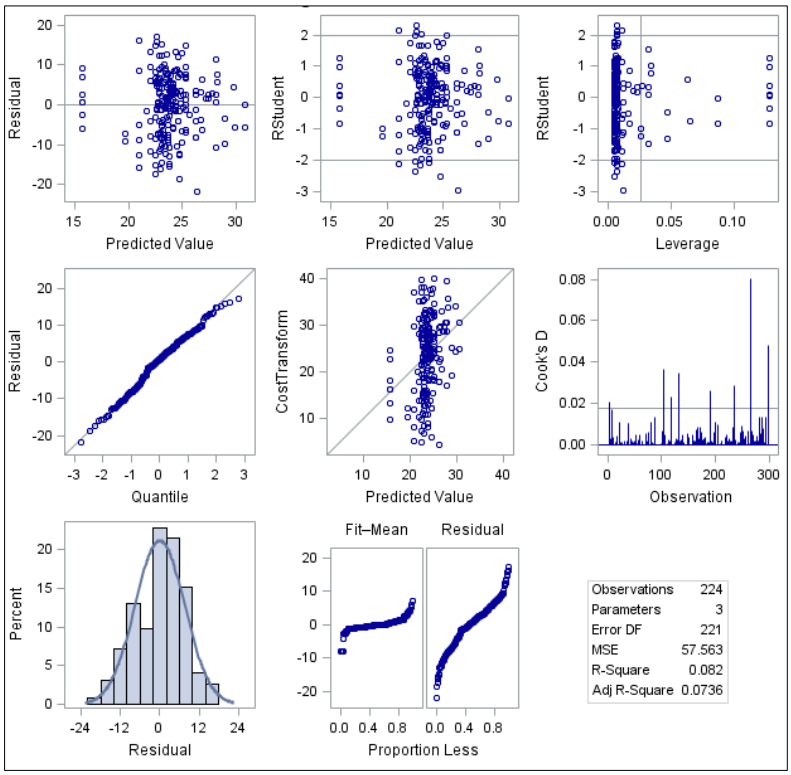


Figure 5.2 Model Diagnostics for LHS-TAMS Regression of Significant Interaction

Table 5.3 Model Results for LHS-TAMS Regression of Significant Interaction

Model F-Value	Model P-Value	Adj R-Square	R-Square
9.86	<.0001	0.0736	0.082

Table 5.4 Parameter Estimates for LHS-TAMS Regression of Significant Interaction

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	22.59703	0.78481	28.79	<.0001
Fatigue X Block X Roughness	1	0.03787	0.01276	2.97	0.0033
(Fatigue X Block X Roughness)$^{-2}$	1	-27.6089	11.72656	-2.35	0.0194

The model diagnostics in Figure 5.2 illustrate that model assumptions appear to be met the plots in the left hand column from top to bottom illustrate acceptable constant variance, acceptable linearity, and acceptable normal distribution. The R-square value in Table 5.3 denotes that about 8% of the variation in the model is explained when only the significant interaction and the nonlinear variable are included. The general linear model composed of the considered pavement distresses with the included interaction and remedial measures is illustrated in Equation 5.2, as discussed previously remedial measures implies that a transformation was applied to the response variable in order to meet statistical model assumptions. In this case, the response variable of estimated recommended M&R cost was transformed by raising it to the 0.3 power. Figure 5.3 illustrates the observed values plotted against the developed model.

$$\hat{Y}^{0.3} = 22.597 + 0.038(\text{FatigueXBlockXRoughness}) - 27.609(\text{FatigueXBlockXRoughness})^{-2}$$

(Eq. 5.2)

