Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
SWUTC/11/169208-1		

4. Title and Subtitle	5. Report Date
IMPACT OF PERFORMANCE GOALS ON THE NEEDS OF HIGHWAY INFRASTRUCTURE MAINTENANCE	July 2011
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Sunny Jaipuria, Zhanmin Zhang	169208-1
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Center for Transportation Research University of Texas at Austin 1616 Guadalupe Street, Suite 4.200 Austin, Texas 78701	11. Contract or Grant No. 10727
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Southwest Region University Transportation Center Texas Transportation Institute Texas A&M University System College Station, Texas 77843-3135	14. Sponsoring Agency Code

15. Supplementary Notes

Supported by general revenues from the State of Texas.

16. Abstract

Although it is widely accepted that establishing suitable performance goal is critical for system maintenance and preservation, a framework that considers the inter-relationship between conflicting objectives of minimum maintenance and rehabilitation costs, deferred maintenance costs, and vehicle operating costs to the users does not exist. This report proposes a methodological framework that is aimed at assisting highway agencies with the problem of objectively analyzing policy decisions in terms of the performance goals for their highway networks that would minimize the total transport costs to the society. In a case study of the proposed framework, the highway network managed by the Texas Department of Transportation was examined for different performance goals. The results from the case study indicate that setting lower performance goals lead to savings in the M&R needs, but at the same time, they also significantly increase the exogenous costs such as deferred maintenance costs and the vehicle operating costs.

17. Key Words	18. Distribution Statement
Performance Goals, Highway Infrastructure, Maintenance, Transport Costs	No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	53	

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

IMPACT OF PERFORMANCE GOA LS ON THE NEEDS OF HIGHWAY INFRASTRUCTURE MAINTENANCE

by

Sunny Jaipuria
Graduate Research Assistant
University of Texas at Austin

and

Zhanmin Zhang, Ph.D
Associate Professor
University of Texas at Austin

Report 169208-1

SWUTC/11/169208-1

Southwest Region University Transportation Center
Center for Transportation Research
The University of Texas at Austin
The Dept. of Civil, Architectural and Environmental Engineering
1University Station, C1700
Austin, Texas 78712

July 2011

EXECUTIVE SUMMARY

Performance goals for a highway system are an indication of the desired system condition, and the level of service to be provided to its users. Setting the appropriate performance goals has a significant impact on the way highway agencies conduct business. With growing needs and limited resources, the consequences of setting different levels of performance goals should be examined and compared to optimize the highway infrastructure needs at the network level.

Three interacting sets of costs are typically considered for a complete economic appraisal of highway projects: construction, maintenance and road use costs. Due to the shift in focus from design-and-build mode to the repair-and-maintain mode, this study focuses on maintenance related costs and the road user cost aspects only. Maintenance and rehabilitation activities on pavement infrastructure are ongoing processes that are required for the entire road network. This suggests that for long planning horizons and geographically extensive networks, their application usually results in significant financial needs. Typically, highway agencies have based their policy decisions such as the target condition levels for the system on the budget needs for maintenance and rehabilitation actions.

Since in most cases, the funding needs exceed the available budget, the required preventive and routine maintenance activities suffer or are overlooked completely. Failure to timely apply these maintenance actions cause the pavements to deteriorate more rapidly into condition states that require for more expensive rehabilitation actions during the life cycle of the pavement. Over time, a vicious cycle is instigated in which the maintenance and rehabilitation needs of the network keep increasing each year. Although most highway administrators acknowledge the fact that pavement preservation is perhaps the most effective way of using the limited budgets available, the costs associated with deferring maintenance actions is oftentimes overlooked when establishing performance goals for the system.

Road user costs in the form of costs for vehicle operation have been recognized as another large component of the total transportation related costs. These costs are then arguably the most important to consider for a complete economic appraisal. Ironically, they are also often disregarded while making important policy decisions. Other road user costs such as those related to the impact of traffic congestion and detours caused by construction and maintenance activities are difficult to quantify and were not accounted for in this study.

Although it is widely accepted that establishing suitable performance goal is critical for system maintenance and preservation, a framework that considers the inter-relationship between conflicting objectives of minimum maintenance and rehabilitation costs, deferred maintenance costs, and vehicle operating costs to the users does not exist. This report proposes a methodological framework that is aimed at assisting highway agencies with the problem of objectively analyzing policy decisions in terms of the performance goals for their highway networks that would minimize the total transport costs to the society. In a case study of the proposed framework, the highway network managed by the Texas Department of Transportation was examined for different performance goals. The results from the case study indicate that setting lower performance goals lead to savings in the M&R needs, but at the same time, they also significantly increase the exogenous costs such as deferred maintenance costs and the vehicle operating costs.

ACKNOWLEDGEMENTS

In thanking the following people for their help it is obvious, yet necessary to state that this document could not have possibly been put together without their assistance.

I express my gratitude to Dr. Zhanmin Zhang for his invaluable criticism that brought about a lot of clarity to my research work. I am also grateful to Dr. Zhang for his guidance that was a continual source of improvement during my years at The University of Texas at Austin. Special thanks are also due for Dr. Randy Machemehl for his gracious support and encouragement during my graduate studies.

My understanding of the subject was greatly enhanced by discussions with my seniors, especially Aris Pantelias. I take this opportunity to also thank Hui Wu, Lu Gao, and Liang Liang for assisting me at various stages during the course of my research. Being a part of a professional research project, solving real-world problems, I was able to learn interactively through teamwork, gaining life-long learning skills.

A number of documents of various authors have been referred in preparation of this research document. I gratefully acknowledge their contributions as mentioned under 'References' at the end of this document. Although adequate care has been taken to acknowledge those whose assistance has been taken in preparing the manuscript, there might have been few omissions in this regard which are unintentional and may be excused.

I would be failing my family and friends if I did not acknowledge their tremendous support and assistance in my endeavor. Special thanks to Mom, Dad, Anna, Neha, Rajesh, Arjun, Sriram and Radhika. As I write this, I hope that all whom I have thanked will feel their efforts well spent not because of the erudition of the study, but because I have put in the best of my efforts and abilities in trying to acquire and understand the multitude aspects of my research. This experience will be invaluable for me since I cannot really wait to be a practicing engineer with several years of work experience to obtain such a wealth of knowledge.

The authors recognize that support for this research was provided by a grant from the U.S. Department of Transportation, University Transportation Centers Program to the Southwest Region University Transportation Center which is funded, in part, with general revenue funds from the State of Texas.

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of information exchange. Mention of trade names or commercial products does not constitute endorsement or recommendation of use.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

The United States highway infrastructure system earned grade D in ASCE's 2005 Report Card for America's Infrastructure. Addressing the 2007 ASCE Annual Civil Engineering Conference, Patrick J. Natale, ASCE's executive director, noted that: "Years of deferred infrastructure investments and maintenance and the failure of public officials to act on infrastructure needs place the public at risk and hinder our country's economic growth and competitiveness" [Reid, 2008]. The maintenance and rehabilitation (M&R) needs of the aging highway infrastructure pose a great challenge to the system managers due to increasing costs and inadequate revenues to meet with these needs. The economic downturn has worsened the situation and the state departments of transportation are experiencing overall reductions in their budgets for operational and capital funds [Christensen et. al, 2010]. This situation calls for careful planning and better management approaches.

The importance of sound infrastructure management practices in highway engineering was recognized long ago by our highway administrators. The Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 had issued a policy directive along these lines that laid emphasis on the preservation of infrastructure assets by specifying six management systems for state departments of transportation (DOTs), namely pavement, bridge, safety, congestion, transit, and intermodal [Hudson et al. 1997]. Various tools and systems have been developed since then by the state DOTs and local highway agencies to support the process of transportation infrastructure management. The Federal Highway Administration (FHWA) also issued a mandate that required each state to have an approved pavement management system (PMS) in place by February, 1993. Pavement management systems have evolved as an invaluable tool that aids the decision maker in finding optimum strategies for providing, evaluating, and maintaining the pavement infrastructure in a serviceable condition over time.

1.2 NEED FOR STUDY

The overall effectiveness of maintenance and rehabilitation programs is controlled by decision makers at top management levels who authorize the appropriation of budgets. The available budgets impact the performance of the highway system and its utility to the users. Poor decisions made at the top level can significantly hinder a highway agency's efforts of improving and maintaining the current highway network condition. These network level strategic decisions in turn impact the decisions made at the project level.

At the network level, the decisions often involve multiple conflicting objectives. As an example, a highway agency may wish to find a maintenance strategy that minimizes the agency cost while maximizing the network performance. However, in order to maximize the pavement performance, the strategy would require that the pavements are maintained at a high level of service; which in turn would increase the agency costs. Additionally, with budget shortfalls and across the board budget cuts, oftentimes the highway agencies defer system preservation efforts which typically lead to a need for more expensive rehabilitation actions in the future. Past studies have also indicated that the operating costs to the users are magnified if a system is operated and maintained at a sub-optimal condition due to increased costs for maintenance and repair, tire wear, and accelerated depreciation of vehicles [Sime et. al, 2000, and Poelman et. al, 1992]. In the midst of such complex interrelationships, a rational methodology for complete economic appraisal of the highway infrastructure needs is required that would account for these conflicting objectives and assist the management in establishing appropriate policy directives that would eventually minimize total transport costs to society.

1.3 REPORT OBJECTIVE

Many transportation agencies have developed system-level performance measures to help track the impacts of program investments, maintenance, and operations improvements. Infrastructure management practices for these agencies are driven by policy, which are expressed through goals established by the decision makers. These performance goals can be objectively compared to the current conditions to determine if the system is performing at a satisfactory level. The basis on which these goals are set varies and there is no generally accepted methodology for their establishment and use in the practice of infrastructure management.

With growing needs and limited resources to address them, the consequences of setting different levels of performance goals should be examined and compared to optimize the infrastructure needs at the network level. Establishing lower performance goals for the pavement infrastructure can lead to savings due to lesser funds required to maintain a lower target condition for the network but can also significantly increase the exogenous costs thereby increasing the total system costs. Although establishing suitable performance goals is critical for system maintenance and preservation, there is no systematic methodology in place which can guide highway agencies to evaluate and choose between alternative goals. The report aims at addressing this issue by providing a methodological framework that can be used to examine different performance goals, leading to the establishment of an appropriate performance goal that can be fully justified by highway agencies.

1.4 SCOPE OF WORK

Based on the objectives of the report and keeping in view the scope, a methodological framework was formulated that aids in evaluating the economic impacts of establishing different performance goals is terms of agency costs and user costs. As part of the work, the highway network under the jurisdiction of Texas Department of Transportation (TxDOT) was evaluated and the pavement infrastructure M&R needs, the vehicle operating costs (VOC) related to changes in network performance goals, and the effect of deferring maintenance actions were addressed by using the Pavement Needs Estimation and Scenario Tool (PaveNEST). This tool was developed by the Transportation Infrastructure and Information Systems (TIIS) Lab of the Center for Transportation Research (CTR) at The University of Texas at Austin. Based on the results from the case study, the current asset management approach of TxDOT in terms of the system architecture and goals and objectives for the system will be reviewed and guidelines will be proposed for any shortcomings that are identified.

1.5 RESEARCH METHODOLOGY

To achieve the objectives of the report, a step methodology was adopted and a detailed literature review of past studies was conducted which helped in generating the basis for this study. Based on the findings, a methodological framework was formulated. Appropriate analysis on a case study was carried out using the decision support system PaveNEST and conclusions were drawn to support the objectives. A review of the more rational methods for managing highway infrastructure such as the utilization based 'Multi-Tier' approach was conducted. Finally, conclusions were drawn and guidelines formulated based on the literature review and findings from the analysis.

1.6 REPORT ORGANIZATION

The organization of this report which presents a methodological framework for analyzing the impact of performance goals on the transport costs to highway agency and system users is as follows:

Chapter 1 is the introduction to this report, illustrating the need for this study and objectives that will be achieved through this research along with the organization of the chapters of this report. Chapter 2 focuses on the concept of infrastructure management with an emphasis on pavement management systems. The chapter focuses on some important questions that pavement management systems can be used to address to aid in the decision making process. It also presents a discussion on the practices adopted by various highway agencies and state DOTs and some findings from relevant research conducted in the past.

Chapter 3 presents a methodological framework for analyzing the impact of different policy directives on issues such as the maintenance and rehabilitation needs of the system, impact of deferring maintenance actions on the network performance and related costs and the cost to the final users of the system. This chapter also includes the procedures and algorithms which are used to assess these costs due to changes in goals established for the system. Chapter 4 provides the results from a case study conducted on the pavement network managed by the Texas Department of Transportation (TxDOT) using the methodological framework. The chapter discusses the 'needs analyses' on the highway network managed by TxDOT such as the impact of limited budget on the overall condition of the system, the M&R needs of the system, cost of operating vehicles under different conditions of the pavement infrastructure, and costs of deferring maintenance actions over an analysis duration of twenty years.

Chapter 5 provides a discussion of the results from the analysis of the TxDOT case study. The chapter presents a discussion on a more rational asset management technique in a limited resources scenario called the 'Multi-Tier' approach to managing highway infrastructure. The concepts and application from the perspective of the Texas highway system are discussed. Chapter 6 concludes this report by summarizing the research and making recommendations for future advancements.

