MODELING PAVEMENT PERFORMANCE AND PRESERVATION

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

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ABSTRACT

Lu, Pan, Ph.D., Program of Transportation and Logistics, College of Graduate and Interdisciplinary Studies, North Dakota State University, September 2011. Modeling Pavement Performance and Preservation. Major Professor: Dr. Denver D. Tolliver.

The number of highway lane-miles in the United States increased by 7% from 1980 to 2007, while vehicle-miles of travel almost doubled. During the same period, the Federal Highway Trust Fund (the major source of funding for highways) grew by only 40% in constant 1980 dollars. With growth in trade and commerce, truck traffic levels are expected to increase significantly in the future. Highway agencies throughout the United States are facing complex decisions about maintaining, repairing, and renewing existing pavements in the most cost-effective ways. Decision makers need to learn: to what degrees different pavement preservation treatments will improve a pavement condition; how pavement conditions will change over time; when to apply which treatment to what section; and what budget level will be needed to maintain and improve pavement conditions.

The objectives of this dissertation are to 1) estimate the effectiveness of appropriate different levels of pavement preservation treatments, 2) evaluate pre-treatment and post-treatment pavement performances, and 3) use the uniformed results (of the first two objectives) to develop a decision making tool for integrated pavement management systems. The dissertation will utilize data from the Long Term Pavement Performance (LTPP) program. LTPP data will be used to estimate statistical models of the benefit effectiveness of preservation-related treatments and pavement performance, including models of performance jump—i.e., the instantaneous improvement in the performance or condition of a pavement due to a maintenance treatment. The forecast values from the statistical models will be used as inputs to optimization models that will allow for the

simultaneous solution of several objectives or constraints. The results will benefit pavement management systems and improve pavement preservation planning in the United States.

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CHAPTER 1. INTRODUCTION

1.1. Background and Motivation

According to Federal Highway Administration (FHWA), there were 40,448,524 miles of public road that carried 3,049,027 Vehicle Miles of Travel (VMT) at 2007. The lane miles increased only slightly more than 7% from 1980 to 2007; however, VMT almost doubled from 1980 to 2007. Meanwhile the Federal Highway Trust Fund grew only around 40% in constant 1980 dollars (3.66% inflation rate) from 1980 (without mass transit revenue) to 2007 (including mass transit revenue). Federal Highway Trust Fund is a major source of funding to manage the highways. The 2005 infrastructure report card published by the American Society of Civil Engineers (ASCE) indicates that "in 1999, total capital investment by all levels of government was $59.4 billion, well short of the needed $94 billion for highway capital investment." (ASCE, 2005, page 35). The ASCE 2009 report states (ASCE, 2009) that in 2009 spending for highway capital improvements totaled $70.3 billion, but the needed cost-to-improve level was $186 billion.

Improvements are needed as pavement deteriorates; pavement deterioration, in terms of roughness, rutting, cracking, etc., is a complex and continuous process. Deterioration is believed to be a function of cumulative traffic loading, seasonal climate variation, and aging. Within the context of greatly increased traffic, continuous pavement deterioration, and stringent funding, all highway agencies throughout the United States face similar problems. Problems such as, how to allocate these limited resources to maintain the highway network to the desired service level; how to facilitate cost-effective spending; what type of road treatments, in terms of maintenance, rehabilitation, and reconstruction, should be chosen to achieve these goals; and when to perform road treatment activities. These questions are of strategic importance, since the U.S. Department of Transportation (USDOT) has identified State of Good Repair as one of its top five goals. The goal is to ensure that the United States "proactively maintains its critical transportation infrastructure in a state of good repair" (USDOT, 2010, p. 21). Two of USDOT's strategies are to "support and advance sound asset management principles to maximize performance benefits resulting from investments in highways and bridges" and "develop a national agenda to identify opportunities for research to manage and preserve surface transportation infrastructure" (USDOT, 2010, p. 24).

This dissertation explores ways of managing and preserving highway pavements to attain state of good repair. Addressing pavement treatment issues is the main motivation. Hence, here the author does not focus on theoretical applications, but on applications yielding advice to pavement management agencies. Before trying to solve the problems that highway agencies categorize as pavement management problems, it is necessary to first have a comprehensive understanding of the background of the pavement management systems (PMS), how pavement management systems presently work for most highway agencies, and what problems pavement management systems are still facing.

1.2. Research Objectives

The main objective of this dissertation is to develop step by step models for resource allocation decision making under multi-criteria decision circumstances. This multi-objective optimization model is intended to enable pavement management agencies to make network level pavement preservation decisions based on conflicting objectives: minimizing costs, maximizing pavement smoothness, or, more appropriately, minimizing average network international roughness index (IRI) and minimizing IRI deviations within a network. The decision solution also needs to satisfy budget and unacceptable pavement condition constraints. The objectives of this research are

(1) To develop a decision making tool for integrated pavement management systems that minimize the average network IRI, and minimize the costs.

(2) To estimate effectiveness of appropriate different levels of treatments such as crack sealing, seal coat, aggregate seal, chip seal, hot mix resurfacing, and hot mill overlay.

(3) To evaluate pre-treatment and post-treatment pavement performances. For pre-treatment pavement performance, analyze the performance functions under with and without routine maintenance activities.

1.3. Methods and Scope of Research

Only pavement segments included in the Long Term Pavement Performance (LTPP) program in the United States and Canada were studied. LTPP data can be fed into statistical models to assist in forecasting future pavement conditions.

Two major types of statistical models related to pavement management system problems exist: treatment benefit effectiveness models and pavement performance models. Both models are based on collected historical data and attempt to build a statistical relationship between independent variables (factors that affect pavement future conditions or treatment effectiveness) and interested dependent variables (pavement future conditions or treatment effectiveness). The models are used to forecast future pavement conditions and treatment effectiveness. The forecast values from statistical models are then fed as input to optimization models to support future pavement management decision making.

The optimization models are based on Pareto optima concept to simultaneously solve all types of concerns or constraints to obtain the optimum targets, in order to minimize costs, and maximize benefits.

Statistical models will be developed based on the LTPP participant pavement segments empirical data. Optimization model will be developed for network level analyses. A case study will be tested for an artificial corridor network and the customized SAS codes are written for purpose of solving the specific multi-objective problem. The process, procedures, and the SAS codes can be transferred to develop models for all state Departments of Transportation (DOTs).

1.4. Research Contributions

Previous research has been conducted on pavement performance models to quantify the pavement performance. Limited previous research has been conducted on treatment effectiveness to quantify the short-term treatment effectiveness. Furthermore, combining short-term treatment effectiveness models with pre-treatment performance models to develop post-treatment performance models for different levels of preservation activities has not been previously researched.

While previous research has been conducted on multi-objective optimization models to optimize pavement preservation decision makings, only a few studies have attempted to integrate all different levels of pavement preservation actions and reconstructions into one true optimization model. Furthermore, the incorporation of a true direct multi-objective model and the post-optimization decision has not been previously researched or implemented in practice.

Integrated, consistent, and step-by-step strategic pavement management budget allocations and treatment selection decision making processes have not been researched or implemented in practice previously. Yet, pavement management specialties have stated that practical, consistent, integrated, and objective pavement management decision making tools are critical to pavement management systems and asset management systems.

The outcome of this research will demonstrate a multi-step strategic decision making process to assist pavement management systems in using a true multi-objective optimization model that incorporates values from regression models and explains pavement treatment short-term effectiveness and pavement performance. Taking into account that budgets are limited and pavement segments need to be preserved or improved in the cost-effective manner, the model will help managers better understand how pavements will be affected by different budget levels. Additionally, the study will provide decision makers a complete set of trade off values among all the objectives. Furthermore, the model will help highway legislators to determine budget allocations for highway preservation and construction over time.

This research will provide pavement management officials with a series of models and requisite knowledge from detailed analyses to undertake complex decision making exercises for often conflicting and multi-objective situations with confidence, considering network level budget allocations. In addition to benefitting pavement management officials, this research will benefit academics and consultants by extending the use of treatment effectiveness integrated pavement performance models and multi-objective optimization models through the distribution of knowledge pertaining to a new approach to selecting pavement management treatments with the potential to reduce pavement roughness and reduce total highway agency costs.

1.5. Organization of the Dissertation

Chapter 1 introduces the background and the objectives of the dissertation. The scope of the study is also highlighted. Chapter 2 presents the background of pavement management systems via examining definitions and the history of highway pavement management. The section will discuss related issues and explain the need for the study. Chapter 3 presents preservation treatment effectiveness analysis. This chapter provides data sources for pavement preservation treatment effectiveness analysis, research foundation, and development of empirical models. Chapter 4 presents a pavement pre-treatment and post-treatment performance analysis. This chapter provides empirical models for pavement performance. The chapter emphasizes the relationship between pre-treatment and post-treatment performances. Chapter 5 presents the multi-objectives optimization model to support pavement preservation decision making. The chapter reveals key research findings and analysis of the optimization. Simulated constraint boundary model, Genetic algorithm and Pareto optima are also provided in this section. Chapter 6 summarizes the significant findings from the previous chapters and states the contributions and limitations of this study. In addition, the chapter addresses areas of future research possibilities.

CHAPTER 2. PAVEMENT MANAGEMENT SYSTEM

2.1. Definitions of Pavement Management Activities

Pavement management activities are categorized into three major types by the intensity and possible structural change of the work. The types are Maintenance, Rehabilitation, and Reconstruction (MR&R). According to FHWA (2005), pavement management activities can be divided into four categories according to the purpose: corrective maintenance, pavement preservation activities, major rehabilitation, and reconstruction. Pavement preservation activities can be divided into routine maintenance, preventive maintenance, and minor rehabilitation. The relationship of the activities is described in Figure 1.

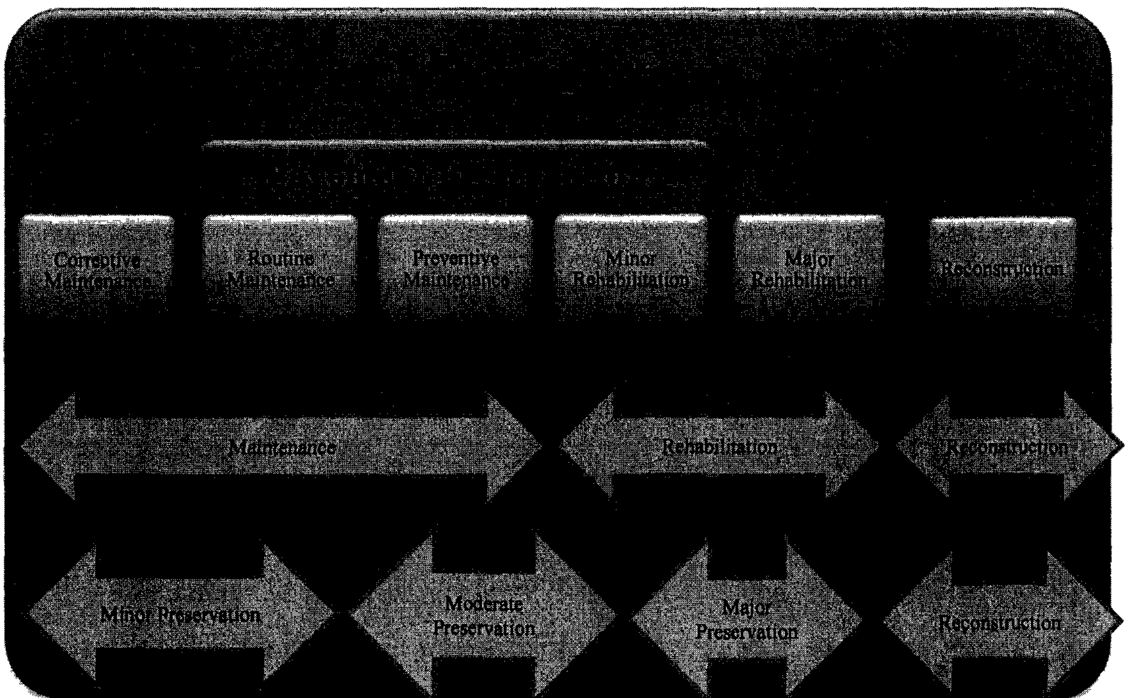

Figure 1. Relationships Among Pavement Management Activities.

FHWA's (2005) definition of corrective maintenance (CM) is "activities performed in response to the development of a deficiency or deficiencies that negatively impact the safe, efficient operations of the facility and future integrity of the pavement section." para. 16 (FHWA, 2005). Corrective maintenance activities are generally reactive and performed to restore a pavement to an acceptable level of service due to unforeseen conditions. It aims to increase structural capacity at a localized area only. Examples of such activities are pothole repair and patching of localized pavement deterioration.

FHWA's (2005) definition of pavement preservation (PP) is "a program employing a network level, long-term strategy that enhances pavement performance by using an integrated, cost-effective set of practices that extend pavement life, improve safety and meet motorist expectations." (FHWA, 2005, para. 7). It is the sum of all activities undertaken to provide and maintain serviceable roadways. It aims to preserve investment in the national highway system, extend pavement life, enhance pavement performance, ensure cost-effectiveness, and reduce user delays. The activities include routine maintenance, preventive maintenance, and minor rehabilitation. Pavement preservation excludes pavement structural capacity improvement and new construction or reconstruction.

FHWA's (2005) definition of routine maintenance (RM) is "consists of work that is planned and performed on a routine basis to maintain and preserve the condition of the highway system or to respond to specific conditions and events that restore the highway system to an adequate level of service." (FHWA, 2005, para. 13). Routine maintenance is a day-to-day activity. Examples of such activities are crack filling, line striping, mowing, and ditch cleaning, where crack filling is pavement-related activity and the others are non-pavement-related activities.

FHWA's (2005) definition of preventive maintenance (PM) is "a planned strategy of cost-effective treatment to an existing roadway system and its appurtenances that preserves the system, retards future deterioration, and maintains or improves the functional condition of the system (without significantly increasing the structural capacity)." (FHWA, 2005, para. 9). Examples of preventive maintenance activities are surface treatments such as crack sealing, fog sealing, chip sealing, slurry sealing, scrub sealing and cape sealing.

FHWA's (2005) definition of pavement rehabilitation consists of "structural enhancements that extend the service life of an existing pavement and/or improve its load carrying capacity. Rehabilitation techniques include restoration treatments and structural overlays." (FHWA, 2005, para. 11). Minor rehabilitation only consists of non-structural enhancements, for example, a less than a one and half inch asphalt overlay. Major rehabilitation consists of structural enhancements which both extend the service life of an existing pavement and improve its load-carrying capability, for example, a three- or four-inch asphalt overlay.

FHWA's (2005) definition of pavement reconstruction is "the replacement of the entire existing pavement structure by the placement of the equivalent or increased pavement structure" (FHWA, 2005, para. 18). The outcome of the treatment is a brand new pavement, which is viewed as the same as new construction.

Zaniewski and Mamlouk (1996) categorize crack filling and crack sealing as preventive maintenance because they define pavement preventive maintenance as "a program strategy intended to arrest light deterioration, retard progressive failures, and reduce the need for routine maintenance and service activities" (p.4) and define pavement maintenance as either routine or preventive. Researchers distinguish between corrective maintenance and preventive maintenance based on treatment timing, but not by treatment type, because the same treatment type can be used both as corrective and preventive maintenance. For example, if a treatment such as crack sealing is applied to a pavement in good condition, it is called preventive maintenance. When the same crack sealing is applied to a pavement in fair to poor condition, the goal is to correct minor-to-moderate distresses and seal the surface. In this case it is referred to as corrective maintenance. However this definition will create confusion among agencies and make it more difficult to implement a good pavement management system, since the same type of treatments can be used as routine maintenance, corrective maintenance, and preventive maintenance.