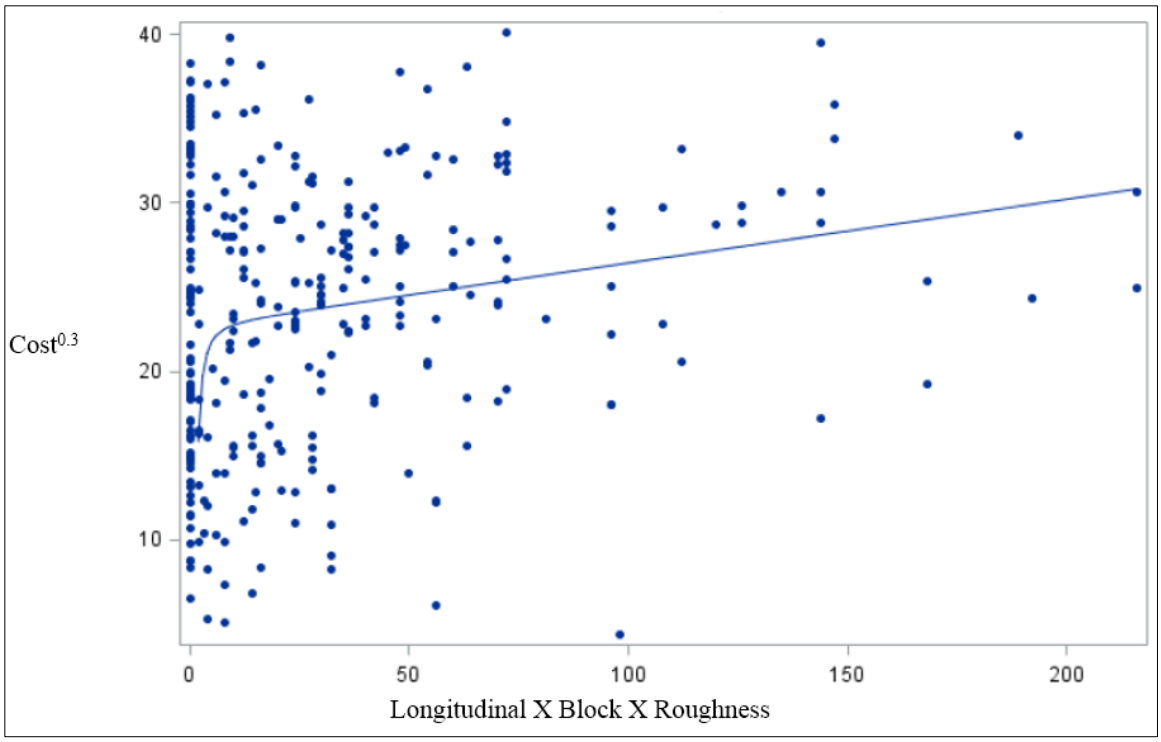


Figure 5.3 LHS-TAMS Regression of Significant Interaction Observed Values Against Predicted Model

In summary, the two proposed models offer an estimated M&R cost based on key significant distresses. The benefit for utilizing Equation 5.1 is that more variation is explained by the model over Equation 5.2, resulting in a higher R-square. However Equation 5.2 addresses possible nonlinearity in the data set. Both of the above models provide an estimated M&R cost based solely on distresses, and they both serve as a tool for engineering technicians in the field. If one model is to be recommended for the LHS data set, it would be the model in Equation 5.1 due to the higher R-square value and the same number of input variables required for a response as Equation 5.2. What the model in Equation 5.2 represents is a deeper investigation and results that a nonlinear variable does not necessarily help address the variation.

5.4.2 Smithfield Data Set for TAMS

The Smithfield data set used in Chapter 4 was further analyzed for the model's sensitivity to the significant variables; a model consisting of only the sensitive input factors was examined. Figure 5.4 illustrates model diagnostics after applying remedial to the response variable of estimated M&R cost, as discussed in Section 5.4. Tables 5.5 and 5.6 illustrate the model results and the sensitivity of the input variables.

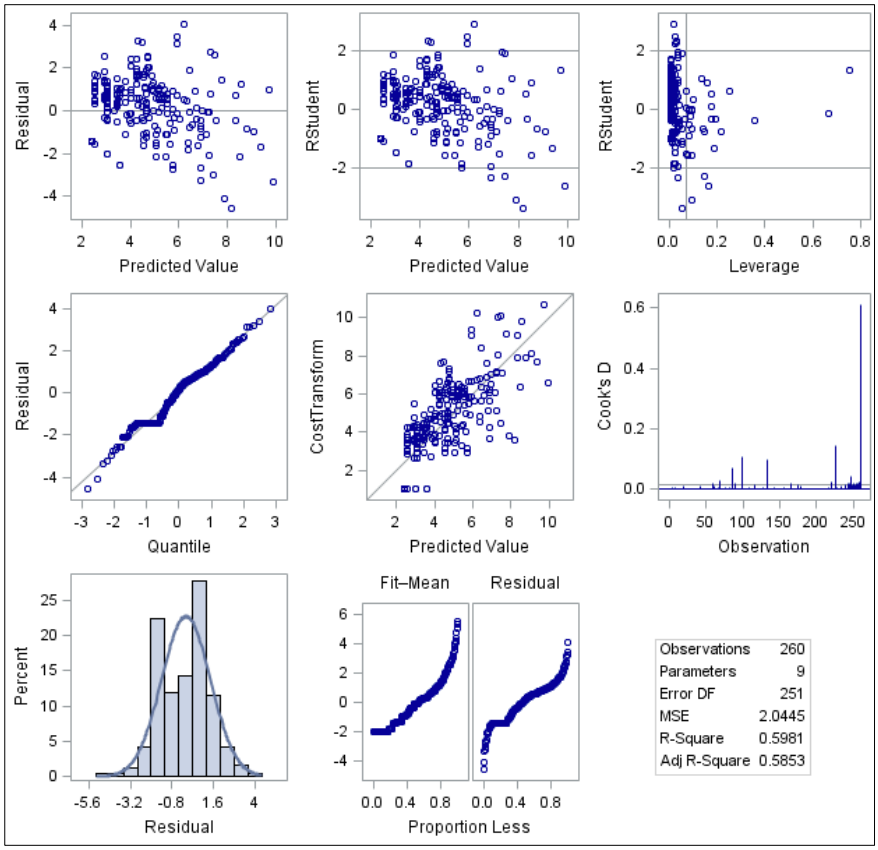


Figure 5.4 Model Diagnostics for Smithfield-TAMS Regression of Significant Variables