CHAPTER 2. LITERATURE REVIEW AND CURRENT PRACTICES

2.1 THE DECISION MAKING PROBLEM

In recent times, the decision making problem has become more complex and far-reaching in its implications due to the competing demands on funds and resources. The decision-making process has been classified in the literature into three categories based on the availability of input data, techniques and procedures, and the output: structured, semi-structured, and unstructured problems. Of these three categories, the semi-structured decision-making problem assumes a special position. These problems are special because either they are so large in size or complexity that a straightforward use of subjective judgment is not feasible, or the underlying uncertainties or assumptions are such that they undermine the reliability of the models. Therefore, considerable interactive work in a computing environment is often times required from the administrators, managers, and engineers to find solutions to these problems. The outcome of such an effort is usually a decision support system (DSS) that serves as an effective tool to aid in the decision-making process [Zhang et al. 1999].

2.2 INFRASTRUCTURE MANAGEMENT

Infrastructure management is a decision making process of coordinating and controlling activities related to planning, design, construction, and maintenance of infrastructure systems in a cost effective manner. Of the many benefits of infrastructure management, the ones that have gained considerable attention include the increased service life of the facilities, reduced user costs and appreciation and preservation of the asset value [Hudson et al. 1997].

The Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 had issued a policy directive that specified the establishment of six management systems for State Departments of Transportation (DOTs) namely pavement, bridge, safety, congestion, transit, and intermodal [Hudson et al. 1997]. Additionally, FHWA issued a mandate that required each state to have an approved pavement management system in place by February, 1993. Since then, various tools and systems have been developed by state DOTs and local highway agencies to support the process of transportation asset management. Pavement Management Systems are one such set of tools that aid the decision makers in finding optimum strategies for providing, evaluating, and maintaining the pavement infrastructure in a serviceable condition over a period of time.

2.3 PAVEMENT MANAGEMENT SYSTEM

A comprehensive definition of Pavement management given by Hass et al. [1994] was "Pavement management involves the identification of optimum strategies at various management levels as well as the implementation of these strategies. It is an all encompassing process that covers all those activities involved in providing and maintaining pavements at an adequate level of service. These range from initial information acquisition to the planning, programming, and execution of new construction, maintenance, and rehabilitation, to the details of individual project design and construction; to periodic monitoring of pavements in service." American Association of State Highway and Transportation Officials (AASHTO) [2001] defined Pavement management system (PMS) as "a set of tools or methods that assist decision makers in finding optimum strategies for providing, evaluating, and maintaining pavements in a serviceable condition over a period of time".

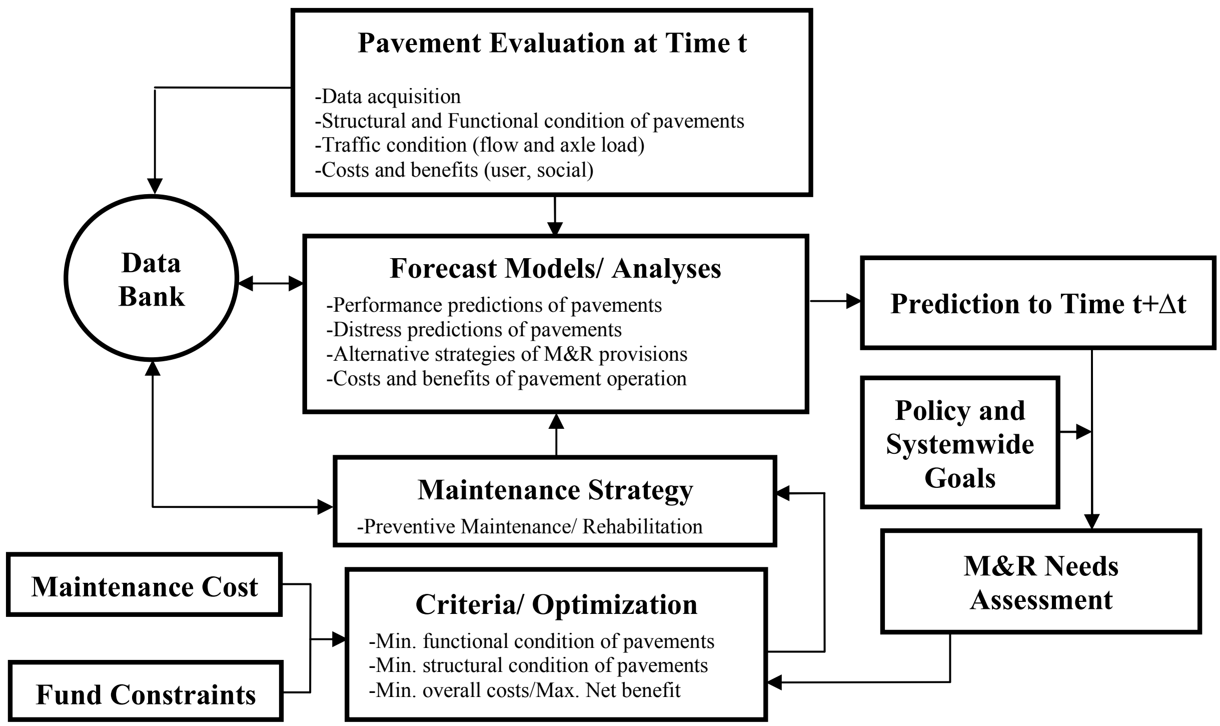


Figure 1: Model Flowchart of Pavement Management Process.

The conceptual framework of the pavement management process is illustrated in Figure 1. Conceptually, the first and key step in implementing a pavement management program is that of setting performance goals and targets for the network under consideration. In terms of physical implementation, the pavement management process begins with the collection of general inventory data and gathering of pavement condition data. Since pavement management is not a one-time activity, the data collection activities are typically carried out on a regular basis so as to reflect the current condition of the pavement network for effective decision making. The next step in the process is prediction of the future condition of the pavement for which the inventory and condition information are combined to develop deterioration models. The difference between predicted future condition and the target network condition based on the agency's goals establishes the short and long-term needs for the network. Based on the future M&R needs, estimates of the funding needed to preserve the pavement network at prescribed levels of performance are prepared and presented to public officials for budget appropriations. In most cases, funding needs exceed the available funding which lead to a budget allocation process in which prioritization and optimization techniques are used to prepare a maintenance and rehabilitation program that is most beneficial. Once the maintenance and rehabilitation program is implemented by the agency, the process of data collection and performance monitoring is initiated again to determine needs for the following year.

2.4 WORKING (NETWORK AND PROJECT) LEVELS OF PMS

The pavement management process operates at two basic decision levels: the network level and the project level. The network level decisions include pavement preservation and rehabilitation programming to develop budgets and allocate resources over the entire network, and are typically made before project level decisions in which detailed consideration is given to alternative design, construction, maintenance or rehabilitation and life cycle costs analysis [Haas et al. 1994]. Decisions made at the network level have a great impact on the decisions made at the project level. The fundamental reasons for having these two different working levels includes the minimization of data collection efforts and costs, and the level of detailed information required by users at different levels such as engineers/ technicians, system administrators, and legislators. The network level analysis typically deals with program and policy issues for overall budget estimates, 'what-if' type of question, and are mostly for use and interest to program managers, budget directors and legislators. The decisions made at the network level often involve multiple conflicting objectives.

2.5 POLICIES AND PERFORMANCE GOALS

Infrastructure management is driven by policy, expressed thorough goals that are established by the system administrators such as the Transportation Commissions and implemented by the state departments of transportation. The administrators formulate policy and provide guidance to the DOTs regarding the construction, maintenance and management of the state highways and transportation systems. An important function of the Pavement Management System (PMS) is to assist with the problem of analyzing changes in policies related to the management of the infrastructure. Such analysis can provide very useful information that can be used by the highway agencies in assessing the impacts of stringent budgets and the effects of deferring the needed maintenance and rehabilitation activities.

Many agencies have developed system-level performance measures that help in tracking the impacts of program investments, maintenance, and operations improvements. The highway agencies set their performance goals based on specific performance measures. The performance goals established by an agency can be objectively compared with the prevailing conditions to determine whether the transportation system is performing at a satisfactory level. The basis on which these goals are set varies and there is no generally accepted methodology for their establishment and use in the practice of infrastructure management. According to a recent study, some state agencies such as those of Iowa, South Carolina, and Tennessee are in the process of setting and attaining these system-wide goals, while others like Florida, Michigan, Minnesota, and Ohio already have fairly refined methods in place. The states using more advanced methods view the goal-setting exercise as a multidimensional process, involving financial concerns such as current and anticipated funding, technical concerns such as the current and forecast conditions or performance, policy objectives including existing priorities, customer and public involvement, and executive and legislative input, and economic concerns such as life-cycle cost considerations [Cambridge Systematics et al. 2006].

Florida Department of Transportation (FDOT) for example, rates pavement using three different annually measured criteria: ride smoothness, pavement cracking, and wheel path rutting. Each of these criteria is rated on a scale of 0 to 10. Ride smoothness and wheel path rutting are automated measurements obtained with laser measurement devices on FDOT vehicles, while pavement cracking is measured visually by experienced survey crews. The FDOT performance goal keeps 80 percent of the pavement in the state highway network at a score of 6 or better in all three criteria [Meyer, 2007].

Among other measures of pavement performance, the Ohio Department of Transportation (ODOT) uses a Pavement Condition Rating (PCR) in its performance goals. PCR scores range from 0 to 100 and are assigned to each segment of pavements in the network. This measure is determined visually by survey crews; the crew starts the rating of a pavement segment with a PCR of 100; then points are deducted from this score for signs of distress such as cracking, potholes, rutting, raveling, etc. For "priority system" roadways, such as interstates and National Highway System routes, ODOT operates under a state-wide performance goal to keep 75 percent or more of the pavement network at a PCR score of 65 or greater; lower volume roadways are classified as "general system," and are subject to a goal to keep 75 percent or more of the pavement network at a PCR score of 55 or greater [Meyer, 2007]. Recently, the Texas Transportation Commission issued a policy directive for TxDOT that calls for maintaining the highway pavement network condition at a score of 90% 'Good' or better by the year 2012 [Saenz, 2004]. The 'Good' or better score refers to the pavement sections with a Condition Score of 70 or more on the scale of 0 to100.

The Washington Department of Transportation (WSDOT) uses three types of condition measures to assess the pavement of its state highway system: a Pavement Structural Condition (PSC) that measures pavement distress, a Rutting score, and the International Roughness Index (IRI) of the pavement. The Pavement Condition Index (PCI), ranging between 0 and 100, is calculated from these three measures. Current policy sets the state performance goal at keeping 90 percent of highway pavement maintained at a PCI of 40 or better [Parsons Brinckerhoff et al. 2008]. The Minnesota DOT (MnDOT) also assigns three condition indexes: a Surface Rating (SR), a Ride Quality Index (RQI), and a Pavement Quality Index (PQI). SR ranges from 0 to 4 and is based on the amount of pavement distress at hand; RQI converts an IRI measurement to a 0 to 5 scale; and PQI is calculated from these two measures. Performance goals for MnDOT are defined in terms of RQI. According to their performance goal, by 2014, 70 percent of primary arterials and 65 percent of lower-volume roads must be in good or better condition, having an RQI of 3.1 or greater [Parsons Brinckerhoff et al. 2008].

2.6 MAINTENANCE AND REHABILITATION NEEDS

A considerable shift in emphasis from new construction to the preservation of the existing pavement network has occurred since the 1980s [U.S.DOT, 1999]. Maintenance and rehabilitation actions that can be undertaken for the network are limited by available manpower, equipment and materials. To the organizations that are responsible for network management, the question of available resources eventually boils down to a question of available funds. If this limitation did not exist, highways could have been constructed to the highest standards of strength and functional use, and deficiencies could be immediately rectified.

With limited funding for pavement network maintenance, the number of pavement miles in need of repair or rehabilitation has increased because of factors such as aging and heavier truck traffic. It has therefore become increasingly important for the highway agencies to evaluate the needs not just on a simple project-to-project basis but from considerations of the road network as a whole. Consequently, the network-level component has evolved as a major, identifiable function in the pavement management systems. It has become more and more necessary for highway agencies to efficiently allocate resources so as to make the best possible use of the limited funds available. In other words, the use of resources must be optimal with regard to the services to be offered.

Pavements deteriorate with age due to traffic or usage and the impacts of environmental forces such as temperature, moisture, etc. As a pavement section deteriorates to a minimum acceptable level, depending on availability of funds, appropriate maintenance or rehabilitation action is required to restore the condition to an acceptable level. A key function of pavement management is the establishment of network M&R needs and timely planning of these actions for the pavement network. M&R actions once conducted in the field reduce the rate of pavement deterioration due to the negative impacts of traffic and environmental effects.

The M&R needs for a highway network are typically based on historical data from the pavement inventory database. Using this data, the agencies can identify which pavement sections need an M&R treatment, what type of treatment is required by each section, and the resources needed to apply that treatment. With condition data and calibrated pavement deterioration models, the future condition of a pavement network can be predicted. The predicted future condition for a particular year of the analysis period, when compared with the target condition for the system set by the highway administrators, indicates the improvement required in the overall network condition. This difference establishes the M&R needs for the network. Finally, combining the unit cost information with the required M&R actions provides the M&R treatments budget needs for the highway network under consideration.