In this research the author proposes the concept that crack treatments, all corrective maintenance treatments, and even rehabilitations should be categorized as pavement preservation activities due to their pavement preservation nature. The treatments all try to preserve pavement by retarding pavement failure and extending the functional life of a pavement. Instead of making distinction between corrective maintenance, routine maintenance, preventive maintenance, rehabilitation, and reconstruction, this author creates a distinction between minor preservation-effect activity, moderate preservation-effect activity, major preservation-effect activity, and reconstruction, defining treatment effectiveness levels in terms of pavement roughness change. The relationship of pavement management activities is shown in Figure 1. By defining pavement activities in this way, the only difference lies between levels of preservation activities and reconstruction. The definition is relatively simple and creates less confusion. Adopting this definition of pavement management activities will help researchers to integrate all different levels of pavement activities into one decision analysis system and to generate a true integrated pavement management system.

Minor preservation-effect activities include all non-pavement related activities (such as mowing, under drain maintenance, and cleaning), as well as activities of simple crack treatment and pothole patching. Those activities are normally referred to as basic routine maintenance (BRM) and corrective maintenance. Minor preservation-effect activities are often applied to pavements as needed usually triggered by signs of appearance. Moderate preservation-effect activities include major crack treatment and all other commonly used preventive maintenance treatments (such as slurry seal, chip seal, ultra-thin-overlay and microsurfacing) and some minor rehabilitation such as thin-overlay (less than one and a half inch overlay). Major preservation-effect activities include the other minor rehabilitation and major rehabilitation (such as a hot mill overlay greater over than 1.5 inches thick).

2.2. Evolution of Pavement Management and Pavement Preservation

Americans saw France's good roads by participation in World War I in 1917 and 1918 and came home convinced the America do just as well. From World War I until the middle of the twentieth century in the United States, officials focused on new construction. In 1948, the American Association of State Highway Officials (AASHO) published a policy regarding maintenance of roadway surfaces. This was the first step in drawing more attention to maintenance instead of focusing on construction. At the time, most of the highway agencies still emphasized building and improvement instead of maintenance and preservation. Maintenance and rehabilitation began to draw more attention from highway agencies later when the interstate highways were opened and traffic levels increased. In this phase of the evolution, highways were used more intensely, showing greater deterioration, and needed to be rehabilitated more quickly if no maintenance was performed. Agencies soon noticed and realized that the pavement damage caused by a dynamic load on a low serviceability pavement is greater than the damage caused by the same load on a higher serviceability pavement. Research has verified this and shows the damage is about 50% greater (Gillespie & Karamihas, 1993). In other words, pavement deteriorates faster when the pavement is in poor condition than in good condition; preservation attempts to keep the pavement in good condition longer, which unfortunately, few researchers and agencies realized at the time.

At the beginning of the era in which the focus shifted from expanding the highway system to preserving and maintaining the highway system, highway agencies allowed pavements to deteriorate to fair or poor condition in terms of both ride quality and structural condition before taking steps to major rehabilitation. During this period, agencies only applied corrective and routine maintenance, but performed no other pavement preservation measures until the highway segment qualified for major rehabilitation or reconstruction. The objective of major rehabilitation is to repair structural damage and restore pavement condition. Thus, it is often associated with higher cost, longer application time and greater interruption to highway users. With limited funding, agencies have applied major rehabilitation to the highway segments with the worst pavement conditions, which is known as the "worst first" strategy. Most highway agencies managed the highway system in a "worst first" manner until the 1970s, when the concept of Pavement Management System (PMS) was introduced to highway agencies.

The concept of PMS was first introduced by Hass and Hutchinson in 1970 with their paper "A Management System for Highway Pavement." American Association of State Highway and Transportation Officials (AASHTO) define the PMS concept as an established, documented procedure treating many or all of the pavement management activities in a systematic and coordinated manner (AASHTO, 2001). PMS should consists of the following essential elements structured to serve decision-making at various management levels: 1. Pavement surveys related to condition and serviceability, 2. Database containing all pavement related information, 3. Analysis scheme, 4. Decision criteria, and 5. Implementation procedures.

Basically PMS is a systematic decision support system to assist highway agencies in finding cost-effective strategies or creating a schedule for managing their highway networks. Only a few states started to develop systematic procedures for managing their pavement networks prior to 2000. However, more decision makers began to look for systematic cost-effective strategies during the 1990s. A 1997 United States Department of Transportation (US DOT) report to congress, "Status of Nation's Surface Transportation System: Condition and Performance," warned that the pavement for over 48% of rural interstate mileage and nearly 60% of urban interstate mileage was rated in fair to poor condition, indicating that the U.S. highway infrastructure needed to be improved and maintained. The results of the report alerted people that U.S. highways needed improved pavement management to achieve better overall pavement conditions. In addition, with limited budgets, more researchers and agencies started evaluating systematic cost-effective strategies and discovered that applying a series of low-cost preservation treatments when the pavement is still in relatively good performance condition can extend the pavement's service life, which not only postpones costly, time-consuming major rehabilitation, lowering overall costs, but also can provide better ride quality in general and greater user satisfaction (Peterson, 1977; Zaniewski & Mamlouk, 1996; Mamlouk & Zaniewski, 2001).

With more detailed research about pavement preservation treatment effectiveness, pavement preservation started becoming more attractive over the "worst first" strategy for some highway agencies. However, without dedicated funding, pavement preservation programs struggled to become successful since federal-aid funding was only available for new construction or major rehabilitation in the 1970s. Some agencies still use the "worst first" strategy and allow highways to deteriorate to fair or poor pavement condition, not only because of shortages of funding for pavement preservation, but also because of the relative availability of major rehabilitation or reconstruction funding.

Pavement management systems have become standard tools in most state departments, though states have different levels of PMS. After the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA), the National Highway System Act of 1995 (NHSA), and the new Transportation Equity Act for the 21st Century (TEA-21) were enacted, most state departments now agree with the importance of pavement preservation. ISTEA allowed federal funds to be used for pavement preservation on interstate highways and required that a PMS be used for all highways, streets, and roads eligible for federal funds. The NHSA of 1995 made the federal funds eligible to all federal-aid highways. The TEA-21 emphasized the need for pavement preservation. With this legislation, agencies started to shift the focus from rehabilitation and reconstruction of highways to preserving highways. Most agencies will not allow highways to deteriorate to fair or poor pavement condition without taking action. Still, a few agencies use the "worst first" decision strategies because of limited funding. The "worst first" decision strategy is easy to understand and implement when there is a lack of the supportive guidance for systematic decision makings.

Two AASHTO documents provide a complete guide to develop a framework for PMS, detailed treatments of PMS, and processes for pavement management. The first, "Guidelines for Pavement Management System" published in 1990, and the other, "Pavement Management Guide" was published in 2001. The two documents still do not provide enough detail for agencies to implement, especially those lacking systematic decision making tools. Many researchers have constructed various models to support PMS decision making. Some of these studies focus on pavement performance and treatment effectiveness, while others focus on optimization models for allocating the budget and scheduling pavement management activities. The detailed literature review will be presented later.

The AASHTO documents and other earlier efforts in support of PMS decision making have greatly enriched the knowledge in PMS; however, few of these models were developed focusing on real world applications to assist in decision making. Dekker (1996) found that many papers published by 1996 focused on mathematical analysis and new techniques, rather than solutions to real problems. He stated, "It is astonishing how little attention is paid either to make results worthwhile or understandable to practitioners, or to justify models on real problems or to consider data problems" (Dekker, 1996, p. 235). Few current models address routine maintenance activities, corrective maintenance activities, preventive treatments, rehabilitation, and reconstruction in the same decision making model due to the complexity of solving the model. In state-of-practice, some states have separate preventive maintenance decision making systems and maintenance, rehabilitation, and reconstruction decision making systems. Other states have preventive maintenance treatment programs that are run ineffectively, while still some states do not consider pavement preventive maintenance (PPM) at all (NCPP, 2005). PMS is designed to address MR&R needs, so pavement preservation should be considered along with all other types of activities. Models that consider all types of pavement treatment strategies systematically and simultaneously to create a truly optimized, integrated maintenance policy have not been researched or implemented in practice; however, there is great need for an integrated model to serve as a highway maintenance and rehabilitation planning guide that considers limited budgeting allocation, cost-effective treatment selection, and optimal schedule planning on both network and project levels. In this dissertation, the author will focus on finding such an integrated budget allocation and treatment schedule model.

2.3. The Challenges for the Effective Pavement Preservation

Preventive maintenance is a major component of pavement preservation, which is gaining widespread popularity so as to preserve the existing highway system and postpone more costly rehabilitation efforts. This translates into a better ride quality, lower user costs and better customer satisfaction. Traditionally, agencies focused on routine and corrective maintenance activities instead of preventive maintenance and minor rehabilitation activities. Routine and corrective maintenance are often triggered by threshold values and/or signs of deterioration, receiving lower priorities than major rehabilitation or reconstruction. Many researchers successfully modeled the effectiveness of the different types of PPM treatments (Hicks & Dunn, 1977), and optimized the timing of the PPM treatments (Mamlouk & Zaniewski, 2001). The work of these researchers clearly demonstrated that PPM treatments applied at the right time are cost effective since they defer the costly treatments by years and improve overall life cycle cost-effectiveness within the network. Other successful experiences with pavement preventive maintenance in many agencies show that every dollar spent now on preventive maintenance can save up to $6.00 in the future (Davies & Sorenson 2000; FP^2, 2001). The successful experiences promote a broad, common realization of the importance of pavement preservation. A survey sponsored by the Foundation for Pavement Preservation (FP^2) conducted in 2000 showed that 10 out of 34 responding agencies said they do not currently have a PPM program and 5 out 23 agencies that currently have a PPM program believe that their PPM program does not meet their needs. The results of the survey raise questions about why people seem to agree that PPM can save money and provide better pavement conditions, but preventive maintenance is not adopted nation-wide. Additionally, even if it is adopted by some agencies, why it is not successful in all of the agencies?

Decision makers face several challenges to implement a pavement preservation program, especially PPM treatment application. One challenge is the separate decision making systems. According to a 2005 survey conducted by the National Center for Pavement Preservation (NCPP) and the FHWA, results from individual state departments of transportation (DOTs) showed that about 66% of the state DOTs have not integrated pavement preservation programs into a comprehensive network strategy that includes major rehabilitation and reconstruction projects; additionally, 59% of agencies have completely separate preservation programs and pavement management systems (NCHRP, 2005). Many researchers have developed effective optimization policy models, but those models either only consider MR&R activities without PPM treatments or only consider PPM and reconstruction activities. Because of this, it is a challenge to convince agencies not to follow the "worst first" strategy since optimal models suggest applying preventive maintenance to road segments that are still in good condition, while several other road segments need rehabilitation as suggested by other models. With limited funding, all of the improvements cannot be implemented at the same time. Hence, there is a great need to evaluate all types of treatments, corrective maintenance, routine maintenance, preventive maintenance, minor rehabilitation, major rehabilitation, and reconstruction, in addition to all possible funding sources within the same model to suggest the best policy. In other words, there is great need to have an integrated optimization model considering all types of treatments and all possible funding sources to use as an aid for pavement management systems.

The second challenge is the lack of a comprehensive applicable planning guide. Many published journal papers and study guide reports attempt to model and guide the optimized planning strategy. Unfortunately, these papers and guides fall short because some of them only consider simplified treatments to create a solution for a complicated mathematical model, while the others only perform cost-benefit analysis timing strategy for a specific treatment at a time. In practice, agencies often feel it is unreliable to use the models since a model often cannot address network problems or provide the true optimized planning result.

The third obstacle is a lack of information about the performance and effectiveness of different treatments, especially preventive maintenance practices. The fact that the effectiveness of pavement preservation activities has not been well documented throughout the United States (Wu & Groeger, 2010) makes pavement preservation philosophy intuitively perfect, but applicably difficult. Several reasons contribute to the limited application of pavement preservation programs. The first is a lack of necessary and adequate information about performance. For example, many preventive maintenance treatments were considered unsuitable for high-volume roadways like chip seals, thus making the related data about performance in various traffic and road conditions inadequate. Also federal funding for preventive maintenance has only been available for 20 years, thus, few agencies have started to invest money to perform preventive maintenance treatments to in-service road segments at different ages, to evaluate the effectiveness of the treatments, and to collect the information about in-service performance and effectiveness. Secondly, pavement condition and performance data are collected and analyzed using different standards and tools across states making it difficult to compare pavement performance between states (Wu & Groeger, 2010). Uniform standards of performance are needed to help better understand pavement management activities' performance and decision making. Finally, lack of long-term monitoring of pavement data makes long-term effectiveness analysis difficult.

CHAPTER 3. PAVEMENT PRESERVATION TREATMENT EFFECTIVENESS

In this chapter a review of pavement preservation treatment benefit effectiveness is conducted. The first section discusses the previous researches regarding pavement preservation treatment effectiveness, followed by a second section where a discussion regarding LTPP database. Then the third section provides discussions regarding empirical treatment short-term effectiveness model formulation and the results of the models. The last section summarizes the chapter.

3.1. Treatment Effectiveness Models Literature Review

Accurate information about benefit effectiveness of maintenance and rehabilitation (M&R) activities is essential and fundamental for a sound effective pavement management system because pavement management decisions are often based on benefits effectiveness. Measures of the effectiveness of M&R activities and costs are the most critical inputs for selection among different alternative treatments in pavement management. Benefits or effectiveness can be defined as to what degree the treatment applied to the pavement accomplishes the agency's intended objectives (Irfan & Khurshid, 2009). Benefits or effectiveness are normally non-monetary (Labi & Sinha, 2003a). In general, two types of effectiveness measurement models were developed in the past: short-term and long-term (Madanat & Mishalani, 1998; Labi & Sinha, 2003a; Irfan & Khurshid, 2009). All the models researched effectiveness on roughness, rutting, cracking, or composite measurements.

Short-term effectiveness measures are the improvement in condition (such as pavement performance jump, deterioration reduction level, or the reduction in the rate of deterioration as a slowing of the deterioration curve). Effectiveness measures are calculated from the related pavement performance measures and can be collected immediately before and after the application of the treatment, or during a finite time period before and after the application of treatment. The lagged finite time period is often one to two years, which is often the maintenance cycle or inspection cycle length. Short-term effectiveness models are useful because they can give not only the immediate effectiveness or impact of treatment, but also make it easy to integrate of the treatment effectiveness with performance curve. Moreover, these models help the long-term effectiveness analysis by making the calculation of incremental benefits due to an individual treatment possible (Labi & Sinha, 2003a). A number of researchers have developed short-term effectiveness models. Summarizing the effectiveness measures in the literature, it is found that there are three types of measurements: performance jump (PJ), deterioration reduction level (DRL), and deterioration rate reduction (DRR).

Performance jump can be defined as the instantaneous elevation in the performance or condition of a pavement due to a maintenance treatment (Smith & Freeman, 1993; Labi & Lemptey, 2007; Labi & Sinha, 2003c). PJ can be expressed in terms of average value and range (Labi & Sinha, 2004) or as a function of treatment and other attributes (Labi & Sinha, 2003a) PJ was researched in a relationship with DRL and DRR so it allows agencies to estimate PJ when data is not available (Labi & Sinha, 2003a). PJ measures immediately before and immediately after treatment pavement performance measurements so it is the ideal direct treatment effectiveness measurement. Few agencies carry out deterioration measurements of both just-before and just-after treatment, which makes obtaining accurate PJ measurements more difficult. Some researchers claim that the unknown pre-treatment condition or after-treatment condition can be easily extrapolated from the previous condition data using linear trend over a one- or two-year time period (Labi & Lemptey, 2007), allowing the prediction of measurements to calculate PJ values.