Table 5.5 Model Results for Smithfield-TAMS Regression of Significant Variables

Model F-Value	Model P-Value	Adj R-Square	R-Square
46.69	<.0001	0.5853	0.5981

Table 5.6 Parameter Estimates for Smithfield-TAMS Regression

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	2.40524	0.14502	16.59	<.0001
Fatigue	1	0.64271	0.07496	8.57	<.0001
Longitudinal	1	0.62639	0.10841	5.78	<.0001
Transverse	1	0.53454	0.05369	9.96	<.0001
Block	1	0.79881	0.19606	4.07	<.0001
Patching/Potholes	1	0.13179	0.06415	2.05	0.041
Rutting	1	1.86755	0.41571	4.49	<.0001
Roughness	1	0.61796	0.19319	3.20	0.0016
Longitudinal X Transverse	1	-0.12476	0.02178	5.73	<.0001

The model diagnostics in Figure 5.4 illustrate that model assumptions appear to be roughly met, the plots in the left hand column from top to bottom illustrate satisfactory constant variance, satisfactory linearity, and satisfactory normal distribution. These results are expected, given the nature of the data for a local government which does not guarantee every distress will be observed. The R-square value in Table 5.5 denotes that about 60% of the variation in the model is explained when only the significant input variables and their interaction are included. A general linear model composed of the considered pavement distresses with the included interaction and remedial measures is illustrated in Equation 5.3, as discussed previously remedial measures implies that a transformation was applied to the response variable in order to meet statistical model assumptions. In this case, the response variable of estimated recommended M&R cost was transformed by raising it to the 0.2 power.

$$\hat{Y}^{0.2} = 2.405 + 0.643(\text{Fatigue}) + 0.626(\text{Longitudinal}) + 0.534(\text{Transverse}) + 0.798(\text{Block}) + 0.132(\text{Patching|Potholes}) + 1.86755(\text{Rutting}) + 0.618(\text{Roughness}) - 0.125(\text{LongitudinalXTransverse})$$

(Eq. 5.3)

In order to further analyze and simplify the model, the introduction of a nonlinear variable was introduced only taking into account the significant interaction of significant variables. Figure 5.6 illustrates the model diagnostics for the interaction of only transverse and longitudinal cracking, as well as the transverse and longitudinal cracking raised to the power of 2. Tables 5.7 to 5.8 illustrate the model results and the sensitivity of the input variables.

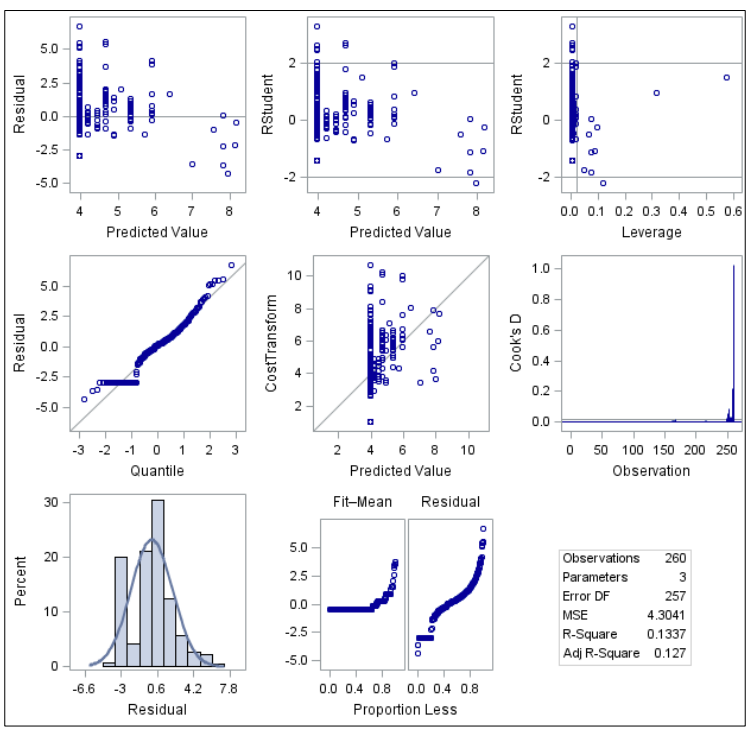


Figure 5.5 Model Diagnostics for Smithfield-TAMS Regression of Significant Interaction

Table 5.7 Model Results for Smithfield-TAMS Regression of Significant Interaction

Model F-Value	Model P-Value	Adj R-Square	R-Square
19.83	<.0001	0.127	0.1337

Table 5.8 Parameter Estimates for Smithfield-TAMS Regression of Significant Interaction

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	3.95148	0.145270	27.2	<.0001
Longitudinal X Transverse	1	0.24942	0.044550	5.6	<.0001
(Longitudinal X Transverse)$^{0.2}$	1	-0.00367	0.000923	-3.98	<.0001

The model diagnostics in Figure 5.5 illustrate that model assumptions are roughly met, given the nature of the data, the plots in the left hand column from top to bottom illustrate satisfactory constant variance, satisfactory linearity, and satisfactory normal distribution. These results are expected, given the nature of the data for a local government which does not guarantee every distress will be observed and also because of the intent of removing additional distress observations. The R-square value in Table 5.7 denotes that about 13% of the variation in the model is explained when only the significant interaction and the nonlinear variable are included.