2.7 VEHICLE OPERATING COSTS

Road user costs are typically the largest component of total transport costs and are thus, arguably, the most important to consider in the decision making process. However, according to Wang et al. [2003], they are generally not included in the analysis since user costs are hard to evaluate precisely and impartially and also because preservation budgets are among the tightest resources for state departments of transportation. Another reason for not including user costs in the decision making process has been attributed to the fact that they are generally much greater than the agency costs and they tend to dominate the decision process [Golabi and Pereira 2003].

Vehicle operating costs (VOC) reflect the component of road user costs specifically associated with vehicle operation as opposed to capital and administrative costs resulting from ownership. The major components of the VOC that have been considered in previous studies include: fuel, maintenance (including tires, oil, and other routine work), unanticipated repairs, and depreciation in the value of the vehicle. Barnes and Langworthy [2003] summarized vehicle operating costs from various data sources including technical reports and trucking literature. Findings from their study indicated that, of the total operating expense, fuel consumption is the primary cost component followed by maintenance and repair costs. The most extensive study addressing the topic of vehicle operating costs was the World Bank’s Highway Development and Management (HDM) Standards studies conducted in the developing nations of Kenya, Brazil, India, and the Caribbean in 1980’s [Bennett et. al, 2001]. Several cost models were developed, however their relevance to the context of roadways in the Unites States has been debated over time due to reasons such as dissimilar vehicular fleets, and roadway construction and maintenance practices.

Previous research has demonstrated the negative influence of increased road roughness and pavement deterioration on vehicle fuel consumption and maintenance costs, factors contributing to the vehicle operating costs. An AASHTO press release [2009] noted that according to a report titled 'Rough Roads Ahead: Fix Them Now or Pay for It, Later', driving on rough roads costs the average American motorist about $400 per year in extra vehicle operating costs because of the accelerated vehicle deterioration, increased maintenance, additional fuel consumption, and tire wear caused by poor road conditions. Previously, research at Westrack had shown an improvement of 4.5 percent in the fuel economy resulting from an improvement in the pavement condition through M&R actions and also a subsequent decrease in the truck maintenance costs, frame fracture and spring failure [Sime and Ashmore, 2000]. Poelman and Weir [1992] studied the effects of surface roughness on vehicle suspension, as measured by a response meter. The results from their experiment indicated that the vehicles experienced accelerated suspension fatigue when the road roughness measured below 2.5 on the Present Serviceability Index (PSI) scale. At a PSI value of less than 1.0, the situation worsened and vehicle experienced 'greatly' accelerated vehicle suspension fatigue.

Accurate quantification of these costs has proven difficult due to the general lack of data and the complexity of factors which influence road user costs. Although, on the whole the VOC work out to be substantially larger than the construction and M&R costs for road projects. For this reason, the highway agencies should consider VOC when evaluating strategies for investment in pavement maintenance and preservation. Thus, a rational economic analysis that estimates the effects of pavement condition on vehicle operating costs at the network level should be conducted when deciding on important policy issues. Such an analysis will provide highway agencies with a mechanism for evaluating the impact of investment alternatives for maintenance and rehabilitation strategies on vehicle operating costs, helping identify options that yield economic and other benefits.

2.8 PAVEMENT PRESERVATION

At a Kansas City workshop [Smith, 2002], pavement preservation was defined as a 'program of activities aimed at preserving our investment in the nation's highway system, enhancing pavement performance, extending pavement life, and meeting our customer's needs. It is the sum of all activities undertaken to provide and maintain serviceable roadways; this includes corrective maintenance, preventive maintenance, as well as minor and major rehabilitation. It excludes capacity improvements and new or reconstructed pavements". The general concept behind pavement preservation is illustrated in Figure 2 [after Davies and Sorenson, 2000].

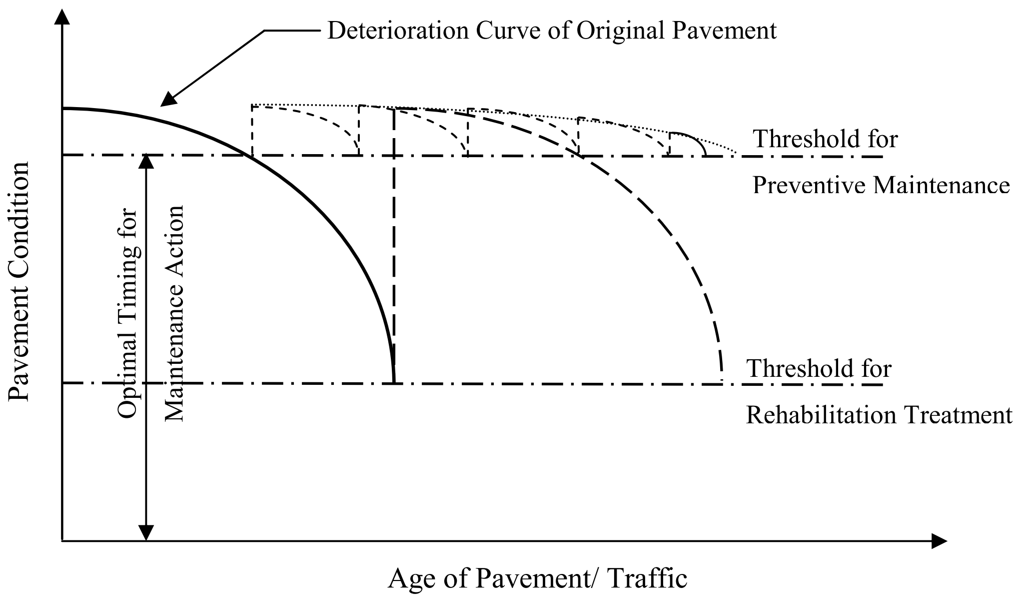


Figure 2: Most efficient use of M&R funds is obtained by applying maintenance actions at optimal times.

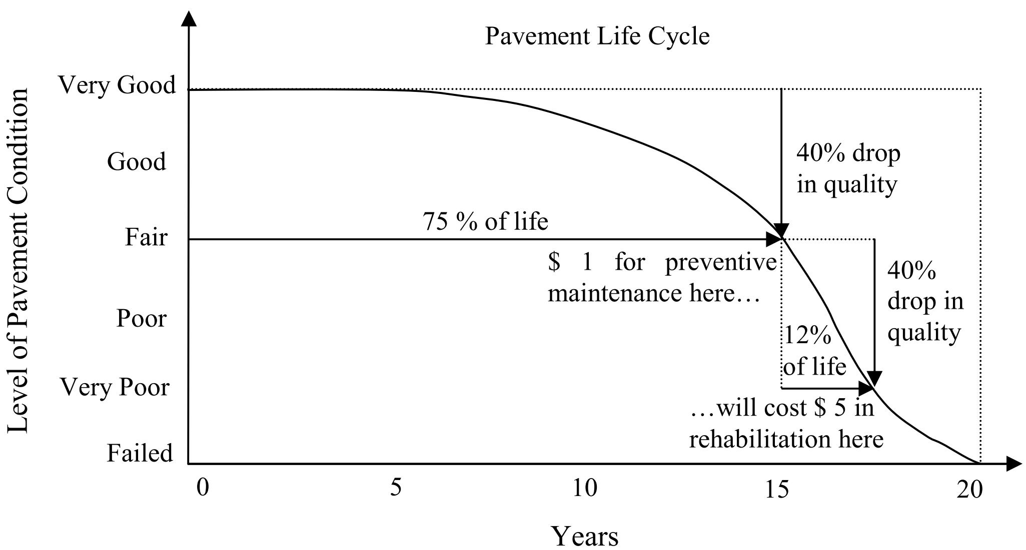
A pavement preservation program usually consists of three components: routine maintenance, preventive maintenance, and some minor non-structural rehabilitation activities. As a component of system preservation, it aims at preserving the investment in highway systems, extending pavement life, and meeting the needs of the systems' users. A pavement preservation program requires the timely application of carefully selected maintenance and rehabilitation (M&R) to maintain or extend a pavement's effective service life, not increasing its strength or capacity.

2.9 CONSEQUENCES OF DEFERRED MAINTENANCE

Deferred maintenance refers to the dollar amount of maintenance and rehabilitation work that should have been completed to maintain the pavements in good condition but had to be deferred due to reduced pavement treatment funding or policy changes for the preventative maintenance and/or pavement rehabilitation programs. Pavements that remain untreated continue to deteriorate. The cost of repairs increases disproportionately as the condition of the pavement decreases over its life. Deferring pavement preventive maintenance and/or rehabilitation can lead to a substantial increase in required repair costs [FHWA, 2005].

Most highway agencies have faced the situation where their funding needs for M&R activities exceed the available budget. As a result, the required routine maintenance and preventive maintenance activities which extend pavement life by slowing down the deterioration process usually suffer, or are overlooked completely. Failure to timely apply these inexpensive treatments causes the pavements to deteriorate more rapidly into conditions that warrant expensive rehabilitation actions at later stages in the pavement life cycle. Over time, a vicious cycle is instigated in which the maintenance and rehabilitation needs of the network keep increasing each year.

Sharaf, Shahin and Sinha [1988] had demonstrated increased M&R costs due to delaying M&R actions. Their study indicated that 'considerable' savings could be achieved by maintaining pavement sections adequately while they were in good condition instead of allowing them to deteriorate to poorer conditions. Based on their analysis, the annual maintenance costs of pavements in very poor condition could be as much as four times the costs if pavements were maintained while they are in good condition. The increment in life cycle costs due to deferred maintenance action is illustrated in Figure 3 [Metropolitan Transportation Commission, 2000].



Time varies depending on traffic, climate, pavement design, etc.

Figure 3: Pavement life cycle and cost of deferring maintenance activities.

Chasey, Garza and Drew [2002] developed a methodological framework that uses dynamic simulation techniques to quantify the impacts of deferred maintenance on the highway system and the effect on user and non-user benefits. Based on their tests of the simulation model on a hypothetical network, they showed how the policy decisions deferring maintenance negatively impacted measures of effectiveness such as total net benefits per capita, revenue less expenditures, and benefit-cost ratio.

CHAPTER 3. METHODOLOGICAL FRAMEWORK

3.1 EVALUATION OF PERFORMANCE GOALS

One approach to performance goals followed by transportation agencies such as FDOT, ODOT and the Texas Department of Transportation (TxDOT) is to have the goals determine the budget: a target condition level is established, the funding necessary to achieve this target is estimated, and the amount actually spent is compared against that estimate. In practice, however, the process is more complex and invariably becomes a ‘to and fro’ process in which condition targets help define budgets and the available funds constrain the performance goal. Because of these budget constraints, highway agencies sometimes have no choice but to set lower performance goals for their pavement network, as the consequences of lowering the performance goal cannot be presented as a clear case to the legislative body that appropriates the state budget [Zhang, Jaipuria et. al, 2010]. Aimed at assisting highway agencies in overcoming this dilemma, a methodological framework is proposed to quantify the total economic effect of setting different performance goals for the pavement network. Figure 4 illustrates the proposed methodological framework, the key components and the relationships among them.

Highways under an agency’s jurisdiction are usually identified and classified by pavement type and highway functional class. Structural and functional pavement condition and other inventory data are typically collected in an annual network-wide condition assessment. The data from these assessments are recorded as part of the agency’s inventory database. Calibrated deterioration models are applied to the current year condition to obtain the subsequent year’s condition. The analysis tool used to assess the total M&R needs prioritizes and selects M&R treatment options for every pavement section in the network based on the particular performance goal set for the network. The following year’s pavement condition is predicted using updated condition scores and the average network condition is determined. If a difference exists in the performance goal and the average condition achieved, the cycle is repeated as a loop for the analysis period, and the total M&R needs over the duration of the analysis are determined. In addition to the M&R Needs, the Vehicle Operating Costs (VOC) and deferred maintenance costs can also be determined for different performance goals, following the outlined methodology. Savings in M&R needs, exogenous VOC expenses, and deferred maintenance costs can then be used to evaluate the overall economic implication under different performance goals for the entire analysis period. Costs for different performance goals can be compared in a combined cost assessment, and the optimal performance goal for the network can be selected to minimize the combined network cost over the analysis period.