The concept of DRL was described as the decrease in deterioration from one year to the next (Labi & Sinha, 2003a) and as change in pavement roughness from one year to the next (Madanat & Mishalani, 1998). It has been used to determine the change in roughness over a one-year period for various types of maintenance treatments and was computed in two ways: (1) difference in deterioration one year before maintenance and just-after maintenance and (2) difference in deterioration just-before maintenance and one year after maintenance (Labi & Sinha, 2003a). Some researchers define DRL as the "increase in infrastructure condition due to maintenance application, calculated on the basis of deterioration measurements taken between two consecutive, spaced-out points in time, typically one year." (Labi & Sinha, 2003c, p. 2). Thus, DRL can be calculated in a third way, as the difference in deterioration one year before maintenance and one year after maintenance (Labi & Sinha, 2003c, p. 2). DRL was the most popular measurement found in the literature (Labi & Sinha, 2003a). Some sought to estimate the effectiveness of general maintenance and rehabilitation (Madanat & Mishalani, 1998), and others modeled maintenance effectiveness as a function of maintenance and pavement attributes (Mohanmad, 1997). As mentioned before, few agencies perform deterioration measurements of both just-before and just-after treatment activity. Often agencies have either one of the measurements or measurements from a short period before or after treatment. For this reason, this method of effectiveness measurement is popular among researchers and is the most available data type. Unfortunately, by using this measurement researchers may not consider the timing between treatment and deterioration measurement, and thus will either underestimate or overestimate the treatment effectiveness and draw improper conclusions (Labi & Sinha, 2003a).

DRR was defined as the difference in the slope of the deterioration curve before maintenance and after maintenance (Labi & Sinha, 2003a). It is the least used application measurement found in literature review (Markow, 1994; Labi & Sinha, 2003a).DRR considers short-term deterioration rate change instead of abrupt performance jump. DRR has its own value for some treatment types such as crack sealing, which may not result in significant performance jump but can have significant short-term deterioration rate reduction (Labi & Sinha, 2003a); under-drain maintenance (UM), which may not yield any performance jump but can yield reduction in the rate of deterioration; and treatment types with short life spans whose effectiveness cannot be captured by any measurements (Labi & Sinha, 2003c). Some researchers suggest that maintenance effectiveness may be better viewed within the context of DRR rather than from a PJ perspective particularly for low-level treatments (Labi & Sinha, 2003c).

Long-term effectiveness measurements found in literature were extension in service life, area bounded by pavement performance curve, and improvement in average pavement condition over treatment life (Lamptey & Ahamd, 2005; Irfan & Khurshid, 2009). A review of the definition of long-term effectiveness shows some variation. Some researchers attempt to determine the direct extension in service life due to a treatment (Peshkin & Hoerner, 2004; Smith & Freeman, 1993; Labi & Sinha, 2003a). Other researchers think it is difficult to isolate the extension in service life offered by one of the several treatments a pavement has over its life and would rather determine the effectiveness in terms of increased area under performance curve or long-term extension in service life due to maintenance strategy; in other words, a series of treatments over a period of time (Labi & Sinha, 2003a). Some define extended service life as how long it takes a treated section to reach the pretreated pavement condition (Labi & Lemptey, 2007). Others define extended service life as how long it takes a treated section to reach the maximum acceptable level of the distress or minimum acceptable level of service (Zaniewki & Mamlouk, 1996). Still others define extended service life as the time elapsed between the application of the treatment and the next treatment of similar or higher level (Labi & Lemptey, 2007). Effectiveness is defined by some by Smith, and Freeman (1993) as the difference in service life between treated and untreated segments and then comparing cost per extended year for each treatment. The comparison is often expressed as the C/B ratio, where C represents cost and B represents extended year. Labi and Lemptey (2007) define effectiveness as the average pavement condition over the treatment life, while another definition of effectiveness by Labi and Lemptey (2007) is the difference in area under performance curves between treated and untreated segments.

The extended life method requires an expert opinion or performance curves and is based on the belief that the longer the extended service life, the more effective a treatment is. The average-condition method requires only condition data over the analysis time and assumes the better average condition value the more effective a treatment is. The area-under-curve method requires performance models to find the area under performance curve and assumes the greater the area under the performance curve the more effective a treatment is. Considering the area under the performance curve is a representation of both average condition and extension in service life. This measurement may be the best measure of long-term effectiveness but it often requires intensive data more than the other two measurement methods (Lamptey & Ahamd, 2005). All three measurements were found equally used by researchers in the literature.

Reviewed research and studies yielded both interesting results and methodologies, giving insight into treatment effectiveness. Most of the research only focuses on specific groups of treatments, such as routine maintenance, or rehabilitation. Few included an integrated effectiveness analysis; in other words, no one developed a uniform effectiveness model for all types of treatment, making it possible to compare the effectiveness of different types of treatments. Considering the variations of definitions of treatment effectiveness, it is difficult to integrate all types of treatment effectiveness models to yield a performance model and an optimum model. It is also difficult to create an integrated decision support system for a pavement management system. For example, considering routine maintenance, effectiveness can be found as the area under the performance curve, but for preventive maintenance, effectiveness can be found as the average extended service life. The difference between those two effectiveness measurements makes it difficult to evaluate effectiveness among different treatments. The detailed review of effectiveness models in different category of treatments follows.

Relatively little research was found on corrective maintenance and routine maintenance effectiveness. Researchers and practitioners believe that routine maintenance can extend pavement life and increase pavement condition (Al-Mansour & Sinha, 1994; Fwa & Sinha, 1986a). The research shows that basic routine maintenance generates a better average pavement condition and longer pavement life than no routine maintenance or poor routine maintenance; the effect increases over time. Figures 2 and 3 show the relationship of pavement condition and pavement age for pavement performance curve with routine maintenance and poor or no routine maintenance.

ESAL in Figure 2 is defined as equivalent single axle load; the most commonly used equivalent load in the United States is the 18,000 pound (80 kN) equivalent single axle load. Pavement condition shown on the y-axis is defined as Pavement Serviceability Index (PSI), which can theoretically range from zero to five, where five represents a pavement in perfect condition. Most pavements are not rated as 5.0 after resurfacing. So, a typically starting value may be 4.2 to 4.5. Typical terminal values may be 2.0 to 2.5.

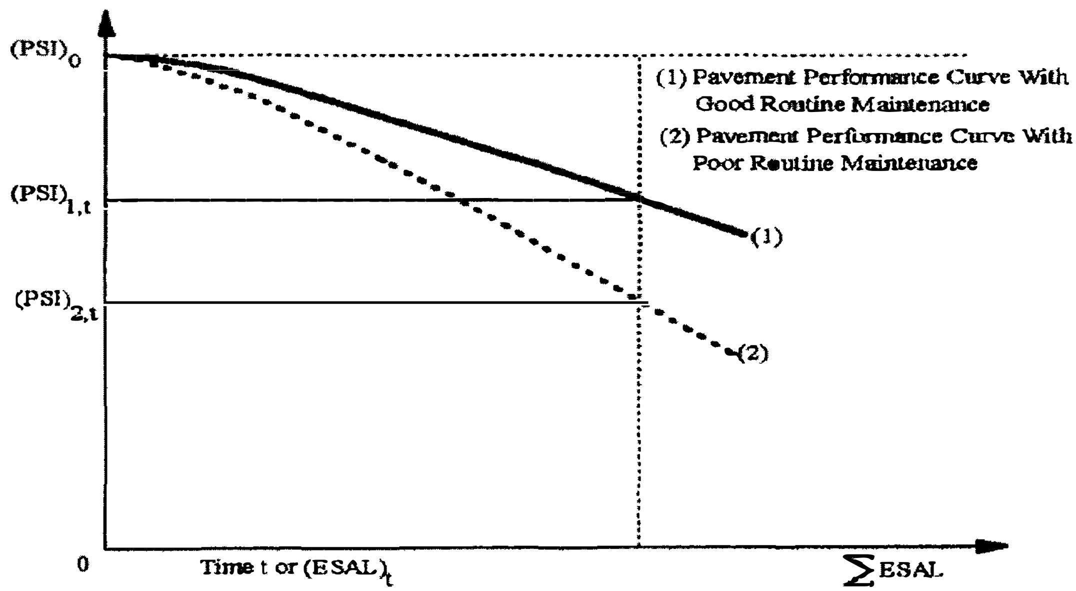

Figure 2. Relationship between Pavement Performance and Routine Maintenance (Fwa & Sinha, 1986a).

Figures 2 and 3 illustrate effectiveness measured as cumulative corrective and routine maintenance treatments effects. Few researchers have addressed individual corrective or routine maintenance effectiveness similar to what was done to the preventive maintenance treatments and rehabilitation.

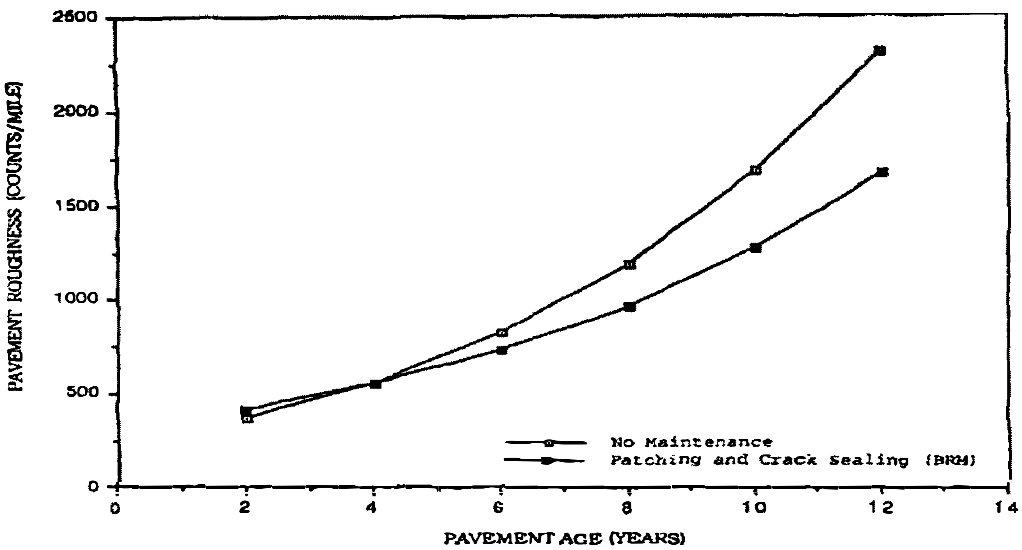

Figure 3. Relationship between Pavement Roughness and Routine Maintenance (Al-Mansour & Sinha, 1994).

Several reasons for this gap in research exist: (1) the individual corrective or routine maintenance treatment effectiveness often would rather focus on the repair performance or treatment life due to short treatment life. For example, the objective of pothole repair operations is to place the longest lasting patch in each pothole with effectiveness of the pothole repair measured by the patch life, often a couple of months (Romine & Stivers, 1995). (2) It is rare to apply only one routine-maintenance treatment within one inspection cycle (typically one or two years). Thus, not enough information is available to evaluate the individual routine maintenance treatment effectiveness in terms of improvement in pavement condition or prolonged pavement life. (3) Individual corrective or routine maintenance treatments normally do not change pavement condition indicator values, such as the International Roughness Index (IRI) or Pavement Condition Index (PCI), because of the minimal direct effect on such indicators. It is difficult to quantify the pavement condition improvement and the potential extended life due to an individual treatment. The cumulative routine-maintenance effect, in terms of pavement condition improvement and extended pavement life, can be detected by comparing the pavement performance curves with and without routine maintenance treatment. Also, in the literature some researchers used the average annual pavement condition difference determined from pavement performance curves with and without routine maintenance as the effectiveness measurement for all routine maintenance treatments applied to the segment, not the individual routine maintenance activity (Al-Mansour & Sinha, 1994; Fwa & Sinha, 1986a). In that way, the specific result can be given but it cannot link the maintenance treatment and effectiveness together, since the effectiveness is the cumulative effectiveness of serial maintenance treatments. Different agencies will produce different effectiveness results, though all claim to have the same regular corrective and routine maintenance because the maintenance levels may be different. Some researchers used average annual maintenance expenditure per lane-mile of the highway section as the quantitative measure for the level of routine maintenance and linked it with the maintenance effectiveness (Fwa & Sinha, 1986b); however, the level of maintenance only showed correlation with expenditure when applied to homogeneous areas and highway classes. The same expenditure level of routine and corrective maintenance on two highway segments does not necessarily indicate the same levels of maintenance and effectiveness of treatments (Fwa & Sinha, 1986b). The maintenance expenditures per lane-mile would be an accurate representation of levels of pavement routine maintenance when particular assumptions are satisfied: (1) the section homogeneity requirement: highway sections with same structural characteristics and similar traffic, environmental, and climatic conditions; (2) the uniformity requirement: highway sections with similar maintenance policy and technology (Fwa & Sinha, 1986b); and (3) the construction homogeneity requirement- similar labor costs, material costs, and source of work (Labi & Sinha, 2004) because cost factors and source of work will affect maintenance expenditures without changing the level of maintenance. Instead of trying to link the maintenance expenditure with effectiveness, some researchers try to find a balance in the relationship between corrective maintenance levels and preventive maintenance levels in terms of expenditure. Researchers discovered that increasing preventive maintenance level can greatly reduce corrective maintenance expenditures (Labi & Sinha, 2004a); again, the validity of the link between expenditure and treatment type need to be confirmed.

More literature was found in studying preventive maintenance and rehabilitation treatment effectiveness. Effectiveness models are found in research literature for both short-term and long-term effectiveness. It has long been known that pretreatment pavement condition affects treatment effectiveness (Smith & Freeman, 1993). Most researchers would agree with this, but they have different opinions regarding the other factors that influence treatment effectiveness. Some researchers claim that short-term effectiveness for a treatment is solely determined by the pretreatment pavement condition and long-term effectiveness is affected by exogenous factors (such as weather, traffic, and pavement classes) (Labi & Lemptey, 2007). These researchers believe that in measuring long-term effectiveness, the exogenous factors start to show greater influence on effectiveness than the pretreatment pavement condition, even making the effect of the pretreatment pavement condition on overall long-term effectiveness not significant. Others believe even short-term effectiveness should be affected by both endogenous and exogenous factors such as pretreatment condition, pavement classes, pavement type, traffic, and age factors (Madanat & Mishalani, 1998). Accordingly, this group of researchers tries to model treatment effectiveness through a single effectiveness model; however, other researchers have proposed a different way to study effectiveness. Rather than having a separate effectiveness model with performance model, these researchers built up an integrated model for a treatment and used intervention analysis technique to estimate treatment effectiveness (Chu & Durango-Cohen, 2008). However, the model considers traffic as the only major exogenous factor. The effectiveness measurement is derived mainly from the difference the traffic factor has on pavement performance before and after treatment.

Researchers have studied either single treatment effectiveness or the effectiveness of a strategy. Several researchers have analyzed the single treatment effectiveness and developed short-term and/or long-term effectiveness models for a single treatment type, such as crack sealing effectiveness in DRR (Labi & Sinha, 2003a), seal coating effectiveness in PJ and DRR (Labi & Sinha, 2004), and microsurfacing effectiveness in both short term and long term (Labi & Lemptey, 2007). Other researchers have analyzed the effectiveness of various strategies over the life cycle of pavement (Labi & Sinha, 2003c; Labi & Sinha, 2005). In this way, instead studying a single treatment, the researchers have studied a predefined series of treatments or the strategy for a pavement section over its life cycle. Many of these types of models are built upon individual treatment effectiveness models.

The aforementioned effectiveness models demonstrate interesting results. Research showed that the direction of effectiveness in relation to the initial pavement condition is not fixed, but depends on the measure of effectiveness used—e.g., PJ and DRR (Labi & Sinha, 2004). Additionally, researchers found that pavements in relatively poor condition were generally associated with greater performance jumps but lower reductions in the rates of deterioration. Also, the direction of effectiveness of different treatments in relation to initial pavement condition is not fixed, rather it depends on the measure of performance used such as IRI, rutting, or fatigue cracking. One study found that even if the crack seal treatment is detected not significant in change in IRI, it may be detected significant in change in rutting (Hall & Correa, 2002). Another researcher found that effectiveness is affected by the pretreatment condition or age of the pavement and measure of performance used. The same treatment may have a positive effect on one measurement of performance, such as cracking, but will have zero or even a negative effect on the other measurement or performance, such as bleeding.

In addition, research showed that timing is important as well. The same treatment normally has better long-term effectiveness (extended life) when it is applied to pavement in poor condition than in good condition or to older pavement than to younger pavement, which seems to contradict some other conclusions—e.g., the belief that a treatment is more effective when applied to pavement of a younger age or in good condition. These findings may not actually contradict each other. One of the reasons is the use of different effectiveness measurements; one model uses long-term effectiveness measurement while the other often uses short-term effectiveness measurement.