The considered pavement distresses with the included interaction and remedial measures was developed for only the interaction of longitudinal cracking and transverse cracking. As discussed previously remedial measures implies that a transformation was applied to the response variable in order to meet statistical model assumptions. In this case, the response variable of estimated recommended M&R cost was transformed by raising it to the 0.2 power. The model is illustrated in Equation 5.4 and Figure 5.6 illustrates the observed values plotted against the developed model.

$$\hat{Y}^{0.2} = 3.951 + 0.249(\text{LongitudinalXTranxverse}) - 0.003(\text{LongitudinalXTranxverse})^2$$

(Eq. 5.4)

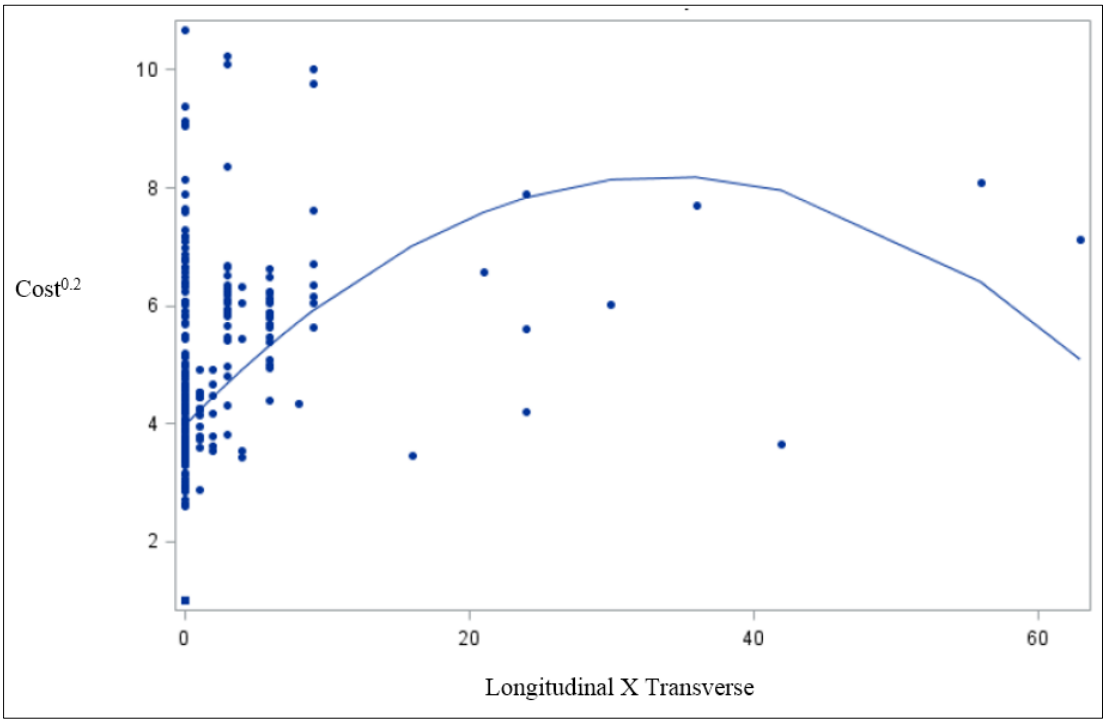


Figure 5.6 Smithfield-TAMS Regression of Significant Interaction Observed Values against Predicted Model

In summary, the two proposed models offer an estimated M&R cost based on key significant distresses. The benefit for utilizing Equation 5.3 is that more variation is explained by the model over Equation 5.4, resulting in a higher R-square. However Equation 5.4 addresses possible nonlinearity in the data set but also excludes significant distresses that can provide more explanation to the variation in estimated cost, in other words a more confident estimate for M&R. Both of the above models provide an estimated M&R cost based solely on distresses, and they both serve as a tool for engineering technicians in the field. If one model is to be recommended for the LHS data

set, it would be the model in Equation 5.3 due to the higher R-square value, however more observations will need to be acquired of the significant distresses to determine an estimate. While the model in Equation 5.4 requires fewer distress observations and addresses possible nonlinearity, the drawback lies in the amount of variation explained. The model in Equation 5.4 represents is a deeper investigation and results that a nonlinear variable does not necessarily help address the variation and thus, may not be as useful of a tool for engineering technicians.

5.4.3 Tremonton Data Set for TAMS

The Tremonton data set used in Chapter 4 was further analyzed for the sensitivity of the model output to significant variables; a model consisting of only the sensitive input factors of was examined. Figure 5.7 illustrates model diagnostics after applying remedial to the response variable of estimated M&R cost, as discussed in Section 5.4. Tables 5.9 and 5.10 illustrate the model results and the sensitivity of the input variables. The model diagnostics in Figure 5.7 illustrate that model assumptions are questionable, the plots in the left hand column from top to bottom illustrate debatable constant variance, debatable linearity, and debatable normal distribution. These results are expected, given the nature of the data for a local government which does not guarantee every distress will be observed and also the City of Tremonton had a fewer variation of distresses than the LHS data set and the Smithfield data set. The R-square value in Table 5.9 denotes that about 48% of the variation in the model is explained when only the significant input variables and their interaction are present.