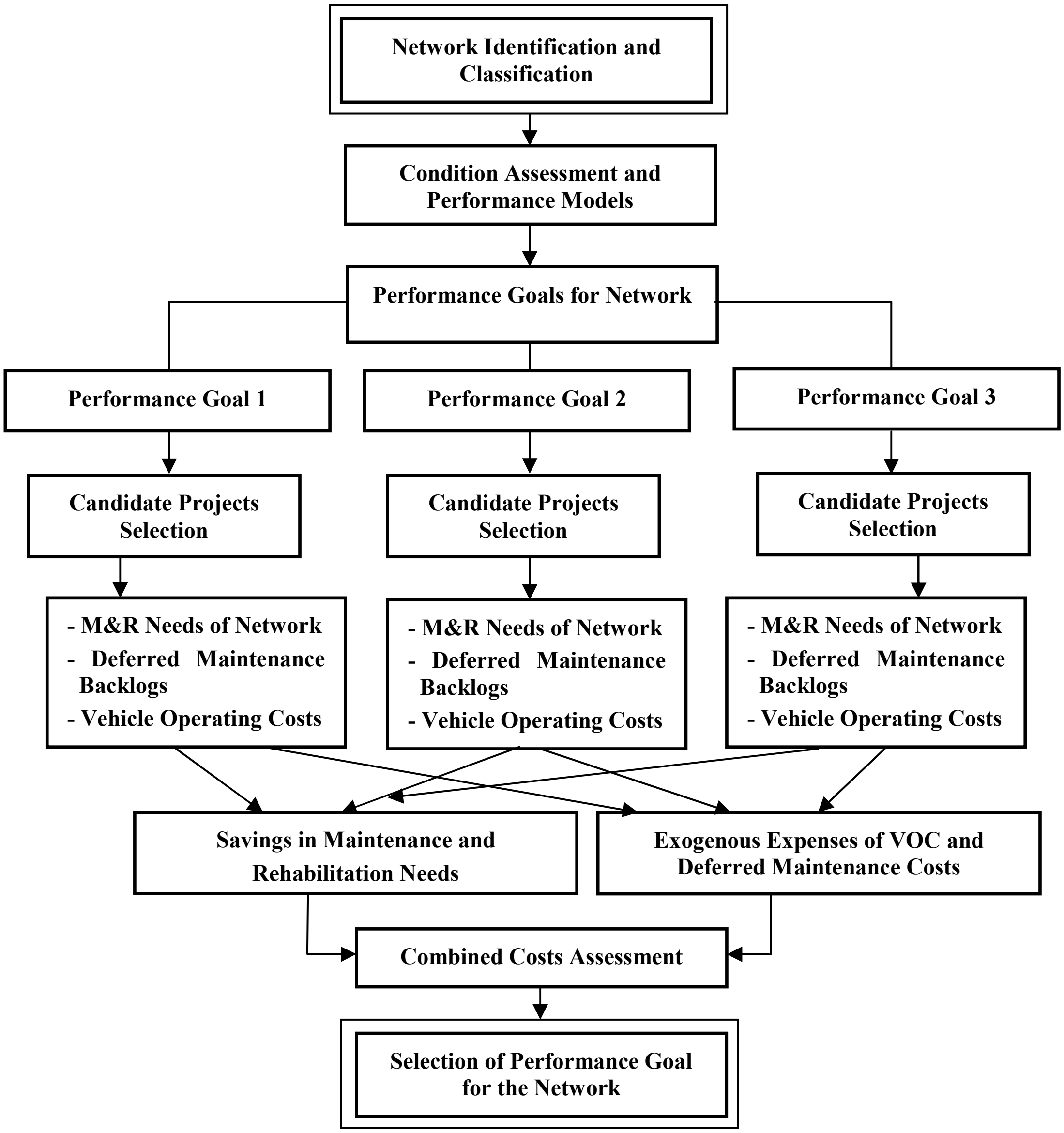


Figure 4: Methodological framework, key components and their relationships.

3.2 ANALYSIS APPROACH

Using the proposed methodological framework a series of "what if" type sensitivity analyses can be conducted that addresses questions such as:

- What are the consequences of allowing the network to deteriorate in terms of costs of operating vehicles to the users?
- What is the impact of a reduced performance goal on the overall condition of the system?
- Is it okay to forgo certain maintenance and rehabilitation activities that are warranted at this time?

Conducting this type of efficient sensitivity analysis can provide the decision makers with a basis for more informed decisions that are in the interest of not just their agency, but also the users of their system.

3.3 M&R NEEDS OF THE NETWORK

The M&R needs for a highway network should be based on historical data from the pavement inventory database. Using this data, the agency can identify which pavement sections need an M&R treatment, what type of treatment is required by each section, and the resources needed to apply that treatment. With the condition data and calibrated pavement deterioration models, the future condition of a pavement network can be predicted. The predicted future condition for a particular year of the analysis period, when compared with the performance goals set by the highway agency indicates the improvement required in the overall network condition. This difference establishes the network M&R needs.

Finally, combining the unit cost information with the required M&R actions provides the budget needs for M&R treatments for the highway network under consideration. This process when carried out in a loop over the analysis period yields the budget needs for M&R treatment for the individual year and also, for the entire analysis period. Establishing lower performance goals means a lesser number of sections will receive treatment to achieve the desired goal, leading to considerable savings in the M&R needs for the highway network over the analysis duration. The following equation can be used to determine the total M&R needs of the network over the analysis period [Zhang, Jaipuria et. al, 2010]:

$$TC = \sum_{t=1}^{T} \sum_{j=1}^{J} \sum_{i=1}^{I} X_{ijt} l_j c_{it}$$

where
TC = total M&R needs
t = analysis year (t = 1, 2, …, T)
j = pavement section in the network (j = 1, 2, …, J)
i = M&R treatments (i = 1, 2, …, I)
X_{ijt} = 1, when pavement section j receives treatment i at year t; 0, otherwise
l_j = length of pavement section j
c_{it} = unit cost for treatment i at year t
The difference in total M&R needs between two different performance goals can be determined using the equation:

$$\Delta TC_{mn} = TC_m - TC_n$$

where
ΔTC_{mn} = difference in total M&R needs between performance goal m and n
TC_m = total M&R needs to achieve performance goal m; m = 1, 2, …, G
TC_n = total M&R needs to achieve performance goal n; n = 1, 2, …, G

3.4 VEHICLE OPERATING COSTS

For a vehicle type, each VOC component is the product of the resources consumed and the unit resource price. Four major components of the VOC that have been considered in previous studies include: fuel, maintenance (including tires, oil, and other routine work), unanticipated repairs, and depreciation in the value of the vehicle. These component costs sum up to a vehicle operation class subtotal cost for that vehicle type. A product of the total VOC and the annual volume of the vehicle type represent the vehicle's total VOC per year. A sum of these VOC per year over all vehicle types gives the grand total VOC per year of the highway network [Bein et al. 1993].

Although vehicle operating costs (VOC) are usually not considered explicitly when making M&R decisions, they can prove to be significant when evaluating network performance goals for large highway networks. As shown in the literature review, it is well documented that decreased pavement condition due to lower ride quality results in increased VOC in terms of maintenance and repairs, tire wear, and vehicle depreciation. By setting lower performance goals for the network, more pavement sections are allowed to deteriorate before they receive a particular M&R treatment. As a result, the average network ride quality deteriorates over the years, resulting in costs transferred to users as higher vehicle operating costs. By setting suitable performance goals, more pavement sections would receive the appropriate M&R treatments, such as preventive maintenance and light rehabilitation at appropriate times, the outcome of which is improved overall ride quality of the network and resultant lower VOC. The following equation can be used to determine the total VOC for the network over the analysis period [Zhang, Jaipuria et. al, 2010]:

$$VOC = \sum_{t=1}^{T} \sum_{r=1}^{R} \sum_{v}^{V} \left(\left(1 + \alpha_r \right) u_v \right) P_{tr} VMT_t$$

where,

VOC = total vehicle operating cost for the whole analysis period
t = analysis year; t = 1, 2, …, T
r = pavement groups by the ride quality or smoothness; r = 1, 2, …, R
v = vehicle groups such as passenger cars, pickups/vans/SUVs, and trucks; v = 1, 2, …, V
u_v = unit vehicle operating cost for vehicle group v
α_r = percentage increase in VOC for pavement group r when compared with the baseline pavement group
P_{tr} = percentage pavements in pavement group r at year t
VMT_t = vehicle miles travelled in year t

The difference in total VOC when the performance goal is changed from m to n can be determined using the equation:

$$\Delta VOC_{mn} = VOC_n - VOC_m$$

where

ΔVOC_{mn} = difference in total VOC when the performance goal is changed from m to n

VOC_m = total VOC when pavement performance goal is set for m; $m = 1, 2, \ldots, G$

VOC_n = total VOC when pavement performance goal is set for n; $n = 1, 2, \ldots, G$

3.5 EFFECT OF DEFERRING PAVEMENT MAINTENANCE ON THE M&R NEEDS

Pavements that remain untreated continue to deteriorate. The cost of repairs increases disproportionately as the condition of the pavement decreases over its life. Deferring pavement preventive maintenance and/or rehabilitation can lead to a substantial increase in the required repair costs. Deferred maintenance refers to the dollar amount of maintenance and rehabilitation work that should have been completed to maintain the pavements in good condition but had to be deferred due to reduced pavement treatment funding or policy changes for preventative maintenance and/or pavement rehabilitation programs. Both routine maintenance and preventive maintenance extend pavement life by slowing down the deterioration process. The following equation [Zhang, Jaipuria et. al, 2010] can be used to determine the deferred maintenance for the network over the analysis period under different performance goals:

$$DMC_{mn} = \left(\sum_{t=1}^{T} \sum_{j=1;\forall j}^{J} \sum_{i=1;i \neq PM}^{I} X_{ijt} l_j c_{it} \right)_n - \left(\sum_{t=1}^{T} \sum_{j=1;\forall j}^{J} \sum_{i=1;i \neq PM}^{I} X_{ijt} l_j c_{it} \right)_m$$

where,

DMC_{mn} = total deferred maintenance cost when the performance goal is changed from m to n

t = analysis year; $t = 1, 2, \ldots, T$

j = pavement sections in the network; $j = 1, 2, \ldots, J$

i = maintenance and rehabilitation treatments; $i = 1, 2, \ldots, I$

PM = Preventive maintenance

X_{ijt} = 1, when pavement section j receives treatment i at year t; 0, otherwise

l_j = length of pavement section j

c_{it} = unit cost for treatment i at year t

CHAPTER 4. CASE STUDY WITH TXDOT HIGHWAY INFRASTRUCTURE

4.1 PAVEMENT MANAGEMENT SYSTEM: TXDOT EXPERIENCE

Although Texas Department of Transportation (TxDOT) spends nearly $2.7 billion annually in maintenance and rehabilitation activities on pavements [TxDOT, 2007], this amount is still insufficient to meet the total needs of pavement infrastructure. TxDOT engineers realized long ago that a good pavement management system could aid in stretching the available budget to obtain better results for managing its vast highway network. After several years of research, the first TxDOT PMS system called Pavement Evaluation System (PES) came into being in 1982. The PES was used for collection and monitoring of the network condition and for assessing the impact of fund utilization for pavement maintenance activities. After several modifications, the PES was replaced in 1993 with a more comprehensive system called the Pavement Management Information System (PMIS) which served the needs of the department at both network, and the project level [Sims and Zhang, 2010]. To this day, the PMIS serves as the largest automated pavement inventory database in the U.S. for storing, retrieving, analyzing, and reporting information to help with pavement-related decision making processes.

In the PMIS database, each pavement section (typically 0.5 mile long) is uniquely identified through an alpha-numeric code using the Texas Reference Marker (TRM) System. For prediction of the future pavement condition, the inventory and condition information from the PMIS database were combined to develop deterioration models that are based on the concept of utility curves. More recently, TxDOT and Center for Transportation Research at The University of Texas at Austin collaborated to create a new interactive, web-based decision support system which focuses on maintenance management and aids in carrying out multi-year, long-term pavement preservation and rehabilitation needs analyses subject to funding availability and performance requirements [Sims and Zhang, 2010]. This new system, named Pavement Performance & Maintenance Management (PPMM) consists of two main modules: the pavement performance module, and the maintenance management module which support different functionalities. The maintenance management module consists of tools that can be used for performing budget allocation and budget planning analyses. Further details on these tools are beyond the scope of this report and the interested reader is referred to the research by Sims and Zhang [2010].

4.2 OVERVIEW OF THE HIGHWAY NETWORK MAINTAINED BY TxDOT

The highway network maintained by TxDOT has several unique characteristics, the most predominant of which is its vast size. TxDOT maintains 79,696 centerline miles and about 192,150 lane miles of paved roadway including 50,189 bridges about 40 percent more than any other state in the nation [2030 Committee, 2009]. Table 1 lists the number of existing lane-miles, by highway system classification, that are managed by TxDOT. It should be noted that the Farm to Market (FM) road system, which primarily consists of surface-treated pavements, constitutes the largest percentage of lane-miles (44%). By contrast, the Interstate Highway (IH) system consists of 15,090 lanemiles (8%) and includes both asphalt concrete pavement (ACP) and Portland cement concrete (PCC) pavements.

Table 1: Number of Lane-miles by Highway System Classification in Texas.

Highway System Classification	**Number of Lane-Miles**	**Percentage of Total Lane-Miles**
Interstate Highway	15,090	8%
U.S. Highway	38,552	20%
State Highway	40,628	21%
Farm-to-Market Road	84,788	44%
Other Types	13,092	7%
Total Lane-Miles	**192,150**	**100%**

As mentioned before, TxDOT maintains the largest inventory database for its entire pavement network termed the PMIS database which continues to get updated every year with new pavement condition and other inventory data. This database contains information for more than 300,000 road sections of roughly 0.5-mile in length.

In a recent study carried out to evaluate the pavement maintenance needs of Texas by year 2030, it was estimated that in order to match up with the Texas Transportation Commission (TTC) goal of preserving the asset value of all pavements by maintaining a 90% 'good' or better pavement condition goal, the pavement preservation needs were about $3.5 billion per year on average [2030 Committee, 2009]. Figure 5 illustrates the annual M&R needs to attain and maintain 90% 'Good' or Better Condition from year 2009 to 2030.