Up until now all the aforementioned models focused on treatment effectiveness itself. It should be noted that effectiveness is only one consideration in researching treatment effectiveness; cost is another consideration. Some researchers use a cost-effectiveness concept and life-cycle analysis techniques to perform the analysis to determine the best treatment type. Some researchers used preventive maintenance expenditure in terms of dollars per lane-mile as the measurement of preventive maintenance effort and found a relationship between preventive maintenance expenditures and the cost-benefit ratio; however, the relationship is not monotonic. The increase in preventive maintenance expenditures will decrease the cost-benefit ratio until a certain threshold, and then the cost-benefit ratio will increase. Differences due to highway type will affect the point position from where the ratio begins to increase (Labi & Sinha, 2005). Because of the non-monotonic relationship, a best performance level for each treatment exists in terms of the cost-benefit ratio.

Some researchers adopted the cost-benefit ratio concept and used the ratios to compare different timing scenarios in order to select the best timing for a treatment to be applied. Research showed that a treatment will provide little or no benefit if it is placed either too soon or too late in the pavement's lifetime (Peshkin & Hoerner, 2004). Research on treatment timing demonstrates that for the same treatment, there is an optimal time for treatment application, in terms of the cost-benefit ratio. Other researchers adopt depreciation cost as the measure of performance in the equation of Cost* Pavement Roughness per year and compare it to different types of roads and pavement pretreatment condition. Researchers learned that the cost-effectiveness of various treatments is related to pavement pretreatment condition; for different levels of pretreatment condition, the best cost-effective treatments differ (Sprague, 2006). In other words, for the same pavement section there is a best treatment type in terms of the cost-benefit ratio.

In summary, several key factors will affect results or conclusions regarding a treatment's effectiveness: (1) application timing; (2) performance measurements; and (3) effectiveness measurements. Additionally, treatment effectiveness does not necessarily equal cost effectiveness and the greatest cost-effectiveness may vary in timing and/or treatment.

Methodologies adopted to build an effectiveness forecasting model or find the effectiveness values found in the literature review: (1) linear or non-linear regression method; (2) time series with intervention analysis technique (Chu & Durango-Cohen, 2008); (3) econometric approach (multinomial logit model) (Madanat & Mishalani, 1998); (4) mean effectiveness value from field measurements with a test of significance between the treated and control groups (Hall & Correa, 2002); and (5) treatment effectiveness survey results or practice experience results (Hicks & Seeds, 2000; Labi & Sinha, 2003a). The most popular method is regression analysis, since not only can it give the estimated effectiveness values, but also express the relationship between influential factors and effectiveness; the analysis is also relatively easy to apply and understand. However, the ability of model forecasting is constrained by data availability, the quality of available data, and formation of the model. Researchers also seek the best form for a model to most accurately represent the true relationship of treatment effectiveness and its influential factors. Another popular method uses the mean value from a survey, other statistics, or practical experience results. Benefits of this method are simplicity and quickness, while still producing a general idea of the state of practice. Unfortunately the mean value from this method is quite general, which makes it difficult for other researchers to adopt it and use it in their own pavement management planning. The lack of consideration of application limitations, especially the influential factors' information, will produce a meaningless result. In fact, both mathematical effectiveness forecasting models and mean values from surveys or field data have the same issue. The model limitations and the mean value application limitations must be carefully examined before the technologies are adopted by other agencies. For instance, if the model is estimated from in-service field data from only new or nearly new pavements, it cannot be used to forecast effect on middle-aged or failed pavement. Also, if the mean value is from a southern climate zone, the value cannot be adopted by the agencies from northern regions. Information on the effectiveness of various pavement related treatments from literature is also summarized in Table 14 of Appendix A.

3.2. Long Term Pavement Performance Program (LTPP) Data Source

In this section, a review of the Long Term Pavement Performance (LTPP) data is presented including an LTPP program overview, aggregated datasets, and data adjustment. Also included in this section is a discussion about the difference between controlled experiment data and uncontrolled, observational, in-service data.

3.2.1. Types of Data

Basically, two types of data sources can be used to support pavement management models: accelerated pavement testing (APT) data from controlled experiments and uncontrolled observational data from in-service pavement sections.

According to a survey conducted by the National Cooperative Highway Research Program (NCHRP) in 2002, there are 15 APT facilities operated in the United States, of which six are operated by state DOTs, five are operated by universities, two are operated by the US Army Corps of Engineers, and the FHWA and a private firm each operate one. APT is the application of wheel loadings to specially constructed or in-service pavements to determine pavement response and performance under a controlled, accelerated accumulation of damage (Safed & Hall, 2003).

Uncontrolled performance data from in-service pavements can come from the pavement management system database of states or local DOTs or the LTPP database. LTPP database is comprehensive, with more than 20 years of studies of in-service pavements. The database has been gathering data from 2,400 pavement test sections across the United States and Canada since 1987 and includes information on environment, traffic, inventory, monitoring, maintenance, materials, and rehabilitation for each test section (Humplick, 1992).

The controlled or uncontrolled types of data each have their own advantages and disadvantages. The most significant advantage of APT is the ability to control factors so researchers know exact traffic weights, traffic numbers, and material characteristics in some cases. Additionally, APT needs a relatively short period of time, a maximum of several months, to simulate the equivalent of several years of passenger car and truck traffic. Moreover, APT is able to test variety of experimental factors within limitations. However, the degree to which this type of testing is related to actual pavement deterioration is often scrutinized (Hong & Prozzi, 2010). For example, the short duration for evaluation of environmental effects often means that environmental effects cannot be adequately reflected, especially the effect of freeze-thaw cycle. APT also has some other disadvantages. APT has a limited total number of applied loadings, the additional cost of operating and purchasing the APT equipment, and the limited variety of test locations, lengths, and sizes. Such issues often can be addressed through in-service pavement data analysis, which also presents some challenges. In-service pavement data is time-consuming to collect and researchers are unable to control all factors that affect the pavement. For the purpose of understanding why some road segments perform better than others and to generate better pavement management strategies while considering data accessibility and availability, in-service data is preferred in this research; more specifically, LTPP is preferred.

3.2.2. LTPP Program Overview

Under the sponsorship of the Federal Highway Administration (FHWA) and with the cooperation of American Association of State Highway and Transportation Officials (AASHTO), the Transportation Research Board (TRB) of the National Research Council undertook a Strategic Transportation Research Study (STRS) of the deterioration of the nation's highway and bridge infrastructure system. STRS published a study report in 1984 as TRB Special Report 202, recommending six strategic research areas. The LTPP program was one of these areas (Elkins & Schmalzer, 2009).

The detailed research plan was published in 1986 as a TRB report entitled *Strategic Highway Research Program (SHRP)—Research Plans*. The period from 1985 to 1987 is viewed as LTPP planning period. LTPP, a comprehensive 20-year study of in-service pavements program, began a series of rigorous long-term experiments monitoring more than 2,400 pavement test sections across the United States and Canada (Elkins & Schmalzer, 2009). LTPP was part of the SHRP program from 1987 to 1992. Now it is managed by the FHWA and functions as a partnership with the States and Provinces.

The original objectives of LTPP program (Elkins & Schmalzer, 2009).

- Evaluate existing design methods
- Develop improved design methodologies and strategies for the rehabilitation of existing pavements
- Develop improved design equations for new and reconstructed pavements
- Determine the effects of loading environment material properties and variability, construction quality, and maintenance levels on pavement distress and performance

- Determine the effects of specific design features on pavement performance.
- Establish a national long-term database to support SHRP's objectives and to meet the future needs of the highway industry.

The core function of the LTPP is collecting, processing, storing and providing quality data. Its main goal is to provide supportive data to answer how and why pavements perform as they do.

3.2.3. LTPP Databases

LTPP includes two types of studies: General Pavement Studies (GPS) and Specific Pavement Studies (SPS). GPS includes 10 studies and SPS is comprised of nine studies. Both include 500-foot sections of pavement.

GPSs are full factorial experimental designs:

- GPS-1, Asphalt Concrete (AC) on Granular Base
- GPS-2, AC on Bounded Base
- GPS-3, Jointed Plain Concrete Pavement
- GPS-4, Jointed Reinforced Concrete Pavement
- GPS-5, Continuously Reinforced Concrete Pavement
- GPS-6A, Existing AC Overlay on AC Pavements
- GPS-6B, New AC Overlay on AC Pavements
- GPS-7A, Existing AC Overlay on Portland Cement Concrete (PCC) Pavements
- GPS-7B, New AC Overlay on PCC Pavements
- GPS-9, Unbounded PCC Overlays on PCC Pavement

The primary factors are subgrade (fine and course), traffic (medium and heavy), temperature (freezing and non-freezing), and moisture (wet and dry). Secondary factors are

AC thickness, AC stiffness, structural number (SN) of base and subgrade, PCC thickness, and joint spacing.

SPSs are fractional factorial experimental designs:

- SPS-1, Strategic Study of Structural Factors for Flexible Pavements
- SPS-2, Strategic Study of Structural Factors for Rigid Pavements
- SPS-3, Preventative Maintenance Effectiveness for Flexible Pavements
- SPS-4, Preventative Maintenance Effectiveness for Rigid Pavements
- SPS-5, Rehabilitation of AC Pavements
- SPS-6, Rehabilitation of Jointed PCC Pavements
- SPS-7, Bonded PCC Overlays on Concrete Pavements
- SPS-8, Study of Environmental Effects in the Absence of Heavy Loads
- SPS-9, Validation of SHRP Asphalt Specification and Mix Design

The primary factors are same as those in the GPS. Secondary factors are AC drainage, AC thickness, AC base type and thickness, PCC drainage, PCC strength and thickness, lane width, and base type.

The LTPP program has produced 10 gigabytes of data, stored in an online database, and nine modules including climatic, general, inventory, maintenance, monitoring, rehabilitation, SMP, SPS, and traffic. The LTPP program has many partners including AASHTO, FHWA, State Highway Agencies, Provincial Highway Agencies, Canadian Strategic Highway Research Program, and TRB. State and Provincial Highway Agencies are responsible for test section data collection, analysis, and product development. The FHWA is responsible for data management and program management.

3.2.4. Aggregate Dataset from LTPP

In this dissertation, the author will target the test sections with all climatic, traffic, maintenance and rehabilitation, pavement roughness information and asphalt surface type.

The International Roughness Index (IRI) will be used to quantify the pavement surface roughness and IRI information dataset comes from the Mon_Profile_Master data table. The IRI value is the mean value of four to ten measurements of runs of both lanes for each test section. In this dissertation, mean IRI values based on the IRI survey year and month will be analyzed.

ESAL values will be chosen to represent cumulative load information for a given year. The reference axle load is an 18,000-pound single axle with dual tires. ESAL values are calculated from Average Daily Traffic (ADT) and considering the truck factor, truck growth rate, analysis period in a year, and lane distribution factor. In this dissertation, ESAL values are abstracted from TRF_MON_EST_ESAL and TRF_HIST_EST_ESAL data tables, using only records after 1990. The ESAL values for each section are determined on an annual basis.

Freeze-thaw days per year will be used to represent the climatic factor. Freeze-thaw days per year values will come from CLM_VWS_TEMP_ANNUAL, CLM_SITE_VWS_LINK, and SPS_GPS_LINK data tables. The freeze-thaw days per year values are calculated annually. Maintenance and rehabilitation information will come from MNT_IMP and RHB_IMP data tables. All the data from the tables will be match-merged together to represent the same test section. Wet days per year will be used as to represent another climatic factor. The values will come from CLM_VWS_PRECIP_ANNUAL, CLM_SITE_VWS_LINK, and SPS_GPS_LINK data tables.

3.2.5. Adjust and Test Maintenance and Rehabilitation Datasets

According to reports and papers, researchers have some counterintuitive pavement performance results from LTPP data. Thus, the focus lies on testing the significant effectiveness of maintenance and rehabilitation treatments. Segments with only one treatment at a time are analyzed. The systematic IRI measurement tool difference is adjusted to make IRI values comparable. A linear interpolation method is used to project immediately before treatment and immediately after treatment IRI values based on the before and after treatment IRI values. Detailed descriptions of LTPP data adjustments and IRI performance jump significance analysis are shown in Appendix B.

3.3. Treatment Effectiveness Regression Model

In this dissertation, 12 targeted pavement treatments will be included in the analysis. The treatments are skin patching, patching, full depth patching, shoulder treatment, crack sealing, seal coat, chip sealing, drainage, aggregate seal, hot mill overlay, hot mix resurfacing, and reconstruction. The selection of the treatment types is based on data availability from LTPP. The detailed definitions of the 12 pavement treatments are included in Appendix C. However, based on the effectiveness significance analysis, only seven treatments will be included in the performance jump regression analysis. These are seal coat, aggregate seal, crack sealing, chip sealing, hot mill overlay, hot mix resurfacing, and reconstruction. The other five treatments (skin patching, patching, full depth patching, shoulder treatment and drainage) will be categorized as minor preservation level treatments and considered in the pavement performance model. Seal coat, chip sealing, crack sealing, and aggregate seal will be categorized as moderate preservation level treatments, while hot mill overlay and hot mix resurfacing will be categorized as major preservation level treatments in this dissertation.

The outcome of the regression analysis identifies the function of treatment performance jump in IRI value, the before treatment IRI level and the after treatment IRI performance curves. Predictive values will be used to develop expected network IRI levels for the optimization model developed in later sections. Uncovering different treatments' effectiveness will give managers greater knowledge when deciding where to allocate resources. Additionally, policy makers will have further knowledge to help guide policy decisions for their regions.

3.3.1. Model Formulation

Labi, Lamptey, and Kong (2007) established a model of performance jump in IRI for microsurfacing treatment. The model is exponential function of pre-treatment pavement condition in IRI in the format of $PJ = \alpha_1 + e^{\alpha_2 * IRI}$, where $\alpha_1$and $\alpha_2$are estimated regression parameters. The model suggests that pre-treatment pavement condition is a vital predictor of treatment effectiveness and account for timing factors before and after treatment is important too. The model also suggests that there is bottom level for the PJ. More specifically, there exists a minimum PJ value for a treatment. Moreover, the model suggested that the further pre-treatment condition is away from the bottom level, the higher PJ can get, in the other words, the worse pre-treatment condition is, the better performance jumps are. The model suggests that there is no maximum ceiling for the potential benefit. The effectiveness curve is shown in Figure 4. In general believing, PJ in IRI should have zero as the lowest limit and also should have some the highest limit too. Because for some treatments, they may not affect IRI value when the pre-treatment IRI is quite low (e.g., a new road) or is severely high (e.g, a deteriorated or rough road). For example, a seal coat may not affect the IRI value for a brand new pavement or for a pavement whose IRI condition is really poor. Considering aforementioned assumption, the author introduces the polynomial function fit the situation more precisely than the exponential function, because the polynomial function can set an upper limit for the dependent variable while the exponential function will not display an upper limit. The polynomial function can be defined as an expression of finite length constructed from independent variables and constants, using only the operation of addition, subtraction, multiplication, and non-negative integer exponents. In general it can be expressed mathematically as an equation (1).

$$Y = \gamma_m \times X^3 + \gamma_{m-1} \times X^{m-1} + \cdots + \gamma_1 \times X^1 + \gamma_0 \quad (1)$$

Where

Y is the dependent variable.

X is the independent variable.

γ_m is the multiplicand parameter.

m is a non-negative integer exponent.

In this dissertation, the dependent variable will be the decrease in the IRI value between measurements taken immediately before and immediately after treatment. The independent variable will represent the IRI value from immediately before treatment. Polynomial functions including a combination of a third-degree term, a second-degree term, a first-degree term, and a constant term were tested for all the treatments.