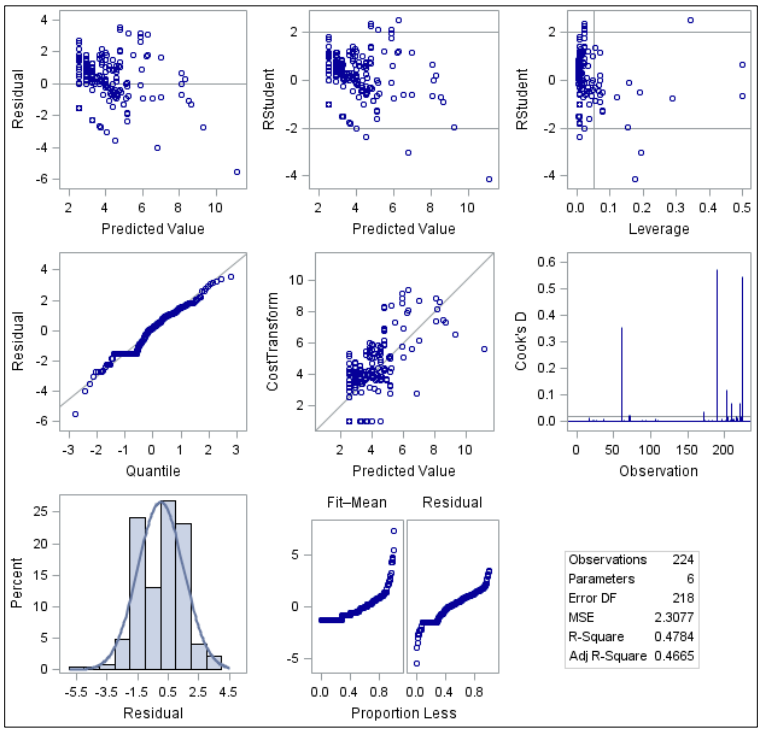


Figure 5.7 Model Diagnostics for Tremonton-TAMS Regression of Significant Variables

Table 5.9 Model Results for Tremonton-TAMS Regression of Significant Variables

Model F-Value	Model P-Value	Adj R-Square	R-Square
39.99	<.0001	0.4665	0.4784

Table 5.10 Parameter Estimates for Tremonton-TAMS Regression of Significant Variables

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	2.53176	0.14866	17.03	<.0001
Fatigue	1	0.74713	0.06870	10.87	<.0001
Longitudinal	1	0.43331	0.10815	4.01	<.0001
Transverse	1	0.37243	0.06833	5.45	<.0001
Roughness	1	2.77503	0.54221	5.12	<.0001
Longitudinal X Transverse	1	-0.08899	0.02399	-3.71	0.0003

A general linear model composed of the considered pavement distresses with the included interaction and remedial measures is illustrated in Equation 5.5, as discussed previously remedial measures implies that a transformation was applied to the response variable in order to meet statistical model assumptions. In this case, the response variable of estimated recommended M&R cost was transformed by raising it to the 0.2 power.

$$\hat{Y}^{0.2} = 2.532 + 0.747(\text{Fatigue}) + 0.433(\text{Longitudinal}) + 0.372(\text{Transverse}) + 2.775(\text{Roughness}) - 0.089(\text{LongitudinalXTransverse})$$

(Eq. 5.5)

In order to further analyze and simplify the model, the introduction of a nonlinear variable was introduced only taking into account the significant interaction of significant variables. Figure 5.6 illustrates the model diagnostics for the interaction of only transverse and longitudinal cracking, as well as the transverse and longitudinal cracking raised to the power of 2. Tables 5.7 to 5.8 illustrate the model results and the sensitivity of the model to these input variables.

The model diagnostics in Figure 5.5 illustrate that model assumptions are questionable the plots in the left hand column from top to bottom illustrate debatable constant variance, debatable linearity, and debatable normal distribution. The R-square value in Table 5.11 denotes that about 7% of the variation in the model is explained when only the significant interaction and the nonlinear variable are included. The general linear model composed of only longitudinal cracking and transverse cracking after remedial measures in illustrated in Equation 5.6.

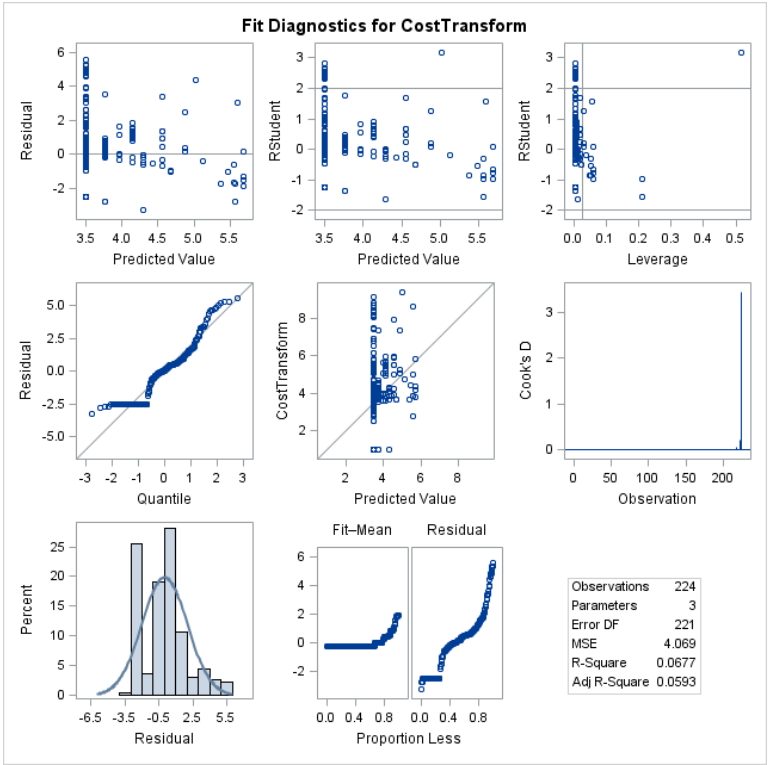


Figure 5.8 Model Diagnostics for Tremonton-TAMS Regression of Significant Interaction