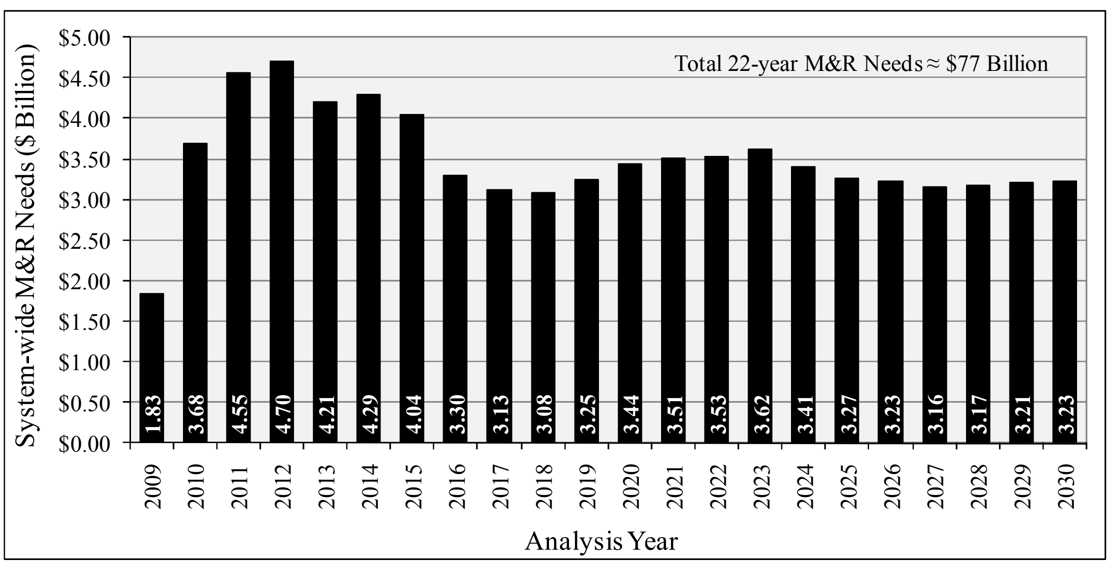


Figure 5: Annual M&R needs to attain and maintain 90% 'Good' or better condition.

The study also noted that whereas Texas had the largest M&R budget compared to the other states, it actually ranked 22nd nationally in terms of the lane-mile M&R expenditures in 2006. This is shown in Table 2.

Table 2: Texas and peer State 2006 M&R expenditure per lane-mile.

State	2006 M&R Expenditures ($ Billions)	State Center-Lane Miles	State Lane-Miles	Average Annual M&R Expenditure per Lane-Mile	M&R Expenditure National Rank
Texas	$1.82	79,489	191,530	$9,523	22
Pennsylvania	$1.32	39,843	88,293	$15,044	11
New York	$1.10	15,549	39,267	$27,907	3
Florida	$1.09	12,069	41,914	$25,999	5
Virginia	$1.06	57,481	124,383	$8,548	26
California	$0.82	15,234	50,594	$15,834	10
North Carolina	$0.69	79,067	168,930	$4,096	45
Illinois	$0.52	16,083	41,990	$11,976	18
Ohio	$0.41	19,266	48,888	$8,484	27
Georgia	$0.21	17,910	47,192	$4,481	43

TxDOT measures ride quality and rates pavement distress on the entire state-maintained highway network each year. The ride quality measurements and distress ratings are then stored in the PMIS database, which (among other things) calculates a series of three scores: Condition Score (CS), Distress Score (DS), and Ride Score (RS). CS combines pavement surface distress (such as rutting, cracking, potholes, punch-out's, and patches measured by DS) and ride quality (measured by RS) into a single index by taking traffic and speed limits into consideration. The CS ranges from 1 (worst condition) to 100 (best condition).

4.3 PERFORMANCE GOALS FOR TxDOT HIGHWAY NETWORK

A case study was carried out to assess the highway infrastructure needs of Texas under different performance goals. Three interacting sets of costs are typically considered for a complete economic appraisal of highway projects: construction, maintenance and road use costs. Since the focus has shifted from design-and-build mode to the repair-and-maintain mode, this study is restricted to maintenance related costs and the road user cost. The highway network under the jurisdiction of TxDOT was evaluated and the systems M&R needs were addressed by using the Pavement Needs Estimation and Scenario Tool (PaveNEST). This tool was developed by the Transportation Infrastructure and Information Systems (TIIS) Lab of the Center for Transportation Research (CTR) at The University of Texas at Austin. These needs were established based on pre-specified performance goals for the overall condition of the highway network. The performance goal set by the Texas Transportation Commission (TTC) was to have 90 percent of the pavements in the network at a condition of good or better. Pavement Condition Scores that are from 100 to 90 are categorized as Very Good; 89 to 70 are Good; 69 to 50 are Fair; 49 to 35 are Poor and 34 and below are Very Poor. In addition to the performance goal set by TTC, the needs of pavement infrastructure under the jurisdiction of TxDOT were evaluated for two other performance goals from the year 2010 to 2030:

1. *Performance Goal 1*: 90 percent 'Good' or better which translates into maintaining 90 percent or more of all pavement sections at a Condition Score level of 70 or more.
2. *Performance Goal 2*: 87 percent 'Good' or better which translates into maintaining 87 percent or more of all pavement sections at a Condition Score level of 70 or more.
3. *Performance Goal 3*: 80 percent 'Good' or better which translates into maintaining 80 percent or more of all pavement sections at a Condition Score level of 70 or more.

4.4 ANALYSIS ASSUMPTIONS

The key assumptions used in the analysis and prediction of the pavement conditions under different budget scenarios and performance goals include the following [Zhang and Murphy, 2009]:

1. *Pavement Network:* The pavement network considered for analysis comprised of the existing pavements under TxDOT's jurisdiction and is stored in the existing PMIS database. The most current version of the PMIS database was used in the analysis, based on the 2010 PMIS data collection.

2. *Base Year Network Condition:* The base year of the analysis was 2010. The condition of the entire State's pavement network was initially determined based on the individual scores of the pavement sections in the PMIS database. The Condition Score of these sections was used as the performance measurement index to calculate the "Good" or Better Pavement Scores.

3. *Deterioration Models:* The deterioration models are based on a statistical analysis that was carried out previously by researchers to analyze the deterioration rate distribution for the different pavement structure types and highway functional classifications. These deterioration models take into consideration the daily temperature range and the precipitation for the four distinct climatic regions of Texas. For each climatic region, separate pavement condition models pertaining to the Distress Score and the Ride score were developed [2030 Committee, 2009].

4. *Maintenance and Rehabilitation Costs:* The treatment costs for each selected M&R action were estimated using unit costs that are based on constant FY 2008 dollars. These costs reflect the project delivery costs including estimated costs for mobilization, traffic control, materials, labor, and ancillary items necessary to actually complete the pavement project in the state of Texas. The costs figures for different treatments used are shown in Table 3.

Table 3: Unit costs for maintenance and rehabilitation treatments by pavement type.

M&R Treatment Category	Unit Cost for Flexible Pavements ($/mile/lane)	Unit Cost for Rigid Pavements ($/mile/lane)
Needs Nothing	$0	$0
Preventive Maintenance	$29,000	$36,000
Light Rehabilitation	$173,000	$60,000
Medium Rehabilitation	$237,000	$256,000
Heavy Rehabilitation	$442,000	$651,000

5. *Improvements in Condition due to M&R intervention:* Based on expert opinion from academia and the industry, a matrix of improvement in condition (in terms of Ride and Distress Score) was formulated due to application of specific M&R treatments. The effects of M&R treatments on the pavement condition are shown in Table 4.

Table 4: Effect of maintenance and rehabilitation treatment on Ride and Distress Score.

M&R Treatment Category	Improvement in Ride Score (RS)	Improvement in Distress Score (DS)
Needs Nothing	0	0
Preventive Maintenance	0.5	95
Light Rehabilitation	1.5	100
Medium Rehabilitation	Reset to 4.8	Reset to 100
Heavy Rehabilitation	Reset to 4.8	Reset to 100

4.5 M&R NEEDS FOR TxDOT NETWORK

M&R needs correspond to the minimum financial resources required to achieve a particular performance goal. Thus, setting different performance goals will lead to different M&R needs for the system. PaveNEST was used to determine the future M&R needs of Texas in order for the network to achieve the specific performance goals. The analysis was based on 2010 pavement inventory data collection. The methodological framework that underpins the PaveNEST [Zhang and Murphy, 2009] is shown in Figure 6.

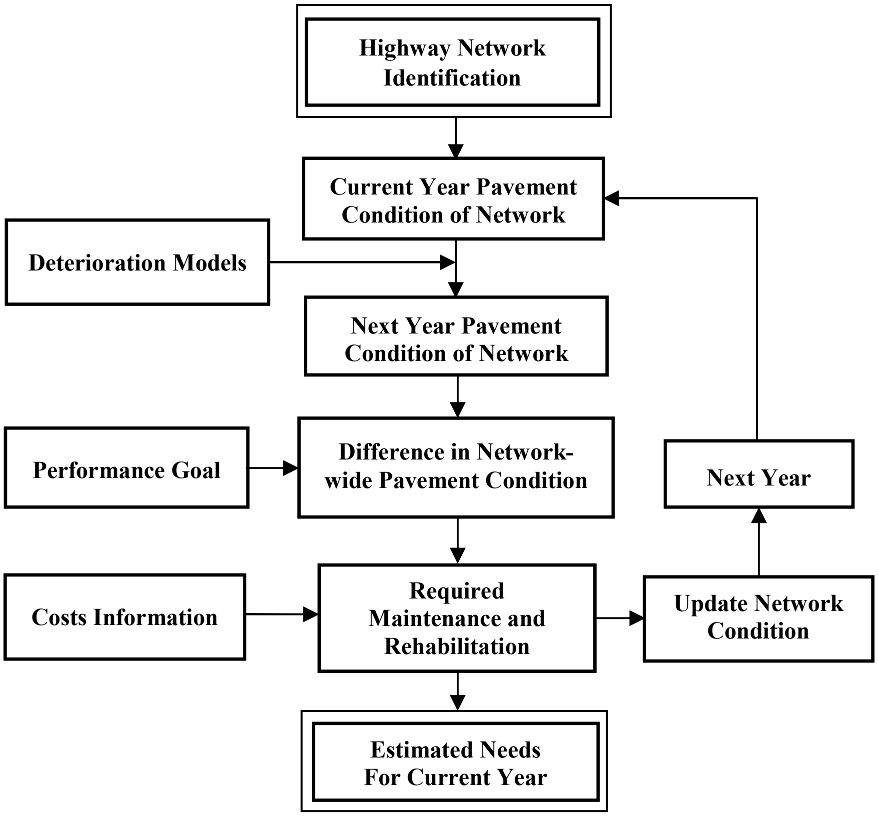


Figure 6: Methodological framework for M&R Needs Analysis using PaveNEST.

Once the projects are selected so that the specific performance goal is achieved, the analysis for the following year commences. The individual sections that receive treatment have their CS updated based on the improvement in the RS and DS, and the overall CS for the entire network is recalculated. This then leads to another cycle until all years in the planning horizon are analyzed. Based on the number of sections treated during the analysis year in order to reach the specific performance goal, the overall statewide M&R needs are determined. The total M&R needs under different performance goals obtained from the analysis are presented in Table 5.

Table 5: M&R needs of TxDOT managed pavement network from year 2010 to 2030.

Performance Goal Scenario	Estimated Total M&R Needs ($ billions)	Estimated Needs for Preventive Maintenance ($ billions)	Estimated Needs for Rehabilitation ($ billions)
90% 'Good' or better	$ 71.60	$ 9.63	$ 61.97
87% 'Good' or better	$ 67.13	$ 8.80	$ 58.33
80% 'Good' or better	$ 58.21	$ 7.27	$ 50.94

These M&R needs for the highway network were identified by assigning M&R actions to the pavement sections and selecting a pool of candidate projects based on a prioritization algorithm. The M&R actions that were assigned to the pavement sections were based on two criteria: the current RS, and the drop in the RS from the previous year to the current year for a particular section. While prioritizing the pool of candidate projects eligible for receiving an M&R treatment, three criteria were considered: the RS, the DS, and the current traffic level on the section as identified in the PMIS database.

The final selection of the sections that would receive an M&R treatment was based on the compliance of the system condition with the established performance goal for that analysis, or the restriction imposed in terms of the available budget during the analysis period. The type of resource allocation analysis being conducted (budget planning or budget allocation) defined this limiting criteria. Figure 7 illustrates the total lane miles requiring a preventive maintenance treatment during each year for the budget planning analysis under different performance goal scenarios.