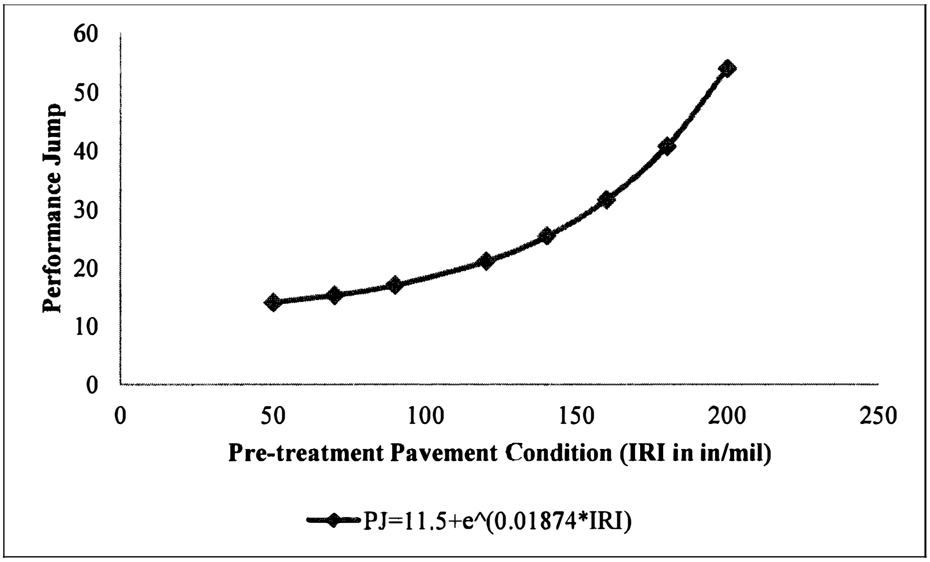

Figure 4. Microsurfacing Performance Jumps (after Labi, Lamptey, & Kong, 2007).

A polynomial function including a third-degree term, a first-degree term, and a constant term were selected to develop IRI performance jump models. The selection is according to fitness results for all treatments. The model can be expressed mathematically in Equation (2).

$$IRI_{drop} = \gamma_3 \times before_{IRI}{}^3 + \gamma_1 \times before_{IRI} + \gamma_0 \qquad (2)$$

Where

IRI_{drop} = IRI difference between immediate before and immediate after treatment

$before_{IRI}$ = IRI value immediate before treatment

γ_i $\{i = 0,1,3\}$ = Estimated parameters

Theoretically, the IRI performance change is a polynomial function of the before-treatment IRI value. This hypothesis is based on three assumptions. (1) The pretreatment pavement condition is a vital predictor of treatment effectiveness (Labi, Lemptey, & Kong, 2007). (2) Typically a maximum effectiveness range or a "ceiling" of effectiveness exists.

Beyond that "ceiling" further increases in performance jumps cannot be attained (Markow, 1991). (3) The height of the ceiling and the pretreatment condition position of the ceiling point for various treatment types should be various. In other words, different treatments' short-term effectiveness is different and the best timing for different treatment is different too.

3.3.2. Model Outcomes

The computed results of treatment effectiveness and the statistics are shown in Table 1. Column one provides N which is sample size of the data. Column two shows ANOVA-p which is probability to test that if there is linear relationship between PJ and before-IRI and before-IRI^3. The smaller p is, the more likely there is linear relationship. Column three shows r-square which is biased proportion of the total variation of PJ explained by the regression line. Column four shows adjusted r-square which is unbiased proportion of variance explained. Column five to seven provide p values to test significance of the estimated coefficients. P-value is the probability of observing a t-statistic that large or larger in magnitude given the null hypothesis that the true coefficient value is zero. The smaller p value is the higher possibility that the estimated coefficient is different than zero.

Modeling results from different treatments produced several outcomes. Pavement pre-treatment condition is a significant predictor of performance jump for all different pavement treatments. This is consistent with the assumption and past research that generally identified pre-treatment condition as a vital factor affecting treatment effectiveness (Labi, Lemppty, & Kong, 2007).

Table 1. Treatment Performance Effectiveness Regression Models Results.

Hot Mix Resurfacing		$PJ = -0.8 + 0.935 \times before_{IRI} - 0.004 \times before_{IRI}^{3}$				
N =266	ANOVA-P <0.0001	r-squre =0.8525	Adj r-squre =0.8524	P <0.0001	P <0.0001	P =0.006
Hot Mill Overlay		$PJ = -0.726 + 0.971 \times before_{IRI} - 0.008 \times before_{IRI}^{3}$				
N =135	ANOVA-P <0.0001	r-squre =0.8801	Adj r-squre =0.8783	P <0.0001	P <0.0001	P =0.006
Seal Coat		$PJ = -0.438 + 0.425 \times before_{IRI} - 0.045 \times before_{IRI}^{3}$				
N =50	ANOVA-P =0.0023	r-squre =0.2633	Adj r-squre =0.2162	P =0.0008	P =0.0057	P =0.0682
Aggregate Seal		$PJ = -0.871 + 0.843 \times before_{IRI} - 0.051 \times before_{IRI}^{3}$				
N =97	ANOVA-P <0.0001	r-squre =0.768	Adj r-squre =0.7606	P <0.0001	P <0.0001	P =0.01
Crack Sealing		$PJ = -0.749 + 0.774 \times before_{IRI} - 0.052 \times before_{IRI}^{3}$				
N =317	ANOVA-P <0.0001	r-squre =0.8348	Adj r-squre =0.8332	P <0.0001	P <0.0001	P <0.0001
Chip Seal		$PJ = -1.637 + 1.606 \times before_{IRI} - 0.081 \times before_{IRI}^{3}$				
N =13	ANOVA-P <0.0001	r-squre =0.5205	Adj r-squre =0.4246	P =0.05	P =0.01	P =0.03
Reconstruction		$PJ = -0.5 + before_{IRI}$				
Assume reconstruction will bring IRI back to 0.5 regardless of pavements' pre-treatment condition.						

A maximum effectiveness of performance jumps for lower preservation level treatments exists. The maximum effectiveness serves as a ceiling beyond which further increase in treatment effectiveness cannot be obtained. As the pre-treatment pavement condition moves further from the ceiling, the treatment becomes less effective, which is consistent with the expectation and past research that identified the ceiling for treatment effectiveness (Markow, 1991). For the higher preservation level treatments, the ceiling is never reached within the life of a pavement. More specifically, within the life of a pavement, a pavement with a worse pre-treatment condition will demonstrate a more significant performance jump for the higher preservation level treatments. The polynomial function fits all different levels of treatment well in showing the different performance jump effectiveness behaviors.

Figure 5 shows the relationship between pre-treatment IRI values and IRI performance jumps for all different treatment types. For the lower effective level treatment, the height of the ceiling is lower than that of the higher effective level treatment. For the lower effective level treatment, the ceiling point is obtained at a better pre-treatment condition or younger pavement age. For higher effectiveness level treatment, the ceiling is obtained at worse pre-treatment condition or older pavement age.

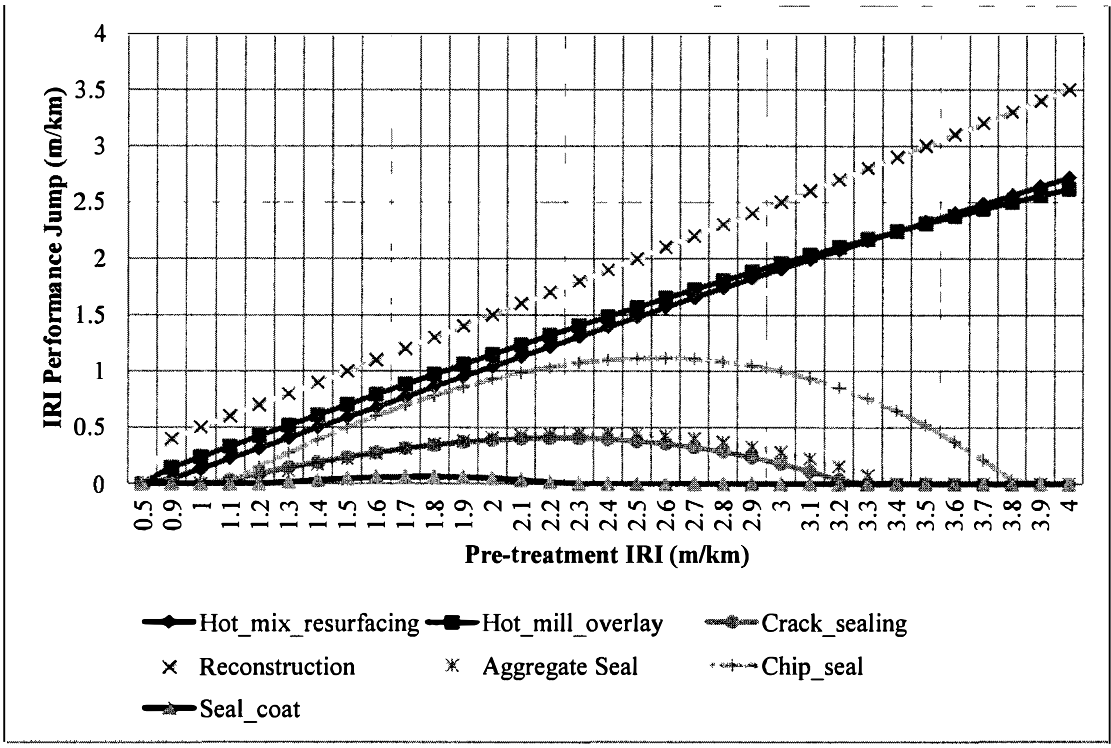

Figure 5. Relationships between Performance Jump and Pre-treatment IRI.

The best treatment application timing to obtain the ceiling is not sensitive for lower preservation treatments. The timing of an application falls within a time range, rather than being an exact point in time. For example, the application timing ranging from 1.6 m/km to

2.8 m/km pre-treatment IRI condition for crack sealing treatment will result 0.3 m/km to 0.4 m/km PJ in IRI;

3.5. Summary

The review of pavement treatment effectiveness in this chapter demonstrated the need for more precise quantitative modeling for pavement preservation treatment effectiveness. Especially the model can demonstrate the ceiling behavior of different treatments effectiveness. An examination of the LTPP data base was used as a data source to determine pavement preservation treatments performance jumps. In addition, a detailed description of how and where the data for analysis was collected for the dissertation provided further background information. The chapter concludes with a discussion regarding treatment performance jump models and model results. The discussion revolved around using a polynomial function and using the pre-treatment IRI value as the sole independent variable. The models results not only meet the expectations, but also are consistent with the general statement about pavement preservation treatment effectiveness from previous research. The models' results match the common expectations in terms of relativity treatments' effectiveness magnitudes.

CHAPTER 4. PAVEMENT PERFORMANCE

In this chapter a review of pavement pre-treatment performance and post-treatment performance is conducted. The first section discusses the previous research regarding pavement performance, followed by a second section with a discussion regarding empirical pavement pre-treatment performance models. Chapter 4 also provides discussions regarding post-treatment performance model calculations based on pre-treatment performance curves and treatment effectiveness models. The last section summarizes the chapter.

4.1. Pavement Performance Models Literature Review

Predicting future pavement performance and condition is often the first and the most important concern for pavement management plans. In modern PMSs, pavement forecasting models are the most essential elements affecting many critical management decisions. Indeed, PMSs have become more dependent on the prediction of the future performance of existing pavements. Reliable performance prediction models are therefore more important than ever before.

Pavement performance forecasting models are generally used to forecast changes in pavement condition over a future time period with a set of explanatory factors that affect performance. Pavement management models can be classified as mechanistic models, mechanistic-empirical models, and empirical models (AASHTO, 2001). Table 15 in Appendix A presents a brief summary of the model types based on AASHTO Pavement Management Guide (AASHTO, 2001). Mechanistic models try to base predictions on an analysis of the pavement degradation process that attempts to show the performance as a function of a number of parameters that are mechanistically determined. The parameters are often loading factors and climatic history. Empirical models look for a relationship between the pavement performance and other accessible observed field data, which characterizes the pavement performance. Mechanistic-empirical models are based on a mechanistic model of the materials' response calibrated with observed field data (ARA, 2004). This chapter will focus on reviewing of empirical pavement deterioration models because the analysis data available is LTPP in-service data and the dissertation seeks the different deterioration behavior under different explanatory situations. Intense review will focus on what's the explanatory variables used in the literature review and how it addresses maintenance and rehabilitation activities.

Empirical regression models are the most popular models found in the literature and have greater practical value because of the infinite complexity of the underlying phenomena (AASHTO, 2001). The models not only provide the pavement performance future changes in response to the known influential factors that cause the changes in those responses, but also provide the relationship between the performance indicators and influential factors. The model's ability to provide this relationship is important to the study in order to understand how the influential factors affect the performance indicators.

There are two basic types of empirical pavement performance prediction models: deterministic or probabilistic (Gendreau & Soriano, 1998). The deterministic models predict an absolute measure of a future pavement condition. They are widely used since they are easy to understand and can provide predictable pavement deterioration over time. On the other hand, probabilistic models predict a distribution of a measure of a future pavement condition, thus providing different possible future conditions as a stochastic process. Many researchers prefer deterministic processes because they are easy to use and understand.

Many of the deterioration models in the literature use only a few explanatory variables; often including only traffic loadings, sometimes pavement age and weather conditions are also included (Hein & Watt, 2005; Mohd Is, Ma'soem, & Hwa, 2005). The inclusion of minimal variables is the result of the difficulties with associating some measurements, such as environmental data or the quality of initial construction, with the deterioration of pavements. Those factors were assumed to be exogenous including climatic factors, traffic, age of the pavement structure (AASHTO, 2001; Gendreau & Soriano, 1998), and even some other detailed information such as soil and construction factors (Gendreau & Soriano, 1998).

Hein and Watt (2005) developed a pavement performance prediction model with age and traffic. Ozbay and Laub (2001) developed a basic IRI prediction model using initial IRI value, pavement age, analysis age, structural number, and cumulative ESAL during analysis age. Gibby and Kitamura (1992) identified the most influential factors affecting the condition of local pavements are previous pavement condition, time elapsed since last major work, soil classification of roadway drainage, surface thickness, functional classification, and individual jurisdiction. Paterson and Attoh-Okine (1992) summarized that roughness progression in flexible pavement is developed by using traffic loading, strength, age, and environmental factors. If all the distress parameters are available, then rutting, cracking, and patching should also be included in the model. Perera and Kohn (2001) summarized that environmental factors are significantly affecting roughness progression in AC pavement. The authors also stated that if a pavement is designed to account for the site conditions—e.g. climatic conditions or traffic—the effect of such factors on roughness of the pavement might not be seen. The above mentioned authors commonly agree the importance of climatic and age factors effects on pavement deterioration. Unfortunately none have studied the different pavement treatments' effects on pavement performance. The studies on this topic lack mostly due to the fact that reliable maintenance and rehabilitation data has not been readily available in the past, so few models can include the effect of maintenance on deterioration (Ramaswamy & Ben-akiva, 1990).

Maintenance and rehabilitations are viewed as important factors that will affect pavement performance. But it was suggested that maintenance and rehabilitations should always be viewed as endogenous variables (Prozzi & Mandanat, 2004; Ramaswamy & Ben-akiva, 1990,). If such variables were incorporated into the model as one of the explanatory variables then the endogeneity bias will occur (Madanat, Bulusu, & Mahmoud, 1995). Endogeneity and multicollinearity bias are the reasons that some researchers have counterintuitive signs for the parameter estimates of important explanatory variables (Ramaswamy & Ben-akiva, 1990,). Pavements that carry a higher traffic load tend to deteriorate faster. Typically, those pavements receive maintenance more frequently and have better pavement condition in general. If both maintenance and traffic were incorporated into the model it is no surprise that the conclusion of higher traffic pavement having a better pavement condition will be drawn. Understanding these situations can help to avoid endogeneity bias and multicollinearity by taking into account the presence of endogeneity and multicollinearity.