Table 5.11 Model Results for Smithfield-TAMS Regression of Significant Interaction

Model F-Value	Model P-Value	Adj R-Square	R-Square
8.02	0.0004	0.0593	0.0677

Table 5.12 Parameter Estimates for Smithfield-TAMS Regression of Significant Interaction

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	3.49519	0.15428	22.6	<.0001
Longitudinal X Transverse	1	0.75438	0.29173	2.59	0.0104
(Longitudinal X Transverse)$^{0.2}$	1	-0.48254	0.20171	-2.39	0.0176

As discussed previously remedial measures implies that a transformation was applied to the response variable in order to meet statistical model assumptions. In this

case, the response variable of estimated recommended M&R cost was transformed by raising it to the 1.1 power. Figure 5.6 illustrates the observed values plotted against the developed model.

$$\hat{Y}^{1.1} = 3.49519 + 0.754(\text{LongitudinalXTranxverse}) - 0.483(\text{LongitudinalXTranxverse})^2$$

(Eq. 5.6)

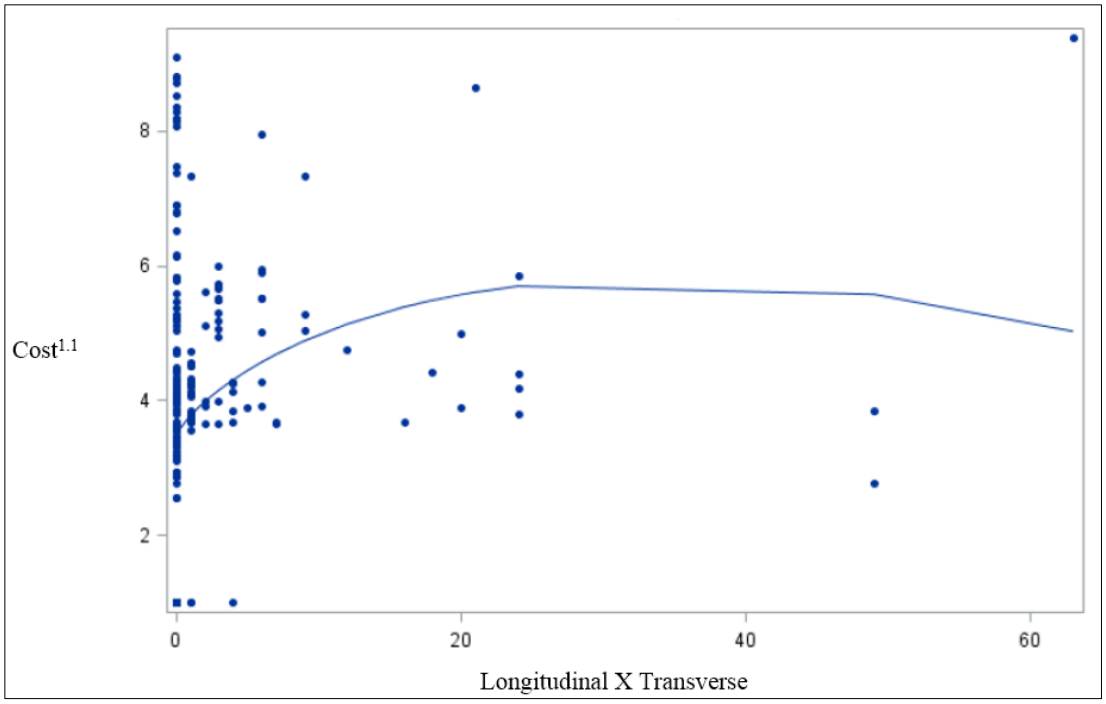


Figure 5.9 Tremonton-TAMS Regression of Significant Interaction Observed Values against Predicted Model

In summary, the two proposed models offer an estimated M&R cost based on key significant distresses. The benefit for utilizing Equation 5.5 is that more variation is explained by the model over Equation 5.6, resulting in a higher R-square. However Equation 5.6 addresses possible nonlinearity in the data set but also excludes significant distresses that can provide more explanation to the variation in estimated cost, in other

words a more confident estimate for M&R. Both of the above models provide an estimated M&R cost based solely on distresses, and they both serve as a tool for engineering technicians in the field. If one model is to be recommended for the LHS data set, it would be the model in Equation 5.6 due to the higher R-square value, however more observations will need to be acquired of the significant distresses to determine an estimate. While the model in Equation 5.6 requires fewer distress observations and addresses possible nonlinearity, the drawback lies in the amount of variation explained. The model in Equation 5.6 represents is a deeper investigation and results that a nonlinear variable does not necessarily help address the variation and thus, may not be as useful of a tool for engineering technicians.