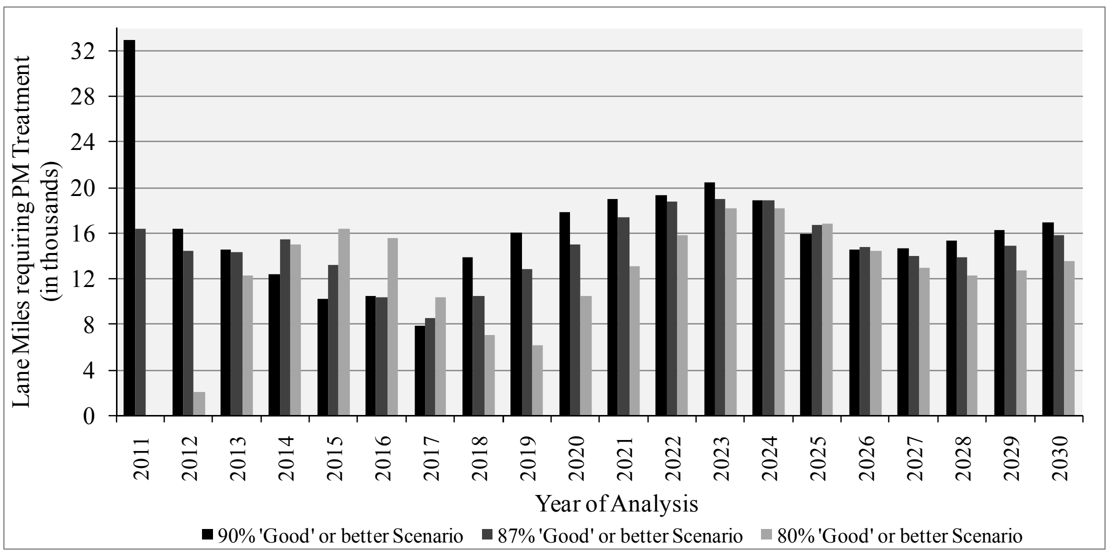


Figure 7: Lane-miles of Preventive Maintenance treatment needed from year 2011 to 2030 to attain and maintain specific performance goals.

Figure 8 illustrates the average lane miles requiring some form of rehabilitation treatment (light, medium or heavy) during each year for the budget planning analysis for different performance goal scenarios.

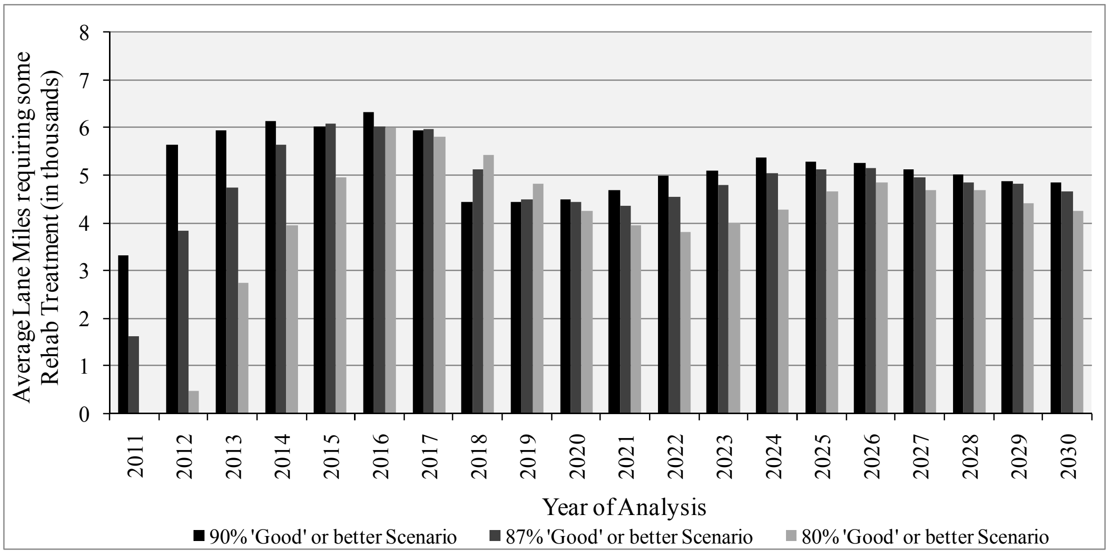


Figure 8: Average Lane-miles of some Rehabilitation treatment category needed from year 2011 to 2030 to attain and maintain specific performance goals.

4.6 BUDGET ALLOCATION SCENARIOS

Similar to the budget planning analysis just discussed, another important set of analyses that can be conducted using a pavement management system is to investigate how changes in funding level will affect the network condition, formally known as budget allocation analysis. This analysis can aid the decision makers at state DOTs to gain insight into the effects of program budget projections, effective allocation of available funds, and answer any questions from the legislature or the transportation commission on the consequences of varying the amount or distribution of required funds.

The budget allocation tool of the Maintenance Management Module was used to allocate specific budgets to the pavement network under consideration. Three budget scenarios are examined. Each scenario tests a particular funding level to preserve the pavement network through a twenty-year analysis period. The network condition is measured by the percentage of system in a ‘Good’ or better condition that translates to a Condition Score of 70 or more on a scale of 0 to 100 as defined earlier.

4.6.1 No Funding

At one extreme end of the range, if no funding is provided for pavement maintenance or rehabilitation the pavement system will experience a slow but steady decline in condition, with an anticipated Condition Score of 21.42 in the next ten years by 2020 and to an alarming 1.22 by the year 2030. This drop is significant because with the large drop in the average Condition Score, a number of pavement sections that would have otherwise qualified for the preventive maintenance treatment category would fall into the much more expensive major rehabilitation category resulting in magnified M&R costs. The resulting predicted pavement performance trend for the ‘no funding’ scenario from year 2010 to year 2030 is shown in Figure 9.

4.6.2 Unlimited Funding

Considering the other extreme end of the scale, if all maintenance and rehabilitation projects were to be funded, in other words the system was allowed to achieve a performance goal of 100% 'Good' or better, a total of about $81.418 billion in M&R needs would be required over the next 20 years. Funding at this level would raise the system average Condition Score to above 93 by 2030. This can be further broken down by the treatment category as $12.26 billion for Preventive Maintenance treatments and $69.158 billion for the Rehabilitation treatment category. The predicted pavement performance trend based on the unlimited funding scenario is shown in Figure 9.

4.6.3 Current Level of Fundy Based on TxDOT's Projections

It was briefly mentioned earlier that in order to match up with the TTC goal of preserving the asset value of all pavements by maintaining a 90% 'good' or better pavement condition goal, the pavement preservation needs were about $3.5 billion per year. Unfortunately, the M&R budget of Texas for FY 2007 was only $2.7 billion [TxDOT, 2007] and has seen a continual downward trend since then. A budget allocation analysis was conducted based on a long term funding scenario provided by TxDOT. The funding allocations for this scenario for FY 2010 to FY 2020 were based on the UTP funding levels and the funding projections from FY 2021 to FY 2030 were generated using the Texas Revenue Estimation and Needs Determination System (TRENDS) model, both provided by TxDOT. Using the PMIS pavement condition data, the funding allocations and projections provided by TxDOT, and the assumptions discussed earlier, the pavement condition analysis was conducted using the PaveNEST tool. The projected pavement performance in terms of the "Good" or better pavement scores for FY 2010 through FY 2030 are presented in Table 6, along with funding allocations and projections.

Table 6: Funding allocations and projected pavement performance from 2010 to 2030.

Year	Cat 1 Total	Cat 1 Total (Net Present Value in 2008 Dollars)	"Good" or Better Score (%)
2010			**86.97***
2011	$781,579,340	$715,255,814	82.59
2012	$781,579,340	$694,423,121	79.54
2013	$781,579,340	$674,197,204	75.49
2014	$1,060,070,000	$887,791,936	70.36
2015	**$1,060,070,000**	**$861,933,919**	**65.18**
2016	$1,285,070,000	$1,014,446,125	58.82
2017	$1,285,070,000	$984,899,150	52.10
2018	$1,285,070,000	$956,212,767	45.89
2019	$1,285,070,000	$928,361,910	39.98
2020	**$1,285,070,000**	**$901,322,243**	**35.18**
2021	$1,368,355,161	$931,783,281	31.12
2022	$1,321,384,391	$873,590,749	27.88
2023	$1,249,795,875	$802,196,414	25.37
2024	$1,173,006,070	$730,978,602	23.33
2025	**$1,055,721,023**	**$638,728,581**	**21.55**
2026	$1,027,531,254	$603,566,318	19.93
2027	$971,083,323	$553,795,250	18.43
2028	$814,036,117	$450,712,061	17.12
2029	$632,832,652	$340,178,734	15.63
2030	**$439,742,216**	**$229,498,165**	**14.02**

*Measured score for the base year of the analysis (FY 2010)

The "Good" or better pavement condition scores for FY 2015, FY 2020, FY 2025, and FY 2030 are highlighted in Table. As shown in Table 4, the "Good" or better pavement condition scores are 65.18, 35.18, 21.55, and 14.02 for FY 2015, FY 2020, FY 2025, FY 2030, respectively. The predicted pavement performance trend for FY 2010 to FY 2030 is also presented in Figure 9, along with the measured pavement performance trend for FY 2002 to FY 2010.

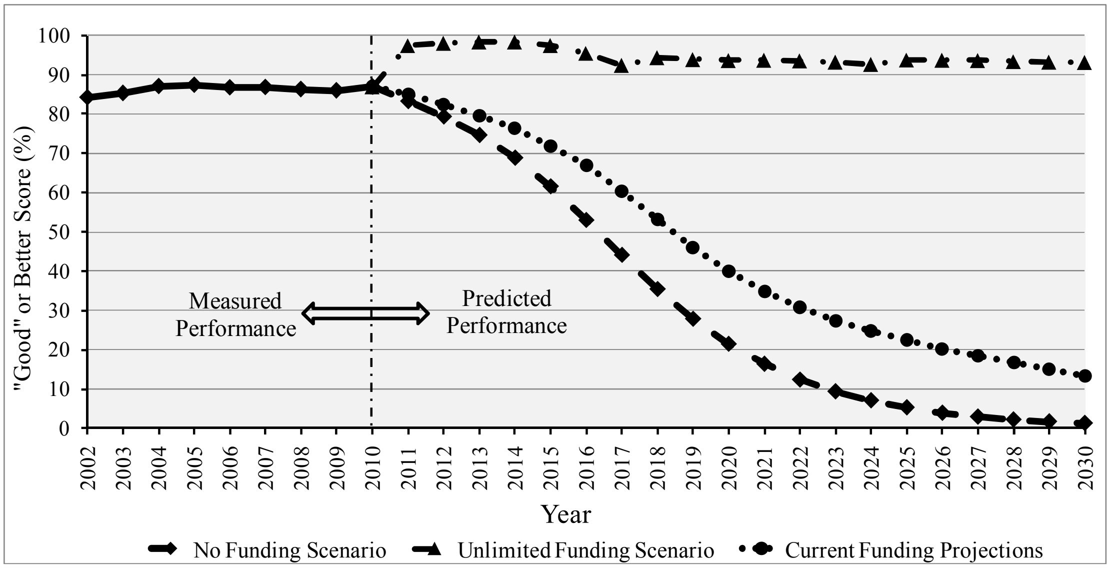


Figure 9: Predicted pavement performance trend from year 2010 to 2030 for different funding scenarios.

Based on the analysis results, it is obvious that these funding allocations and projections are significantly below the funding needs required to achieve and maintain the 90 percent 'Good' or better pavement Conditions that were estimated under the 2030 study. More specifically, with the current funding allocations and projections, the 'Good' or better pavement score will drop below 80 percent by year 2012; and by year 2018, the score will drop below 50 percent. The "Good" or better pavement condition scores based on current funding projection by TxDOT are 65.18, 35.18, 21.55, and 14.02 percent for FY 2015, FY 2020, FY 2025, and FY 2030, respectively.

Each scenario results in very different results at the end of the analysis duration. Together, they define the envelope delimiting a range of options in funding pavement infrastructure preservation. The predicted performance trends under the three scenarios can be used as the background information for discussion with the policy makers so that proactive measures can safeguard the system from deteriorating into unacceptable conditions.

4.7 VEHICLE OPERATING COSTS FOR TxDOT NETWORK

PaveNEST was used to relate increased VOC due to changes in the network performance goals which eventually lead to a change in the ride quality of the TxDOT highway network. The VOC calculations were specifically based on the findings of Barnes et al 2004 and the baseline unit costs for automobiles, pickup/van/SUVs, and commercial trucks that were developed in their study [Barnes and Langworthy, 2003]. Based on their findings, road roughness affects the maintenance, tire, repair, and depreciation cost components of vehicle operation. Their research suggests that a baseline Present Serviceability Index (PSI) of 3.5 (equivalent to an IRI of 80in/mile or 1.2m/km) has no impact on the VOC. Furthermore, a maximum multiplier of 1.25 for PSI values of 2.0 or lower (IRI of 170in/mile or 2.7m/km) is suggested. A linearly interpolated multiplier between 1 and 1.25 is suggested for roughness values between these limits. The proposed baseline operating unit costs (u_v) per vehicle category (v) from their study were 15.3 cents per mile for automobiles, 19.2 cents per mile for pickup/van/SUV, and 43.3 cents per mile for commercial trucks.