Researchers such as Lytton (1987) have long recognized the need to develop models that respond to exogenous interventions but also integrated with effect of maintenance activities. Many researchers tried to perform such tasks by accounting for maintenance and rehabilitation effects and also avoiding endogeneity and multicollinearity bias. Maintenance and rehabilitations affect the pavement condition directly and often are triggered by the condition of a pavement. In this situation, it is not recommended to include maintenance and rehabilitation directly as exogenous explanatory variables (Ramaswamy & Ben-akiva, 1990).

Fwa and Sinha (1986b) developed a model that can address overall pavement performance and aggregated routine maintenance expenditures. By applying such a model, routine maintenance effects on pavement performance can be captured by quantifying the routine maintenance expenditure level. The study provides a great insight to quantify the routine maintenance effect on pavement performance. Unfortunately, the study does not identify the specific pavement distresses and the types of maintenance and rehabilitation activities. Ramaswamy and Ben-Akiva (1990) developed a model that can simultaneously reflect pavement deterioration processes caused by exogenous influential factors and maintenance activities as a response to the deterioration. Pavement condition and maintenance depend both on exogenous factors, as well as on each other. The study compared the result of a single regression equation, which contains maintenance directly as an exogenous variable, and the result of a simultaneous equation, which is estimated simultaneously with a set of maintenance equations. The results shows a great improvement on having all the expected signs for all the significant parameters, therefore the model appears to be a more realistic model for predicting the deterioration of pavement with effects of maintenance activities. The study was first to shed light on the difficulties associated with combining deterioration and maintenance. The drawbacks are that 1) the simultaneous equation estimator gets rid of the endogeneity bias, but in the process the model's fit become less precise (R^2 values is 0.28); 2) the model assumes pavement condition and maintenance simultaneous depend on each other which make it difficult to forecast conditions under various M&R policies and therefore, the models provide less use to support M&R decision making.

Another type of approach involves separate estimations of maintenance effectiveness and pavement performance models. Al-Mansour and Sinha (1994) developed a serial performance model by grouping two different highway classes and five different maintenance categories. The exogenous factors used for developing models are pavement age, mean annual ESALs, and region as a dummy variable representing the effect of climatic regions. Maintenance effect pavement performance models shows intuitiveness and consistency with expected results, although maintenance effectiveness indices may continue to increase with pavement age with the models. Madanat and Mishalani (1998) developed a similar pavement performance model for different maintenance and rehabilitation activities using the grouping technique. Chu and Durango-Cohen (2008) summarized that such models provide estimates of the pavement condition improvement associated with various maintenance and rehabilitation interventions as a function of cumulative exogenous factors. However, separate maintenance and deterioration models are hard to combine to generate condition forecasts under different M&R policies, because performance models explain continuous deterioration while maintenance effectiveness models provide incremental condition changes. The reason it is difficult to use the models to support M&R decision making is because each performance model for a maintenance activity is unique, having been established using maintenance grouping. More specifically, the model treated pavement segments that received the same type of maintenance similarly, but did not address the timing difference of the maintenance. As decision makers consider decisions, they want to know when to apply which type of treatment and how the solutions differ; unfortunately, the models do not provide this type of information.

Some researchers see the need for more sophisticated yet simple enough to apply performance models that are still applicable to inform various M&R policies. These models need to not only can take care of endogeneity bias, but also take into account maintenance and rehabilitation effects.

Gao and Zhang (2010) developed a performance modeling method that can identify observations which were affected by maintenance interventions with some probability. Unfortunately, their model did not demonstrate how to develop the performance model using the identified data. Moreover, the model only can detect if the observation was affected by maintenance interventions or not but cannot tell the different level of maintenances.

Prozzi and Madanat (2004) developed a pavement performance model by combining experimental and field in-service data. They first developed a riding quality model based on AASHO road test experimental data and then re-estimated the parameters by applying joint estimation with the incorporation of the field data set. With well-designed experimental data, the endogeneity bias will be avoided. In the model, Prozzi and Madanat (2004) did not incorporate seasonal effects and maintenance activities, but stated that if data is available then it can be incorporated. The model shows great benefits of using joint estimation such as improving the forecasts, lowering the estimate variance, and avoiding bias in the parameters. The main drawback of the model is that it requires both field data and well-designed experimental data for the regions with homogeneous weather conditions and level of maintenance activities if such data are not available.

Haider and Dwaikat (2010) introduced the idea that direct analysis pre-treatment performance curves, treatment performance changes, and post-treatment performance curves in simple format. Pre-treatment performance curves are connected with post-treatment performance curves by treatment performance changes. They analyzed different treatment application timing effects and compared the pavement condition changes to the post-treatment deterioration rates for different timing policies. This method separates pavement performance models from maintenance effect models and finds a way to combine the effect with performance models. The drawback of Haider and Dwaikat's model is that the model requires pre-treatment historical data to formulate pre-treatment performance curves and different post-treatment datasets to formulate different post-treatment performance curves. To research the different timing effect for each treatment requires too many post-treatment performance datasets. Such datasets are not always available, and may be too expensive to obtain.

4.2. Pavement Performance Models

All the previous researchers' studies provide great insights on pavement performance, the influential factors which will affect pavement performance, and the potential problems in model formulation.

Drawing from the previous studies, this dissertation will incorporate the idea of developing pre-treatment performance models and post-treatment performance models separately to avoid endogeneity bias. Additionally, the performance models will take into account the effectiveness of different treatments applied at different times as discussed in the previous chapter.

4.2.1. Pre-treatment Pavement Performance Model Formulation

In this dissertation, there will be two types of pre-treatment performance models developed. First, a pre-treatment performance model with absolutely do nothing strategy will be developed. Second, the dissertation will develop a pre-treatment performance model with minor preservation level maintenance activities. The rationale for developing two pre-treatment performance models stems from that minor preservation level maintenance activities may not directly affect pavement surface condition indicators but will lower the deterioration rate. To capture the effect of minor preservation level maintenance activities, one can compare performance curves with and without those minor preservation level maintenance activities. As previously mentioned, skin patching, patching, full depth patching, shoulder treatment, and drainage will be categorized as minor preservation-level treatments since they did not pass the effectiveness significance tests and often are categorized as routine maintenance. The study will assume the same level of minor preservation maintenance as those in LTPP program data.

Prozzi and Madanat (2004) stated that if pavements that are designed and expected to carry higher traffic load during their design life are designed to higher standards, then the bearing capacity of the pavement is higher than those pavements designed to carry lower volumes of traffic. In that situation, if any variable, such as structural number, which indicates bearing capacity, is incorporated into the pavement performance model, the model will encounter endogeneity bias. Perera and Kohn (2001) stated that if a pavement is designed to allow for the site conditions for some factors like climatic conditions or traffic, the effect of such factors on roughness of the pavement might not be seen. Inspired by Perera and Kohn's findings and to avoid endogeneity and multicollinearity bias, simple regression models are developed using IRI as dependent variable and pavement age as independent variable for different precipitation and freeze thaw cycle regions. Traffic factors are not included in the research because of data was not available. Ninety percent of the dataset used for this dissertation has low volume of traffic.

Three levels of freeze-thaw regions are defined according to the number of freeze-thaw days within a year. The regions are categorized as no freeze-thaw, medium freeze-thaw, and severe freeze-thaw. A freeze-thaw day is defined by a day's air temperature; if the air temperature changes from less than 0 degrees Celsius to greater than 0 degrees Celsius (or from less than 32 degrees Fahrenheit to greater than 32 degrees Fahrenheit), then that day is counted as one freeze-thaw day (USDOT & FHWA, 2010). Regions are also classified based on levels of precipitation and are defined as a dry region or wet region based on the number of wet days per year. A wet day is defined by a day's amount of precipitation; an amount greater than 0.25 mm (or 0.01 inches), then that day is counted as one wet day (USDOT & FHWA, 2010). The detailed category information is shown in Table 2.

Table 2. Definition of Analysis Region for Pre-treatment Performance Models.

Freeze-Thaw Region	Definition	Size 1	Size 2
• No Freeze-Thaw	0 ≤ freeze thaw days per year < 70	48	697
• Medium Freeze-Thaw	70 ≤ freeze thaw days per year < 140	52	955
• Severe Freeze-Thaw	140 ≤freeze thaw days per year < 230	21	97
Precipitation Region			
• Dry	0 ≤ wet days per year < 100	49	373
• Wet	100 ≤ wet days per year < 270	72	1376

In Table 2, the values in Size 1 represent the number of observations of segments with do-nothing strategy in the corresponding region; Size 2 values represent the number of observations of segments with performing regular minor preservation activities.

Table 3 summarizes the number of observations for all six analysis regions: no freeze-thaw, dry region; no freeze-thaw, wet region; medium freeze-thaw, dry region; medium freeze-thaw, wet region; severe freeze-thaw, dry region; and severe freeze–thaw, wet region.

Table 3. Analysis Data for Pre-treatment Performance Models.

Analysis Region	Size 1	Size 2
• No Freeze-Thaw, Dry	15	181
• Medium Freeze-Thaw, Dry	22	155
• Severe Freeze-Thaw, Dry	12	37
• No Freeze-Thaw, Wet	33	516
• Medium Freeze-Thaw, Wet	30	800
• Severe Freeze-Thaw, Wet	9	60

In Table 3, values listed in Size 1 represent the number of observations of segments with do-nothing strategy in the corresponding region; the values in Size 2 represent the number of observations of segments with performing regular minor preservation activities.

IRI data in the LTPP have shown that IRI with time can be modeled by using an exponential functional form (Haider & Baladi, 2010; Haider & Dwaikat, 2010). In this study, it is assumed that the pre-treatment performance curve can be represented by exponential models as shown in equation (3).

$$\mathrm{IRI_{pre}}(t) = \alpha_1 * e^{\beta_1 * t} \quad (3)$$

Where

α_1= model parameters representing the initial value of IRI for pre-treatment performance curve

β_1= model parameters representing the deterioration rate in IRI for pre-treatment performance curve

t= pavement age in months

Several factors have a role in pavement deterioration. Pavement age in months (t) represents the number of months for a pavement from the initial construction year or most recent reconstruction year. This variable is important because the pavement deterioration is expected to change while pavement is aging. Because of pavement age's relationship with deterioration, the variable is expected to have a positive sign.

Additionally, moisture is recognized as another important factor in pavement deterioration. The more moisture that penetrates a pavement under the surface layers, the faster the pavement will deteriorate.

The freeze-thaw cycle is another important factor to affecting the pavement deterioration rate. More frequent freeze-thaw cycles results in faster pavement deterioration a pavement experience the faster the pavement will deteriorate.

The initial value of IRI for pre-treatment performance curve,α_1, is assumed to be 0.5 m/km. IRI benchmark value of 0.5 m/km can be used for a brand new road (Haider & Baladi, 2010; Haider & Dwaikat, 2010). Typical initial serviceability 4.5 PSI was suggested by AASHTO (1993.). It is PSI value of 4.4 if convert from IRI value of 0.5 m/km by using correlation was reported by Al-Omari and Darter (1994): $PSI=5*e^{-0.26*IRI}$. In this dissertation, the initial IRI of 0.5 m/km is assumed. It basically means that when the pavement is brand new the IRI index value is 0.5 m/km.

Table 4 shows the information of dependent and independent variables for pre-treatment models. The specific form of the model is exponential of pavement age in months as shown in equation (3).

Table 4. Variables and Data Categories for Pre-treatment Performance Regression Models.

Dependent Variables	**Units**
IRI= International Roughness Index	m/km
Independent Variables	**Units**
t= Age of a Pavement	months

4.2.2. Pre-treatment Pavement Performance Model Results

The models key properties and parameter estimates are shown in Table 5. All twelve models have R-square values higher than 0.69, which suggest that all six models explain greater than 69% of the variation in pavement IRI values. The smallest number of observations for six models with minor level maintenance activities is 60, which is sufficient to realize large sample properties. It is rare to truly apply nothing to a pavement, especially to those segments located in a severe weather condition region. So it is not surprising to see that the available data with do nothing strategy is limited. In this case the least number of observations are found in the severe freeze-thaw, wet region, which only contains nine observations and the next severe weather condition region is severe freeze-thaw, dry region, which only contains twelve observations. The lowest deterioration rate is found in the no freeze-thaw, dry region with minor preservation activities. It matches the expectation since the region is in the least freeze-thaw and the least precipitation affected region. The detailed analyses for each single influential factor will be discussed next.

Table 5. Key Model Properties and Parameter Estimates.

Analysis Region	No Freeze-Thaw, Dry	
	With Minor Level Maint.	With Do Nothing
Estimated β_1	0.00433	0.00496
Prob. > | t | for β_1	< .0001	< .0001
Prob. > F for the model	< .0001	< .0001
r-square	0.8502	0.779
Adjusted r-square	0.8494	0.7632
Observations	181	15
Analysis Region	Medium Freeze-Thaw, Dry	
	With Minor Level Maint.	With Do Nothing
Estimated β_1	0.00457	0.00526
Prob. > | t | for β_1	< .0001	< .0001
Prob. > F for the model	< .0001	< .0001
r-square	0.777	0.8103
Adjusted r-square	0.7755	0.8103
Observations	155	22
Analysis Region	Severe Freeze-Thaw, Dry	
	With Minor Level Maint.	With Do Nothing
Estimated β_1	0.00479	0.00642
Prob. > | t | for β_1	< .0001	< .0001
Prob. > F for the model	< .0001	< .0001
r-square	0.88987	0.9143
Adjusted r-square	0.8033	0.9065
Observations	37	12
Analysis Region	No Freeze-Thaw, Wet	
	With Minor Level Maint.	With Do Nothing
Estimated β_1	0.00453	0.00519
Prob. > | t | for β_1	< .0001	< .0001
Prob. > F for the model	< .0001	< .0001
r-square	0.6913	0.796
Adjusted r-square	0.6907	0.7315
Observations	516	33
Analysis Region	Medium Freeze-Thaw, Wet	
	With Minor Level Maint.	With Do Nothing
Estimated β_1	0.00487	0.00555
Prob. > | t | for β_1	< .0001	< .0001
Prob. > F for the model	< .0001	< .0001
r-square	0.9055	0.849
Adjusted r-square	0.895	0.8438
Observations	800	30
Analysis Region	Severe Freeze-Thaw, Wet	
	With Minor Level Maint.	With Do Nothing
Estimated β_1	0.00503	0.0062

Table 5. (Continued)

Prob. > | t | for β_1	< .0001	< .0001
Prob. > F for the model	< .0001	< .0001
r-square	0.8649	0.8835
Adjusted r-square	0.8626	0.8689
Observations	60	9

To compare with minor preservation and do nothing strategies, it is found that the deterioration rate is higher with a do nothing strategy than with a minor preservation strategy. The result is expected, because it is widely accepted that routine maintenance or minor preservation activities can reduce pavement deterioration rate. The comparison is shown in Figure 6.