5.5 Discussion of Models

The models developed through the statistical procedures each varied depending on the observation of distresses in the sample set. This evidence suggests that each local government may have a unique model for the response of estimated recommended M&R cost. The model results generated under the LHS sample set for the TAMS software focused on three distress variables and their interaction, while the local government data sets of Smithfield and Tremonton resulted in additional distresses that required consideration.

Two models were developed for each data set in order to investigate effectiveness and simplification of acquiring an estimated M&R cost based on pavement surface distresses. The motive behind developing such models is to assist engineering technicians in utilizing the models as tools for decision making purposes, such as assurance of visible distresses and assistance in deciding between conflicted severities. The first model

developed considered only significant distress variables and was approached as a general linear regression model. The second model developed considered fewer significant distress variables while also considering nonlinear terms. Both models address the initial motive of development, however of the two models one was found to explain more variation in the data, thus becoming the favored model for use.

5.6 Summary and Recommendations

To address the proposed research question of, “can a general statistical model be used to estimate a cost based solely on pavement distresses?” it appears that the appropriate model for each sample set, or local government, should consist of unique pavement distresses that govern the results of the statistical models.

For each of the sample sets analyzed, results varied both in sensitivity of distresses and explanation of variation (R-square) on the response. For this reason it is recommended that although a general statistical model cannot be proposed for all local governments, unique models pertaining to specific local governments be developed within and updated over time to provide an accurate tool for local government technicians.

In addition, two models were developed and evaluated for each data set for the purpose of providing a tool for engineering technicians. It was determined that a general linear regression model would best suit this purpose as it explains more variation and therefore predicts a more accurate and confident estimated M&R cost. The effectiveness of the model was determined by the provided R-square value, which by definition is the amount of variation explained by the model. A higher R-square value signifies the

percentage of variation explained by a given model and the considered variables, which in this case was the estimated M&R cost explained solely by pavement distresses.

Therefore, the general linear regression model was determined to be the best suited for use as a tool by engineering technicians. Although more distress observations are required to be collected, the confidence in the results far exceeds the models developed when considering fewer distress variables and nonlinear effects.

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Summary and Conclusion

The work presented in this thesis investigated the sensitivity that the initial data collection process of a Pavement Management System (PMS) procedure has on the later economic analysis step of a PMS. The PMS process has already been implemented and proven to be successful in planning and utilization of limited funding. The anticipated contribution of this thesis is the exploration of identifying pavement distresses that the economic analysis portion of a PMS is sensitive to. In addition, the identification of pavement distresses significance provides engineering technician insight in what pavement distresses require more careful consideration and observation during the data collection process. These contributions can amplify the quality of a PMS in a local government setting. Although there are high quality and high detail PMS software packages available, taking assertive actions to increase the precision of PMS through statistical approaches can be completed regardless of the analytical level of a PMS.

Three data sets of pavement condition data were collected under the methodologies of the Micro PAVER™ software package and the TAMS software package, resulting in six total data sets available for analysis. The sources of the three sample sets consisted of a Latin-Hypercube Sample (LHS) Set, the current local government pavement condition assessment of the City of Smithfield and the current local government pavement condition assessment of the City of Tremonton.

Upon collection of pavement condition distress data, an economic analysis was performed for the six data sets under their respective PMS software package. Thus, each PMS software package resulted in a common output of estimated recommended M&R costs. The two statistical approaches of an Analysis of Covariance (ANCOVA), and a general linear regression were used in order to determine the effect each pavement distress had on the estimated recommended M&R cost. In the statistical procedure, the response variable consisted of the estimated recommended M&R cost, while the predictor variables consisted of the distress observations.

The results of the statistical procedures resulted in one common pavement distress with high sensitivity in all of the data sets; this distress consisted of alligator cracking/fatigue. The sensitivity of additional pavement distresses appeared to vary within sample sets as well as with the PMS software package utilized. This result suggests that each local government pavement system may be sensitive to uniquely different pavement distresses. This variation may be due to socioeconomic influences, weather and the annual average daily traffic of an individual road segment.

Furthermore, an investigation of developing a tool for engineering technicians in the field was addressed through the use of statistical models. Through the method of linear regression, each of the aforementioned data sets was used to develop statistical models that would predict the estimated M&R cost based solely on observed pavement surface distresses. The motive behind producing such models was to aid engineering technicians in having a rough estimate of the amount of M&R required to treat a pavement segment. From having this knowledge, the engineering technician may use

better judgment in recording pavement distresses that do not govern a pavement segment or between two pavement severities.

6.2 Conclusion and Recommendations

Pertaining to the main research question of "*What attributes of a PMS should local governments focus on to provide adequate economic analysis estimates for their pavement network?"*, two subsequent questions were presented as a foundation to address the main question:.

1. What pavement distresses should local government technician's focus on in order to obtain a confident recommended M&R estimated cost?
2. Can a general statistical model be used to estimate a cost based solely on pavement distresses?

It was determined that the response of estimated recommended M&R cost was highly sensitive to alligator cracking/fatigue distress in all of the data sets analyzed. Thus, it is recommended that local government technicians pay special attention to the distress of alligator cracking/fatigue as one to have the greatest impact in the economic analysis portion of the PMS software packages of TAMS and Micro PAVER™.