For the analysis, based on the truck VMT provided by TxDOT, 12.5 percent of the traffic comprised of commercial trucks which was assumed constant over the duration of the analysis. It was assumed that the remaining traffic comprised equally of automobiles and pickup/van/SUV vehicle categories had an aggregate baseline unit operating cost of 17.25 cents per mile. The pavement sections were classified into three different roughness categories (r) (Category 1: Ride Score ≤ 2.0, Category 2: 2.0 < Ride Score < 3.5, Category 3: 3.5 ≤ Ride Score) and the percentage of network pavements in each category (P_{tr}) was determined for every year of the analysis period. The final VOC unit cost for each year from 2009 to 2030 was determined by factoring in the effect of pavement sections roughness.

The multiplication factors ($1+\alpha_r$) used were 1.25, 1 and interpolated values between 1.25 and 1, for sections in Category 1, 3, and 2, respectively. The combination of the baseline unit costs with the percentages of the different vehicle classes as well as the percentages (and corresponding multiplication factors) of the sections in the different roughness categories, yielded the final unit costs for operating vehicles for each year of the analysis period. The total annual VOC was estimated by multiplying the annual average unit operating cost with the annual VMT.

For the annual VMT, an initial VMT value of 174.76 billion for year 2006 was obtained from information sources maintained by the Federal Highway Administration (FHWA) (13). The initial 2006 VMT was increased based on the forecasted total state VMT by Cambridge Systematics [2008]. The TxDOT on-system VMT was derived from the overall state VMT using the 2006 percentage which was 74.1 percent. This percentage was assumed to remain constant throughout the analysis period. The analysis by Cambridge Systematics provided state VMT values in 5-year intervals. Values for years in between were interpolated assuming a linear relationship. The results of VOC under different performance goals obtained from the analysis are summarized in the Table 7.

Table 7: VOC to the users under different performance goals from year 2010 to 2030.

Performance Goal Scenario	Estimated VOC ($ billions)	Difference in VOC due to change in Performance Goal ($ billions)
90% 'Good' or better	$ 993.879	$ 0.000
87% 'Good' or better	$ 1,000.848	$ 6.969
80% 'Good' or better	$ 1,015.075	$ 21.196

4.8 DEFERRED MAINTENANCE COSTS FOR TxDOT NETWORK

PaveNEST was used to obtain a summary of sections falling into different CS ranges during the analysis period. For specific performance goals, these sections were grouped into CS categories and the total section-lane-miles for each category by pavement type (Flexible or Rigid) was determined. M&R treatment trigger levels were set to establish the condition states along the standard deterioration model at which different treatments would typically be considered. Table 8 shows the CS range values that were used to appropriately identify M&R treatments:

Table 8: Condition Score ranges and corresponding M&R categories.

M&R Category(i)	M&R Description	CS Range
1	Preventive Maintenance	CS ≥80
2	Light Rehabilitation	60≤CS<80
3	Medium Rehabilitation	40≤CS<60
4	Heavy Rehabilitation	0≤CS<40

The unit costs for M&R treatments (c_{it}) for flexible and rigid pavements were used to calculate the total dollar needs for pavements falling in each of the M&R treatment categories (i). Cost due to deferring maintenance actions (DMC_{mn}) was determined from the shift in section-lane-miles from the preventive maintenance category to the more expensive rehabilitation categories under different performance goals. Change in performance goals and the corresponding shift in the sections to more expensive treatment categories, resulted in a significant amount of deferred maintenance costs. The results obtained from the analysis are summarized in Table 9.

Table 9: Deferred maintenance costs from year 2010 to 2030 to TxDOT due to change in performance goals for the system.

Performance Goal Scenario	Average Shift in Sections from PM to Rehabilitation Category (%)	Deferred Maintenance Costs due to change in Goal ($ billions)
90% ‘Good’ or better	-	$ 0.000
90% to 87% ‘Good’ or better	3.21%	$ 21.272
90% to 80% ‘Good’ or better	10.47%	$ 69.451

Figure 10 illustrates the shift in percentage of network section-lane-miles from the less expensive preventive maintenance category to the more expensive rehabilitation categories by lowering the performance goal from 90 percent to 87 percent and 80 percent ‘Good’ or better for the network.

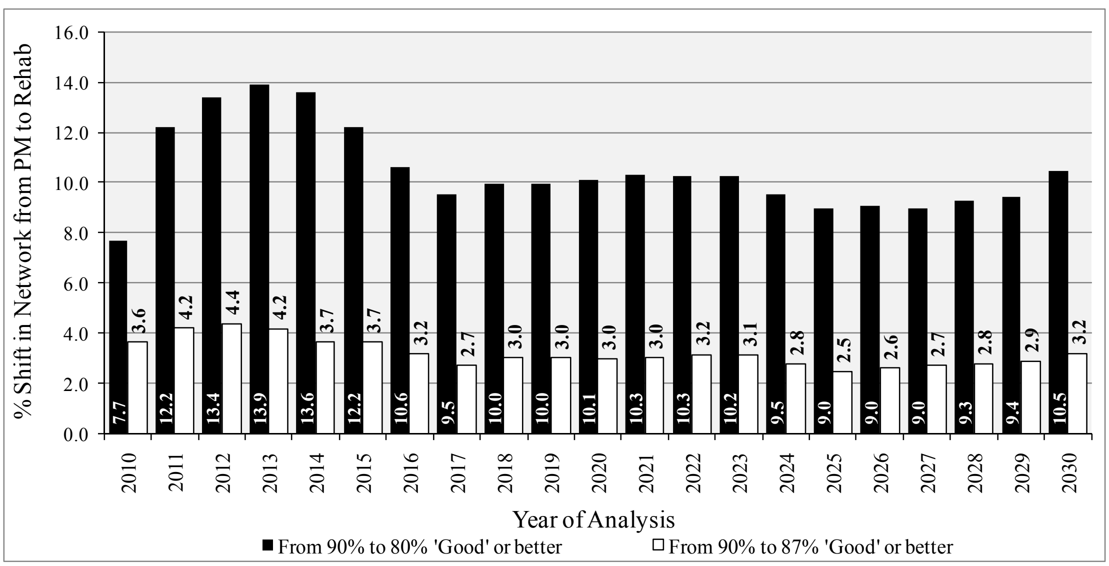


Figure 10: Shift in percent of network from Preventive Maintenance to Rehabilitation category due to reduction in performance goal from 90% 'Good' or better to 87% or 80% 'Good' or better.

CHAPTER 5. DISCUSSION OF RESULTS AND MULTI-TIER APPROACH

5.1 DISCUSSION OF RESULTS

The budget allocation and budget planning analysis bring out some issues that need serious consideration for the preservation and maintenance of the highway infrastructure managed by TxDOT. The results from the analyses are repeated below for the reader's convenience.

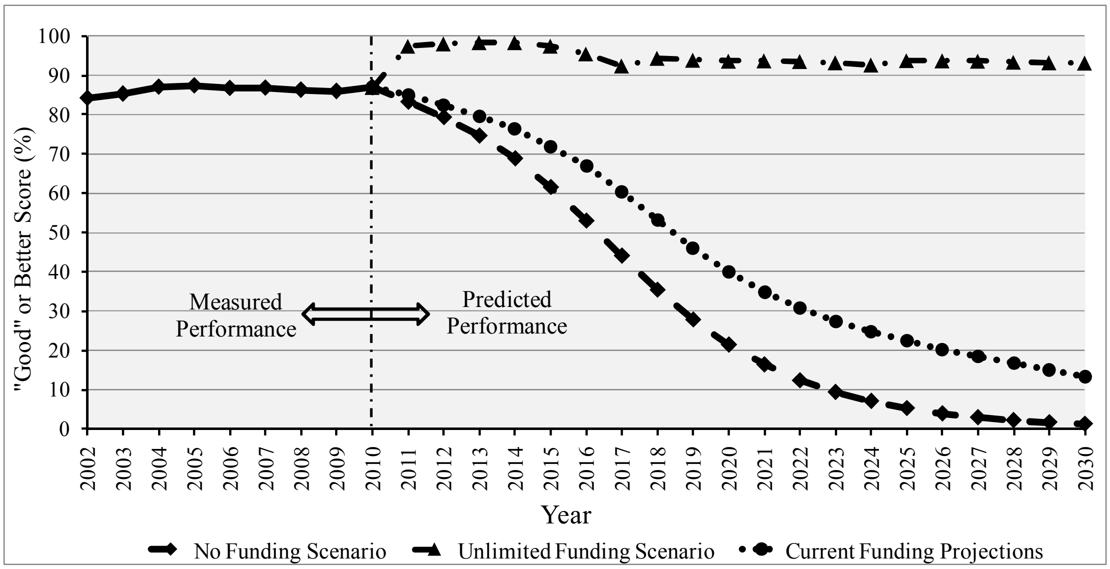


Figure 11: Predicted pavement performance trend from year 2010 to 2030 for different funding scenarios.

The results clearly indicate that the at current levels of funding for M&R programs and the future funding projections, from 2010 to 2030 as obtained from TxDOT, the 90% 'Good' or better goal cannot be achieved and maintained. At these funding levels, the system will continue to deteriorate to unacceptable levels. Additionally, a closer look at the funding projections shown earlier in Table 9, indicate that the funding for M&R programs is likely to drop significantly beyond year 2025. This would lead to a further degradation in the pavement condition of the network which could make the situation worse for subsequent years.

Furthermore, it was briefly discussed earlier, that currently about 87 percent of the highway network under the jurisdiction to TxDOT has a CS greater than or equal to 70. Based on the analysis of different performance goals for the system, the question that needs to be answered is: should the performance goal of 90 percent set by the TTC be maintained or should it be lowered to 87 percent (i.e, maintain the current level of performance condition) or 80 percent. To assist in the deliberation, a combined assessment of the benefits (as savings in M&R costs) and costs based on the TxDOT highway network is presented in Table 10.

Table 10: Combined costs for TxDOT managed highway network under different performance goals.

Performance Goal (*m*, *n*)	**Goal Description**	**Total M&R Needs for the Network (TC) ($ billions)**	**Vehicle Operating Costs (VOC) ($ billions)**	**Deferred Maintenance (DMC_{mn}) ($ billions)**
1	90%	$ 71.601	$ 993.879	$ 0.000*
2	87%	$ 67.128	$ 1,000.848	$ 21.272
3	80%	$ 58.212	$ 1,015.075	$ 69.451

*Deferred maintenance costs calculated relative to the 90 percent performance goal.

Considering the savings in M&R needs establishing an 80 percent performance goal would clearly reduce TxDOT's costs. When compared to a 90 percent goal, savings of about $13.389 billion accrue over 20 years. However, by reducing the goal from 90 percent to 80 percent, there are exogenous expenses of about $21.196 billion of VOC and $69.451 billion in deferred maintenance costs. These exogenous costs clearly outweigh the resulting savings by lowering the performance goal from 90 percent to 80 percent 'Good' or better.

Furthermore, maintaining the network at the current performance level of 87 percent would also result in significant costs in terms of VOC and DMC against little savings in M&R needs. Table 11 summarizes the key findings from the performance goal scenarios of the case study.

Table 11: Savings in M&R needs and corresponding increase in VOC and DMC for different goal scenarios.

Performance Goal (*m*, *n*)	**Goal Description**	**Savings in M&R needs (ΔTC_{mn}) ($ billions)**	**Increase in VOC (ΔVOC_{mn}) ($ billions)**	**DMC ($ billions)**
1	90%	$0.000[†]	$ 0.000[†]	$ 0.000[†]
2	87%	$4.473	$ 6.969	$ 21.272
3	80%	$13.389	$ 21.196	$ 69.451

[†] Savings in M&R needs, Increase in VOC and Deferred Maintenance Costs calculated relative to 90 percent performance goal.

5.2 MULTI-TIER SYSTEMS

From the discussions so far, it is clear that there is never enough money to pay for the maintenance and rehabilitation work that is required to keep the overall condition of the state-maintained highway system at the current target condition level. This situation has raised the prospects for a more rational 'utilization' based asset management technique, known as the 'Multi-Tier' approach to managing the highway network. This approach recognizes the fact that some highways are more important than others and need to be maintained accordingly. The top tier includes the high-priority highways, while the bottom tier(s) include all other roads built or maintained by the state. Re-structuring the system in this way can provide some interesting perspectives that can assist in understanding the user needs and expectations, establishment of goals that are realizable and can produce the desired results, and effective investment decision making.

5.2.1 Recent applications of Multi-Tier approach

Many states DOTs have adopted or are exploring multi-tiered system goals which involve reviewing the state's infrastructure needs by classifying transportation facility and service needs into multi-tiers- by interest and use. Without a tiered system, typically a 'worst-first' approach is adopted; however, since different roadways don't have the same function, a multi-tiered system helps these state agencies better manage their maintenance and rehabilitation needs. For these multi-tier systems, the needs of the highway infrastructure are prioritized based on the level of utilization of the roadways falling within each tier, for example, more resources are directed towards tiers that comprise the more heavily used roadways such as Interstate highways, and US routes.

Most DOTs follow the tier structure based on the national perspective of state roadways as developed by FHWA. Some other state DOTs such as California Department of Transportation (Caltrans) and Minnesota Department of Transportation (MnDOT) break down their highway network into two major categories: Interregional and Intraregional. This classification is based on the rationale that as a state DOT, the agency is 'sole provider' of the interregional transportation system, whereas it is a 'partner' in providing the intraregional transportation system. Thus, these DOTs have been able to lay greater emphasis on the performance goals and resource allocation for their interregional roadway systems [Markow and Racosky, 2001].