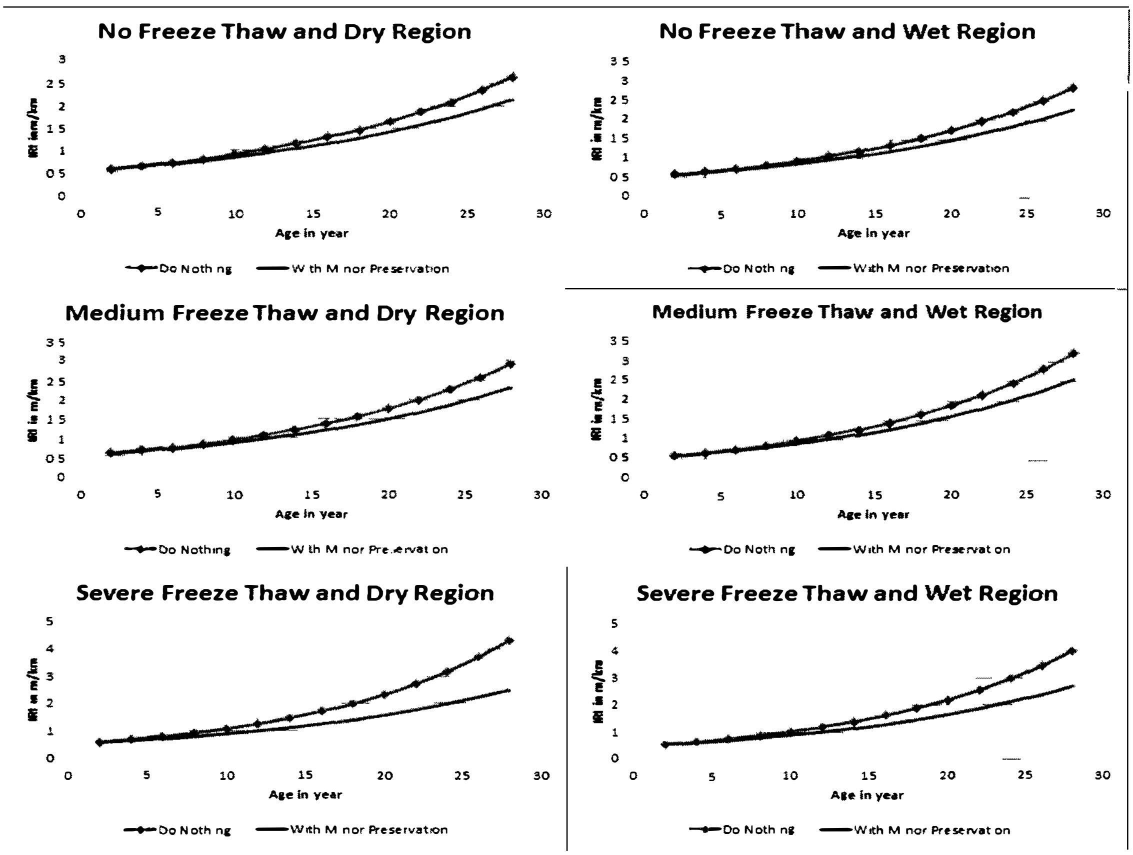

Figure 6. Pre-treatment Performances for Different Minor Preservation Strategies.

The deterioration rates for the do nothing strategy are higher than with the minor preservation strategy, but the magnitudes of the difference for each analysis regions are different. Differences in severe weather condition regions tend to be greater than in other regions with less severe weather conditions.

To compare the differences of the freeze-thaw cycle effect, it is found that deterioration rate increase with the freeze-thaw cycle level increase. The result is expected because freeze-thaw activity is commonly studied that will speed up the pavement deterioration. The more freeze-thaw cycles within a year, the more quickly the pavement condition will deteriorate, leaving the pavement in worse condition. The comparison is shown in Figure 7.

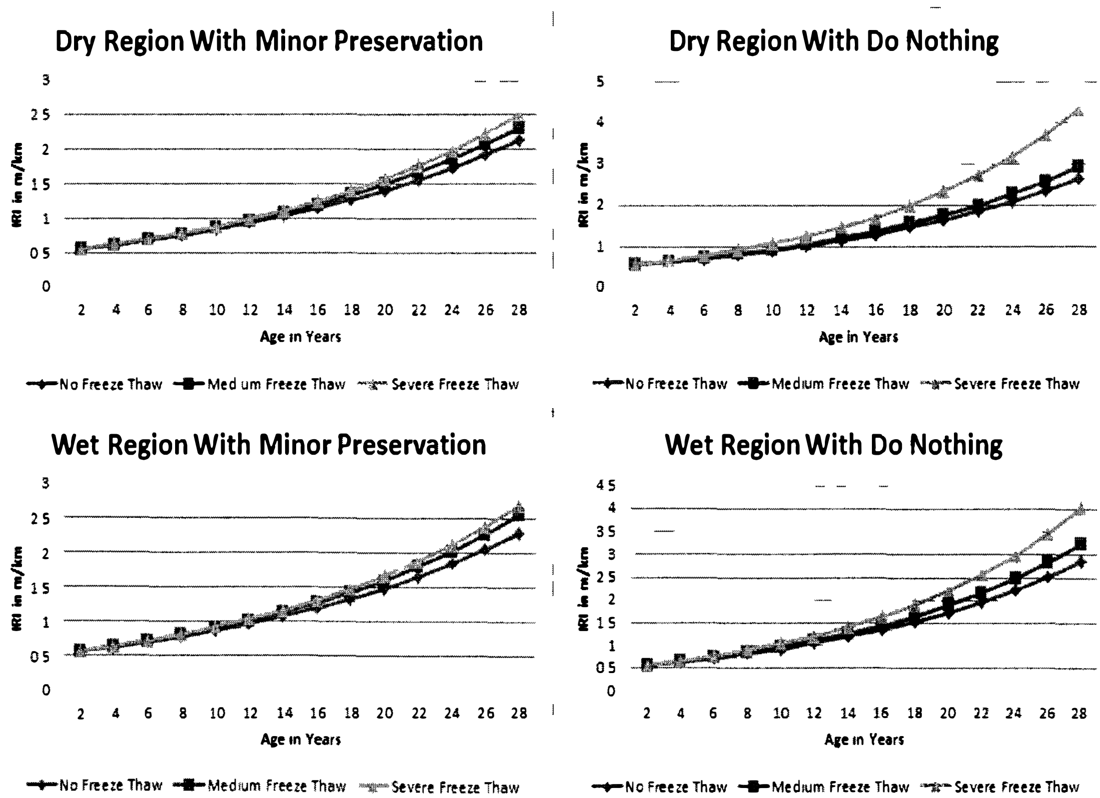

Figure 7. Pre-treatment Performances for Different Freeze Thaw Regions.

Notice that severe freeze-thaw cycles always have the highest deterioration rates and no freeze-thaw cycles always have the lowest deterioration rates for all four analysis categories. However, range of the differences among three freeze-thaw regions is less for "minor preservation" strategy regions than for "do-nothing" strategy regions. It shows that minor preservation activities are even more important in severe freeze-thaw regions than in no freeze-thaw regions because such minor preservation activities will decrease the pavement deterioration rate more significantly in severe freeze-thaw regions than in no freeze-thaw regions.

To compare the differences of the precipitation effect, it is found that in general the deterioration rate is higher in wet regions than in dry regions. The result is expected because it is widely accepted that precipitation is an important influential factor contributing to pavement deterioration. The more precipitation a region receives within a year, the worse the pavement condition will be or the faster the deterioration rate will be. The comparison is shown in Figure 8.

Notice that in most cases, wet regions have higher deterioration rates than dry regions. However, the differences are minimal for all the analysis regions. It shows that precipitation is an influential factor attributing to pavement deterioration and the effects of wet region and dry region are similar.

In the severe freeze-thaw regions using do nothing strategy, the region that is also classified as wet has a lower pavement deterioration rate than the dry region with similar properties. It is counterintuitive, since it is expected with the highest deterioration rate would be in the severe freeze-thaw, wet region using the do nothing strategy and the lower deterioration rate would exist in the severe freeze-thaw, dry region using the do nothing strategy. The reason of the counterintuitive result may be caused by the limited number of observations, 9 and 12, respectively. As mentioned before, it is rare to apply absolutely no treatment to a pavement, especially to a pavement located in a severe weather condition region. The result is more like a statistical average than a regression result with an insufficient number of observations. The author could do nothing to improve the model result at this point, because the data is not available.

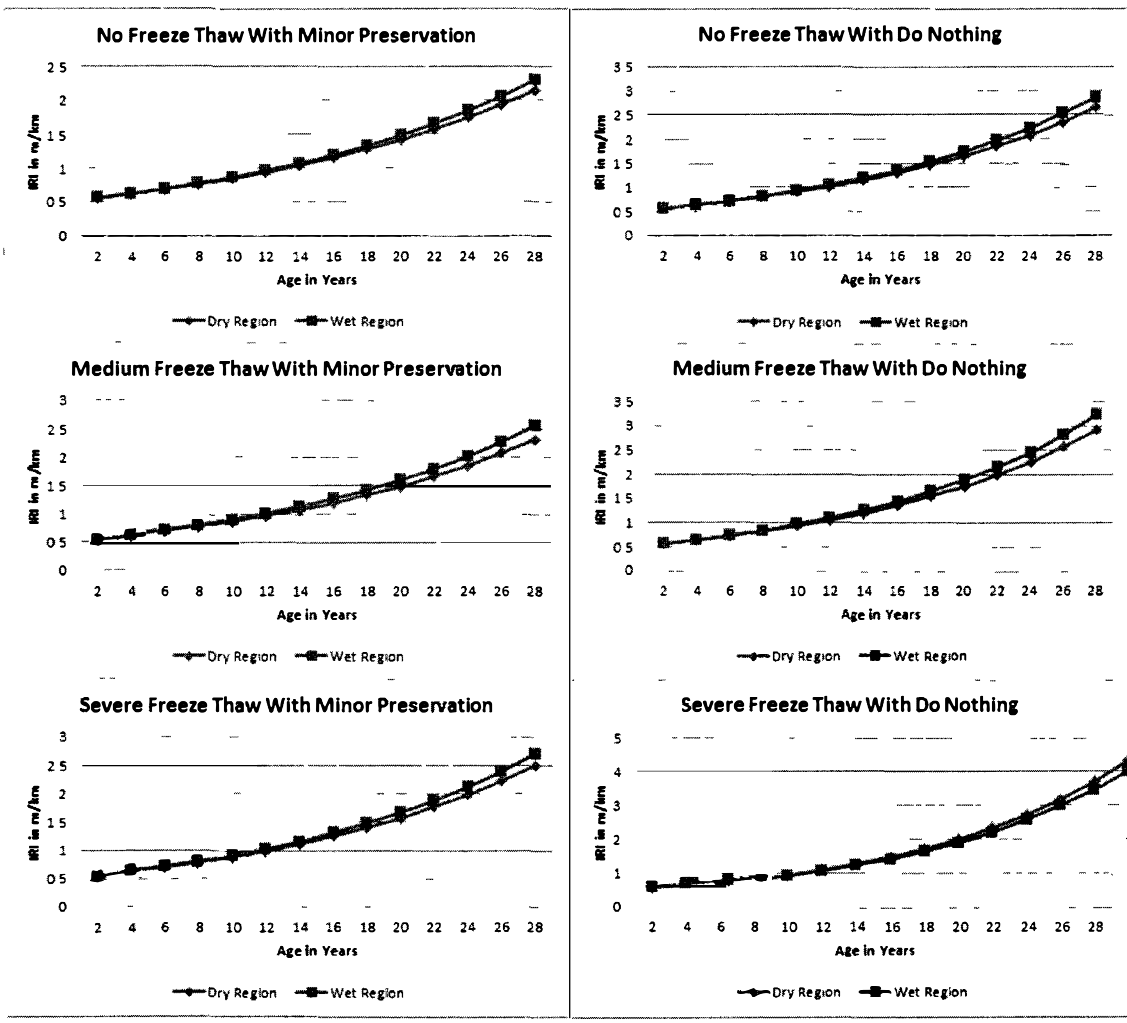

Figure 8. Pre-treatment Performances for Different Precipitation Levels.

4.2.3. Post-treatment Pavement Performance Model Formulation

It is assumed that post-treatment performance curve can be represented by exponential models as shown in equation (4).

$$IRI_{post}(t) = \alpha_2 * e^{\beta_2 * t} \quad (4)$$

Where

α_2= model parameters representing the initial value of IRI for post-treatment performance curve

β_2= model parameters representing the deterioration rate in IRI for post-treatment performance curve

t= pavement age in months since last medium or major preservation activity

Figure 9 shows the relationship between pre-treatment performance curve, short-term treatment performance jump, and post-treatment performance. The Figure 9 shows that the pre-treatment IRI follows the pre-treatment performance curve AFBC, unless a treatment is applied at point B, then the IRI value of the pavement will jump to point D. The treatment performance jump denoted by PJ is defined as the difference in pavement condition immediately before and immediately after the application of a treatment. Then the post-treatment IRI value will follow the post-treatment performance curve DE.

It is assumed that the post-treatment and pre-treatment performance curves are connected by treatment performance jump. Then the initial value of a post-treatment curve can be represented by equation (5).

$$\alpha_2 = IRI_{pre} - PJ \quad (5)$$

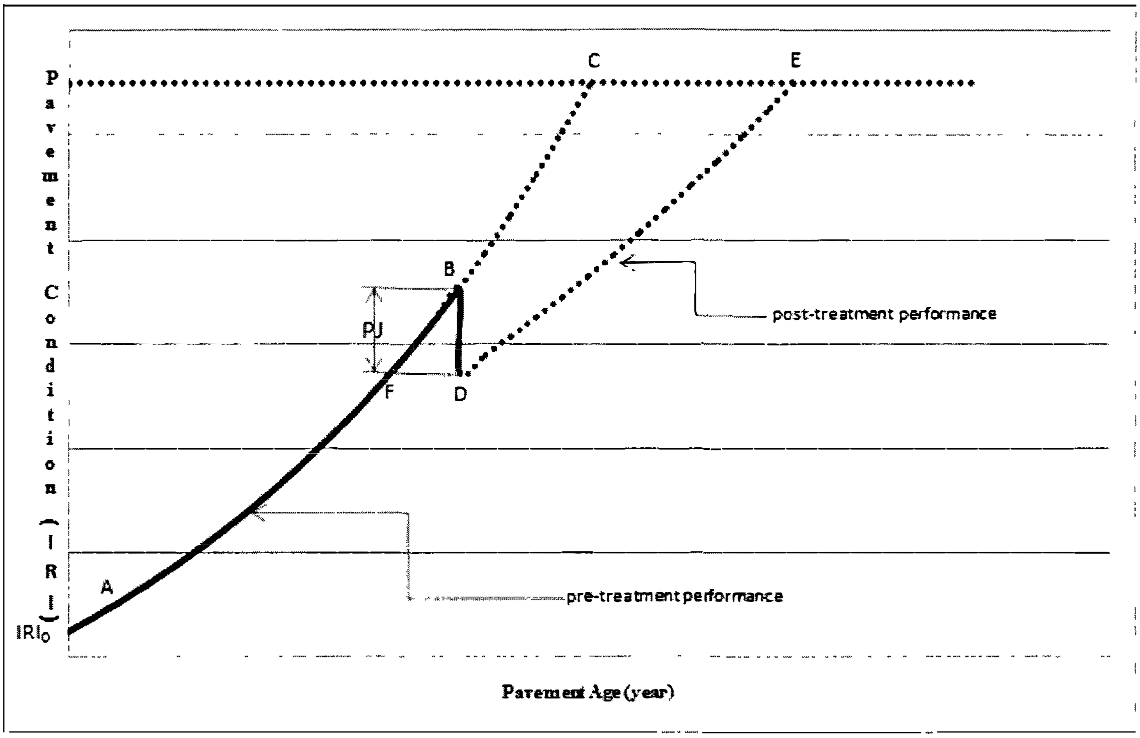

Figure 9. Relationship of Pavement Performance and Treatment Performance Jump.

$$\alpha_2 = IRI_{pre} - PJ$$

With equation (5), pre-treatment performance curve and treatment effectiveness equations, it is not difficult to calculate α_2 for a pavement having a treatment applied at any time. Then the next task is to calculate post-treatment deterioration rate. Figure 9 shows the behavior of the post-treatment deterioration rate. A treatment applied to a pavement at point B restores the pavement's surface condition back to the IRI value associated with point D or point F. Treatment should lower the deterioration rate at the moment, which is the deterioration rate at point D is supposed to be no greater than the deterioration rate at point B depending on the effectiveness of the treatment. The treatment should not improve the original condition of the pavement, which is the deterioration rate at point D is supposed to be no smaller than the deterioration rate at point F depending on the treatment effectiveness. For example, a reconstruction is considered as the highest effectiveness treatment. If a reconstruction applied to a pavement, it will restore IRI value and the deterioration rate back to the original conditions.

To find the long-term post-treatment performance deterioration rate, β_2, is very challenging. If the experimental data after a treatment is applied at any age of a pavement are available, it is not difficult to find the post-treatment performance deterioration rate. Unfortunately, such data are rarely available and expensive to obtain, thus, the reason why some researchers' studies show some unrealistic results.