It was also determined that that each sample set, or local government pavement network, will likely consist of unique pavement distresses that may govern the results of the statistical models. For this reason it is recommended that although a general statistical model cannot be proposed for all local governments, unique models pertaining to specific local governments be developed and updated over time to provide an accurate tool for local government technicians.

6.3 Future Work

Future work in the PMS field is available in all aspects of the process. This includes the initial methods of data collection, analytics of determining pavement condition as well as the effectiveness of such methods, and alternative approaches to economic analysis optimization. This research specific research focused on investigating the direct association between pavement distress observations and the estimated recommended M&R cost in a PMS software package. This was accomplished by utilizing statistical models to identify significant distress variables the economic analysis was sensitive to. Additional models, such as time-series models, can be integrated if continuous pavement condition data as well economic analysis results are available, which could possibly leading to a more descriptive and unique model for local governments.

Another possible future research area could be the statistical evaluation of the time taken to collect pavement distress data. Utilizing the TAMS software package, data collection consists of a windshield survey approach, while that of the Micro PAVER™ ASTM standard requires a more involved and time consuming data collection process. The time required to collect data under each method may be significant and impact the resources, budget and time of a local government and their engineering technicians. Thus, evaluating alternative pros and cons between the two PMS software packages may include additional variables of observation with the PMS that were not discussed in depth in this research.

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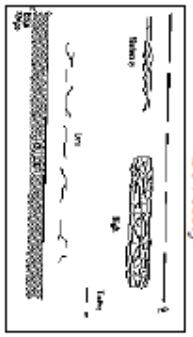
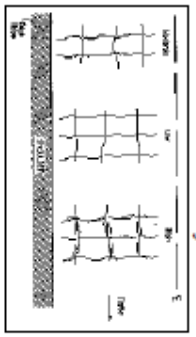
APPENDIX

Appendix: TAMS Distress Identification Matrix (Utah LTAP, 2010)



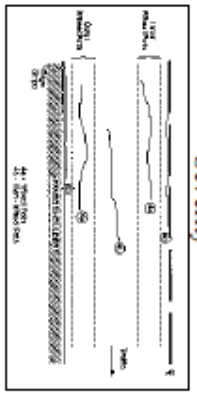
FATIGUE CRACKING

Severity \ Extent	Low	Medium	High
0 None	1 Crack WP or 1' off C&G Length	2 Crack WP or 1'-2' off C&G Length	>30% of Surface Area or Length
Low Cracks < 1/4"	1	2	3
Medium Cracks 1/4" to 3/4"	4	5	6
High Cracks > 3/4"	7	8	9



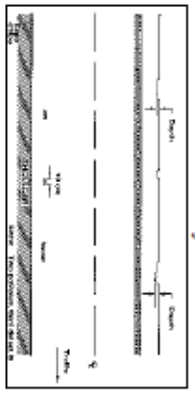
BLOCK CRACKING

Severity \ Extent	Low	Medium	High
0 None	> 15'x15' Squares	15'-10'x Squares	< 10'x10' Squares
Low Cracks < 1/4"	1	2	3
Medium Cracks 1/4" to 3/4"	4	5	6
High Cracks > 3/4"	7	8	9



LONGITUDINAL CRACKING

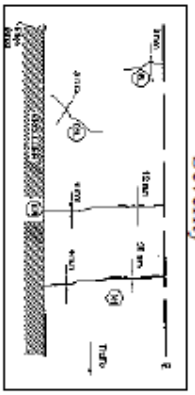
Severity \ Extent	Low	Medium	High
0 None	1 Crack Full Length	2 Cracks Full Length	> 2 Cracks Full Length
Low Cracks < 1/4"	1	2	3
Medium Cracks 1/4" to 3/4"	4	5	6
High Cracks > 3/4"	7	8	9



UTILITY CUTS

Severity \ Extent	Low	Medium	High
0 None	0-10% of Length	10-30% of Length	>30% of Length
Low Cracks < 1/4"	1	2	3
Medium Cracks 1/4" to 3/4"	4	5	6
High Cracks > 3/4"	7	8	9

Note: to rate potholes use the same form with the following changes to the severity: **Low** is <1" deep, **Med** is 1"-2" deep and **High** is >2"

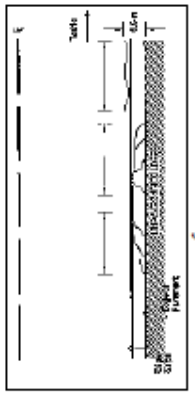


TRANSVERSE CRACKING

Severity \ Extent	Low	Medium	High
0 None	> 100' between Cracks	100'-20' between Cracks	< 20' between Cracks
Low Cracks < 1/4"	1	2	3
Medium Cracks 1/4" to 3/4"	4	5	6
High Cracks > 3/4"	7	8	9

Drainage / Roughness

Excellent	Good	Fair	Poor



EDGE CRACKING

Severity \ Extent	Low	Medium	High
0 None	0-10% of Length	10-30% of Length	> 30% of Length
Low 0-6" from Curb	1	2	3
Medium 6-18" from Curb	4	5	6
High 18" from Curb	7	8	9

Rutting

Excellent	Low	Med	High
0	<3/8"	1/2"-3/4"	>3/4"