The Transportation Commission overseeing the operations of the Colorado Department of Transportation (CDOT) established system-wide goals for its multi-tiered transportation system. Under their direction, the performance goal for CDOT's Interstate roadway system has been set at 85 percent 'good or fair', 70 percent 'good or fair' for the National Highway System (NHS), and 55 percent 'good or fair' for other roadways. Together, the 'blended' target pavement condition for the entire CDOT roadway system is 60 percent 'good or fair' after accounting for the number of lane-miles in each tier [Markow and Racosky, 2001]. The authors rightly claim that the existing structure based on the major roadway categories from the NHS by itself is not adequate for some investment decision-making or performance monitoring and targeting. In order to have an adequate level of discrimination of system assets to understand the user expectations, support setting goals and objectives, and making investment decisions, state departments of transportation need to explore innovative ideas such as the multi-tiered system approach.

5.2.2 TxDOT and Multi-Tier Systems Approach

TxDOT has experienced a funding decrease in pavement preservation in the past few years, due largely to the federal rescissions, inflation of construction costs, the reduced fuel tax revenues that have been experienced, and the competition for mobility dollars. Based on results from the analysis, it is clear that the current and future predicted funding trends will be insufficient to provide TxDOT the resources to even maintain the pavement network at 80% 'Good' or better performance level. Consequently, TxDOT is now investigating a multi-tier system for managing the pavement network. The multi-tier system proposed is set up by taking into consideration functional classification of highways, the ADT, truck traffic, and the speeds on the highway system.

A review of the PMIS database brings out some interesting facts that suggest that structuring the system into multiple tiers could perhaps be a good idea. The database reveals that about 24% of the total highway system primarily consisting of Interstate and U.S. Highways currently carry about 70% of all truck traffic and also about 70% of all vehicles miles traveled. The local and state corridors serve as intermediate traffic routes that are important to the economy. These corridors constitute about 16% of the system total lane miles and carry about 17% of VMT. A distinct characteristic of these routes is that they experience appreciable truck traffic which average to over 700 trucks per day. Finally, the low traffic routes- mainly farm-to-market (FM) roads consist of about 60% of TxDOT on-system highways, whereas its share of VMT is only about 13%.

Considering these facts, it is arguable that the high traffic corridors which carry about 70% of TxDOT on-system VMT (and about 70% of all truck traffic) should be given top priority in terms of maintenance and rehabilitation needs. As the analysis of the 'blended' system indicated, the users of these facilities would also possibly incur a lion's share of the total system vehicle operating costs. Therefore it seems justified to set the highest performance standards (and corresponding goals) for these facilities. Also, since the low traffic routes consist of about 60% of total state lane-miles of roadways, and primarily consist of surface-treatment pavements, these would be in maximum need of the M&R program budget for each year. Further research is needed in this area to substantiate these observations and provide a solid case for framing a multi-tier system for better management of the state pavement infrastructure. As was the case for the 'blended' system, it can be quite a challenge for decision makers to establish appropriate performance goals for a multi-tier system, and objectively compare between different possible goals for each tier. The proposed methodological framework can be adapted to investigate the interrelationships between competing objectives and setting of performance goals for such a multi-tier system.

CHAPTER 6. CONCLUSIONS

6.1 CONCLUSIONS

The key objective of this study was to evaluate the consequences of setting different target condition levels on the needs of highway infrastructure. In order to meet this objective, a methodological framework was proposed that can assist highway agencies in objectively analyzing key policy decisions and the resulting total transport costs to the society. More specifically, the framework allows the estimation of the M&R needs of pavement infrastructure, and exogenous costs such as deferred maintenance costs and vehicle operating costs. A case study was conducted on the highway infrastructure under the jurisdiction of TxDOT and 3 scenarios were analyzed to address the question: 'what if' the target performance goal for the system was reduced to a lower threshold instead of the current goal of 90 percent 'Good' or better. Based on the findings, the following conclusions are drawn from this study:

1. With the current level of funding and future funding projections, it would be impossible to achieve and maintain the 90 percent 'Good' or better goal set by the Texas Transportation Commission. Unless drastic improvements are made to the future funding levels for M&R programs, the pavement infrastructure will deteriorate to unacceptable conditions in the years to come.

2. The proposed methodological framework proved to be a viable tool for examining different performance goals that are critical to the cost-effective preservation of pavement infrastructure and is generic and flexible enough for adoption by highway agencies with local data and practices.

3. Based on the proposed methodological framework, the relative importance of specific performance goals can be assessed and can aid the decision maker in planning safely within the constraints to meet desired objectives. In this sense, this methodology is a system-wide cost minimization exercise based on specific objectives and constraints.
4. The case study on TxDOT managed pavement infrastructure clearly indicates how changes in the performance goals for the system can affect both the agency maintenance costs (as M&R needs and deferred maintenance costs) and the road-use cost (VOC). Higher performance goals increase the M&R needs of the network, but at the same time, reduce the costs related to deferring maintenance actions and the transfer of the costs to the users as increased VOC.

5. From the results of the case study for Texas, it can be concluded that the ideal strategy for the Texas highway network would be to adopt the performance goal scenario of keeping 90 percent of the highway network at a condition 'Good' or better. This performance goal has been compared with other goals by looking at the overall network needs. Not only does this improve the overall network performance, it also results in significant savings in VOC and deferred maintenance costs over the other goals. As explained by the results of the 80 percent performance goal, Texas would be required to spend a significant amount of money on expensive rehabilitation and reconstruction projects due to the shift in sections from preventive maintenance to rehabilitation needs categories.

6. To deal with budget shortfalls and across the board budget cuts, the highway agencies will need to rethink the way they manage their assets. More rational techniques such as multi-tier systems can lead to more effective and efficient allocation of limited resources and aid in understanding user needs and expectations, and the establishment of goals that can be realized.

6.2 FUTURE SCOPE OF WORK

This present study can be extended further to look at various other possibilities to approach this subject such as:

1. The effects of establishing lower performance goals to control the percentage of the "very poor" pavements in addition to the existing practice of setting higher goals for the network. Doing so might help in reducing the amount of expensive rehabilitation treatments and prevent some pavements from reaching unacceptable standards while maintaining the overall network condition.

2. If the current 'blended' system approach does not seem sustainable, and a multi-tier asset management approach is considered, several issues will need to be addressed such as: the number of tiers and their composition, level of performance goals to be adopted for each tier of the system, considerations of safety and minimum acceptable conditions for specific tiers, changes required in the tier-structure over time, potential risks involved, as well as long term socio-economic and political implications, and institutional issues.

REFERENCES

Reid, R. L., *The Infrastructure Crisis*, Civil Engineering, The Magazine of the American Society of Civil Engineers, Volume 78, Number 1, January 2008

Christensen, J., and Skinner, M., *Communicating Budget Funding Solutions with Top Level and Elected Officials to Maintain Pavement Preservation Programs*, Compendium of Papers from the First International Conference on Pavement Preservation, Chapter 2: Paper 96, 2010, pp. 63-72

Hudson, W.R., Haas, R. C. G., and Uddin W., *Infrastructure management: Integrating Design, Construction, Maintenance, Rehabilitation, And Renovation*, McGraw-Hill, NY, 1997

Haas, R., Hudson, W.R. and Zaniewski, J., *Modern Pavement Management*, Krieger Publishing Company, Malabar, Florida, 1994, Chapter 33, pp. 421-422

Zhang Z., Hudson, W.R., and Haas, R., *Applied Asset Management*, Unpublished Manuscript, August 1999

American Association of State Highway and Transportation Officials, *Pavement Management Guide*, AASHTO, Washington, D.C., 2001

Cambridge Systematics, Inc., PB Consult Inc. and Texas Transportation Institute, NCHRP Synthesis of Highway Practice 551: *Performance Measures and Targets for Transportation Asset Management,* Transportation Research Board, National Research Council, Washington, D.C., 2006

Meyer, M. D., Cambridge Systematics, NCHRP Project 20-68, *U. S. Domestic Scan Program: Best Practices in Transportation Asset Management*, February 2007, p. 2-7, 2-57, 2-59

Saenz, A., Innovative Practices, *Testimony before the Senate Committee on Infrastructure Development and Security*, TxDOT, 2004

Parsons Brinckerhoff, Chait E. P., and Cambridge Systematics, Inc. *NCHRP Synthesis of Highway Practice 608: GASB 34—Methods for Condition Assessment and Preservation*, Transportation Research Board, National Research Council, Washington, D.C., 2008

U.S. Department of Transportation, *Asset Management Primer*, Federal Highway Administration, Office of Asset Management, December 1999

Wang F., Zhang Z., Machemehl, R. B., *Decision Making Problem for Managing Pavement Maintenance and Rehabilitation Projects*, Submitted to 82nd TRB Meeting, Washington D.C., 2003

Golabi K., and Pereira P., *Innovative Pavement Management and Planning System for Road Network of Portugal*, Journal of Infrastructure Systems, Vol. 9, No. 2, pp. 75- 80, June 2003

Barnes G., Langworthy P., *Per Mile Costs of Operating Automobiles and Trucks*, Transportation Research Record: Journal of the Transportation Research Board No. 1864, Transportation Research Board of the National Academies, Washington, D.C., 2004, pp. 71–77.

Bennett, C. R., and Greenwood, I. D., *Modeling Road User and Environmental Effects in HDM-4*, Version 1.0, HDM-4 Highway Development and Management, Vol. 7, November 2001

AASHTO Press Release, *Rough Roads Costing Motorists Hundreds More per Year*, 2009 http://news.transportation.org/press_release.aspx?Action=ViewNews&NewsID=231

Sime, M. and Ashmore, S. C., *Westrack Track Roughness, Fuel Consumption, and Maintenance Costs, TechBrief*, FHWA-RD-00-052, 2000

Poelman, M.A. and Weir, R.P., *Vehicle Fatigue Induced by Road Surface Roughness*. Vehicle, Tire, Pavement Interface, ASTM STP 1164, J.J. Henry and J. C. Wambold, Eds., pp. 97-111. American Society for Testing and Materials, Philadelphia, 1992

Smith, R. E., *Integrating Pavement Preservation into a Local Agency Pavement Management System*, Transportation Research Record 1795, Paper No. 02-3739, Transportation Research Board, National Research Council, Washington, D.C., pp. 27–32., 2002

Robert M. Davies and Jim Sorenson, *Pavement Preservation: Preserving Our Investment in Highways*, Public Roads, January/February 2000· Vol. 63· No. 4. http://www.tfhrc.gov/pubrds/jan00/pavement.htm

Federal Highway Administration, *Pavement Preservation Definitions*, U.S. Department of Transportation, FHWA, 2005 http://www.fhwa.dot.gov/pavement/preservation/091205.cfm

Chasey, Allan D., Garza, Jesus M. de la, and Drew, Donald R., *Using Simulation to Understand the Impact of Deferred Maintenance,* Computer-Aided Civil and Infrastructure Engineering, 2002, pp. 269–279

Zhang Z., Jaipuria S., Murphy M., Sims T., and Garza, T., *Pavement Preservation: Performance Goals and Its Implications,* Transportation Research Record: Journal of the Transportation Research Board No. 2150, Infrastructure Maintenance and Preservation, Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 28–35.

Sharaf E.A., Shahin M. Y., and Sinha K.C., *Analysis of the Effect of Deferring Preventive Maintenance*, Transportation Research Record 1205, Transportation Research Board, National Research Council, Washington, D.C., pp. 29–35

Metropolitan Transportation Commission, *The Pothole Report, an Update on Bay Area Pavement Conditions*, March 2000

Chesher, A.D., Harrison, R. and Paterson, W.D.O., *Vehicle Operating Costs: Evidence from Developing Countries*, World Bank, Washington, D.C., 1988

Bein P., Biggs D. C., *Critique on Texas Research and Development Foundation Vehicle Operating Cost Model*, In Transportation Research Record 1395, Transportation Research Board, National Research Council, Washington, D.C., 1993, pp. 114–121.

Texas Department of Transportation, "*Statewide Preservation Program*", Unified Transportation Program, TxDOT, 2007 ftp://ftp.dot.state.tx.us/pub/txdotinfo/tpp/2007spp.pdf

Sims, T. B., and Zhang, Z., *Texas Pavement Performance and Maintenance Management System*, Compendium of Papers from the First International Conference on Pavement Preservation, Chapter 3: Paper 13, 2010, pp. 149-160

Federal Highway Administration, *Highway Statistics 2008*, U.S. Department of Transportation- FHWA, 2008 http://www.fhwa.dot.gov/policyinformation/statistics/2008/fi10.cfm

2030 Committee, *Texas Transportation Needs Report*, Texas Transportation Institute, College Station, February 2009, pp. 9

Zhang Z., Murphy M., *Processes and Procedures for Pavement Needs Analysis*, 2030 Committee Texas Transportation Needs Report, Texas Transportation Institute, College Station, February 2009, pp. 107-116

Cambridge Systematics Inc., *Final Report Description of Current Texas Transportation Mobility and Maintenance Needs*, June 2008

Markow M. J., Racosky J., *Asset Management Implementation Plan and Tiered System Process*, Colorado Department of Transportation Research Branch, Report No. Cdot-Dtd-R-2001-13, 2001, pp. 120