Syed and Monther (2010) showed that if a treatment applied early in the pavement's life, the result is a lower treatment performance jump and slower post-deterioration rate; treatment applied later in the pavement's life results in a higher treatment performance jump and a faster deterioration rate. The conclusion is not always accurate since the higher treatment jump can be combined with slower post-treatment deterioration rate. More specifically, if a treatment has a higher performance jump, it is supposed to lower the deterioration rate at the point instead of increasing the deterioration rate. From Figure 9, deterioration rate at point D should be no greater than deterioration rate at point B ; and if a treatment has a lower performance jump, it is supposed to lower the deterioration rate at the point but not lower than the deterioration rate at after-treatment IRI value point on pre-treatment curve. From Figure 9, deterioration rate at point D should be no smaller than deterioration rate at point F.

The main reason for Syed and Monther to draw such a conclusion is because of the difficulty to obtain various post-treatment field performance data. They selected one section of pavement post-performance data with one control section pavement performance data to calculate the treatment effective and deterioration rates. The number of data is insufficient and the results are very sensitive to the available pavement performance data.

Before the post-treatment performance data become available, one can hardly verify the long-term, post-treatment deterioration rates. However, if researchers only focus on the short term treatment effectiveness, that is researchers only look at treatment performance within one year after treatment is applied to the pavement, it is realistic to assume that if a treatment can restore the IRI value it can also restore the deterioration rate based on the new IRI value. Explained in Figure 9, it is that deterioration rate at point D is the same as the deterioration rate at point F. In this case the pre-treatment deterioration rate, β_1, should equal to the post-treatment deterioration rate, β_2, because the treatment effect is basically a restoration effect. The mathematical derivation of the relationship is shown in the next paragraph.

If a treatment applied to a pavement at its age of t_i with performance jump PJ_i, the pre-treatment condition can be expressed via Equation (4) as Equation (6) and pavement age associated with post-treatment IRI condition, t_j, can be expressed via Equation (4) as Equation (7).

$$IRI_i^{pre} = \alpha_1 \times e^{\beta_1 \times t_i} \tag{6}$$

$$t_j = \left[\ln\left(\frac{\alpha_1 \times e^{\beta_1 \times t_i} - PJ_i}{\alpha_1}\right)\right] / \beta_1 \tag{7}$$

Restored deterioration rate behavior can be expressed as in Equation (8).

$$\left.\frac{df_{pre}(t)}{dt}\right|_{t=t_j} = \left.\frac{df_{post}(t)}{dt}\right|_{t=0} \tag{8}$$

Calculating the derivative of pre-treatment performance curve and post treatment performance functions one can get the Equation (9).

$$\alpha_1 * \beta_1 * e^{\beta_1 * t_J} = \alpha_2 * \beta_2 \tag{9}$$

By replacing Equation (5), (6), and (7) in Equation (7), a relationship between β_1 and β_2 at treatment application time t_ι will be obtained as shown in equation (10).

$$(\alpha_1 \times e^{\beta_1 \times t_\iota} - PJ_\iota) \times \beta_1 = (\alpha_1 \times e^{\beta_1 \times t_\iota} - PJ_\iota) \times \beta_2 \tag{10}$$

Since $\alpha_1 \times e^{\beta_1 \times t_\iota} - PJ_\iota = \alpha_2 \neq 0$, the post-treatment deterioration rate should equal to the pre-treatment deterioration rate.

4.2.4. Post-treatment Pavement Performance Model Results

Six weather condition regions, two minor preservation strategies, and seven treatment activities will result in 84 post-treatment performance analysis categories. In each category, there should be many post-treatment performance curves depending on the treatment application time. In general, post-treatment performance curve function can be expressed in Equation (11)

$$IRI_{Jt_\iota} = (\alpha_1 \times e^{\beta_1 \times t_\iota} - PJ_{Jt_\iota}) \times e^{\beta_1 \times t} \tag{11}$$

Where

IRI_{Jt_ι}= post-treatment IRI when treatment j applied to a pavement at t_ι

α_1= model parameter representing the initial value of IRI for pre-treatment performance curve

β_1= model parameter representing the deterioration rate in IRI for pre-treatment performance curve

t_ι= pavement age when a treatment applied to the pavement

PJ_{Jt_ι}= pavement IRI performance jump when treatment j applied to the pavement at age t_ι

t= post-treatment pavement age in months

In this section the author will choose a medium freeze-thaw, wet region to show how to calculate post-treatment performance curves for different treatment application times and then analyze the results for the obtained post-treatment performance curves. All the other weather regions should have the similar post-treatment performance behaviors.

Figure 10 shows pavement performance curves for hot mix resurfacing treatment applied to the pavement located in a medium freeze-thaw, wet region at various pavement ages from year 8 to year 26. From Figure 10 shows that post-treatment performance rates at the treatment application moment are always less than the pre-treatment performance rate at the moment. Treatment short-term effectiveness in terms of IRI value performance jumps and deterioration rate reductions are different when the treatment is applied to the pavement of different ages.

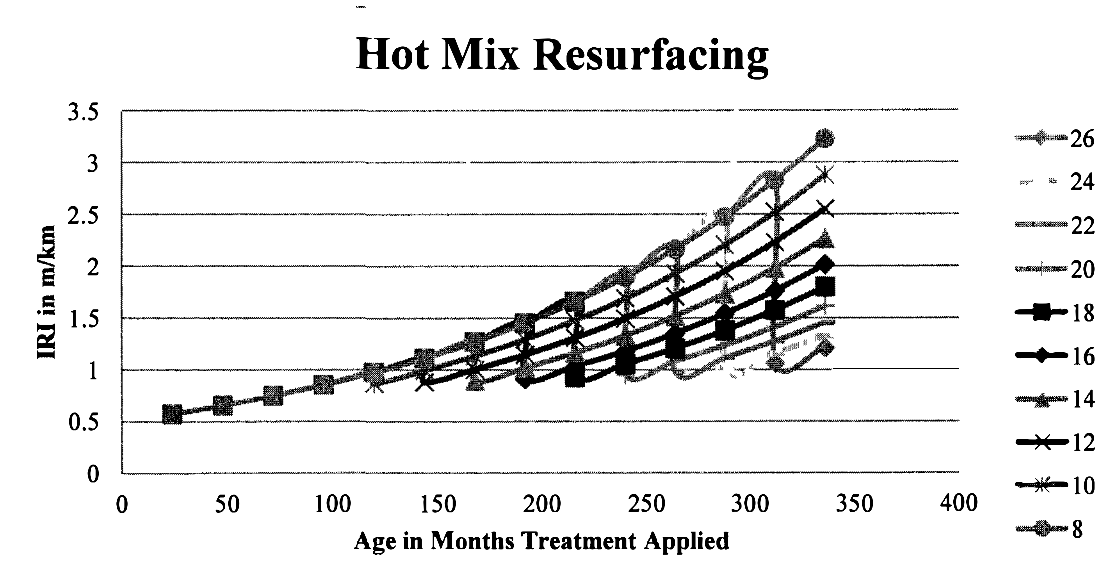

Figure 10. Pavement Performance Curves for Different Application Times.

Figure 11 shows pavement performance curves for aggregate seal treatment applied to the pavement at various pavement ages from year 10 to year 26. A comparison of Figure 10 and Figure 11 demonstrates that different treatments will affect the IRI values and deterioration rate differently. The higher reservation level treatment, the higher IRI value reduction and pavement performance rate reduction will be in general.

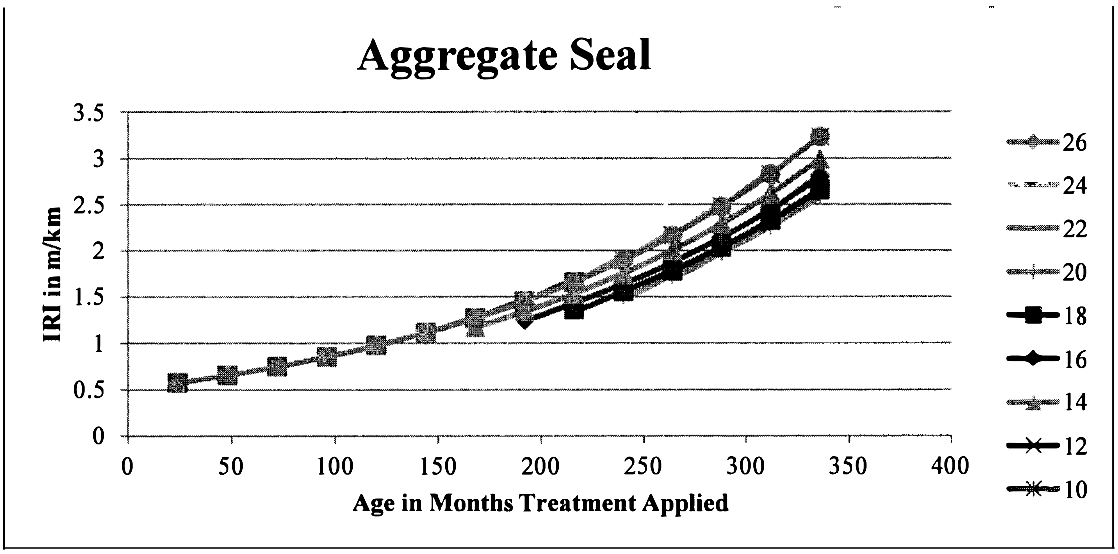

Figure 11. Pavement Performance Curves for Different Application Times.

Figure 12 shows pavement deterioration rates for different treatments applied to the pavement at various pavement ages from year 2 to year 28. Figure 12 illustrates that the post-treatment deterioration rates at the moment are always no greater than pre-treatment deterioration rate at the moment no matter when a treatment is applied to a pavement. However, a treatment cannot always reduce the pavement deterioration rate. It will only decrease the deterioration rate when a treatment is applied to a pavement at certain ages. If it is applied to a pavement too early or too late, the deterioration rate at the moment will remain the same.

Figure 13 shows the deterioration rate change in percentage for different treatments applied to pavement at different age. Deterioration rate change is defined as the difference between pre-treatment deterioration rate and post-treatment deterioration rate divided by pre-treatment deterioration rate.

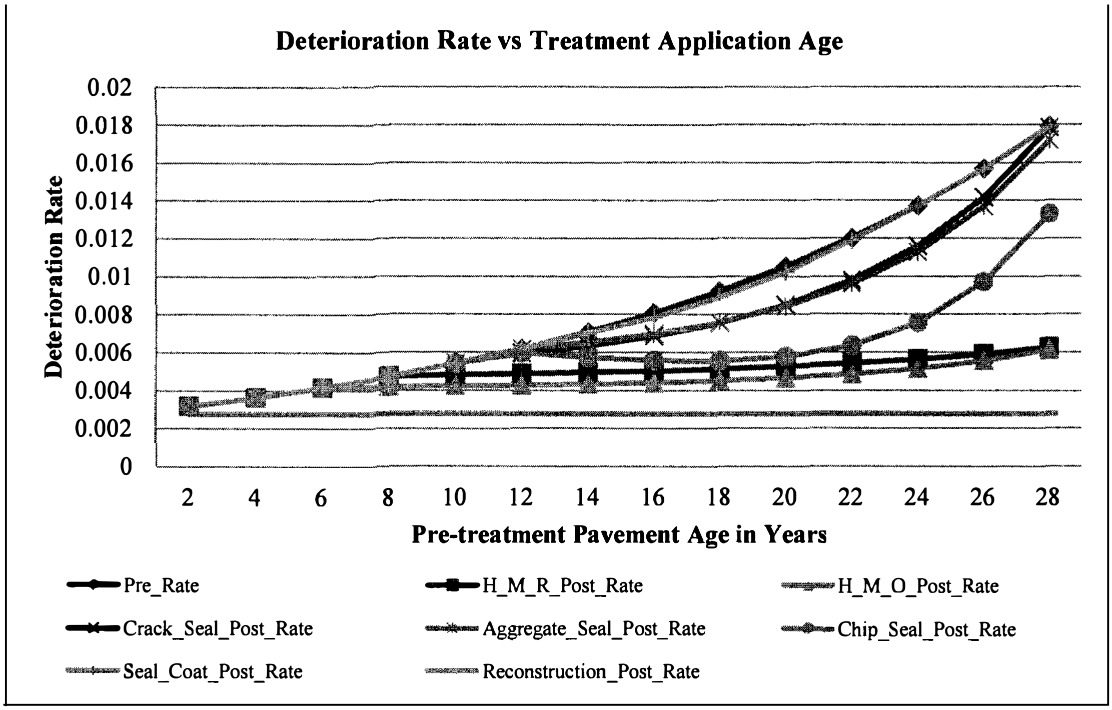

Figure 12. Pavement Deterioration Rates for Different Treatment at Different Application Times.

Figure 13 shows that 1) when a treatment is applied to a pavement too early or too late, it will not reduce deterioration rate; 2) each type of treatment has its own highest deterioration change effect beyond which no more deterioration rate change can be obtained for the treatment; 3) lower level preservation treatment has lower magnitude of the best deterioration rate change in general; 4) the best deterioration rate reduction point for lower level preservation treatment is earlier than it for the higher level preservation treatment (in other words, it can be obtained at younger age of a pavement); and 5) the curve is flat which means the "best" treatment application time is not very sensitive. It is rather a best treatment application time range than a best application time point.

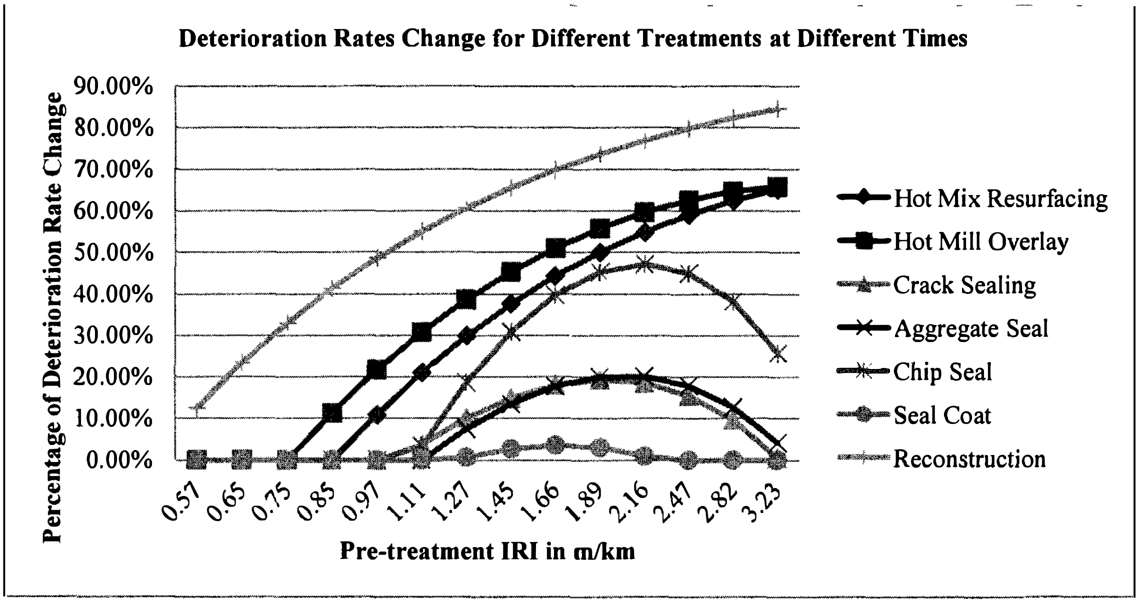

Figure 13. Short Term Deterioration Rate Changes for Different Treatments at Different Application Times.

Considering a hypothetical road network which consists 24 road segments crossing six weather analysis regions, and contains one corridor, a researcher can calculate all road segments' IRI values a year later after a treatment is applied to the segments by using pre-treatment performance or post-treatment performance functions.

Figure 14 shows the hypothetical road network. The hypothetical road network consists 24 equal length road segments crossing six weather analysis zones. The network contains one corridor, road segment one through road segment seven. The road segments' IRI conditions vary, ranging from 1.3 m/km to 3 m/km with a mean-value of 2.08 m/km and standard deviation of 0.49 m/km.

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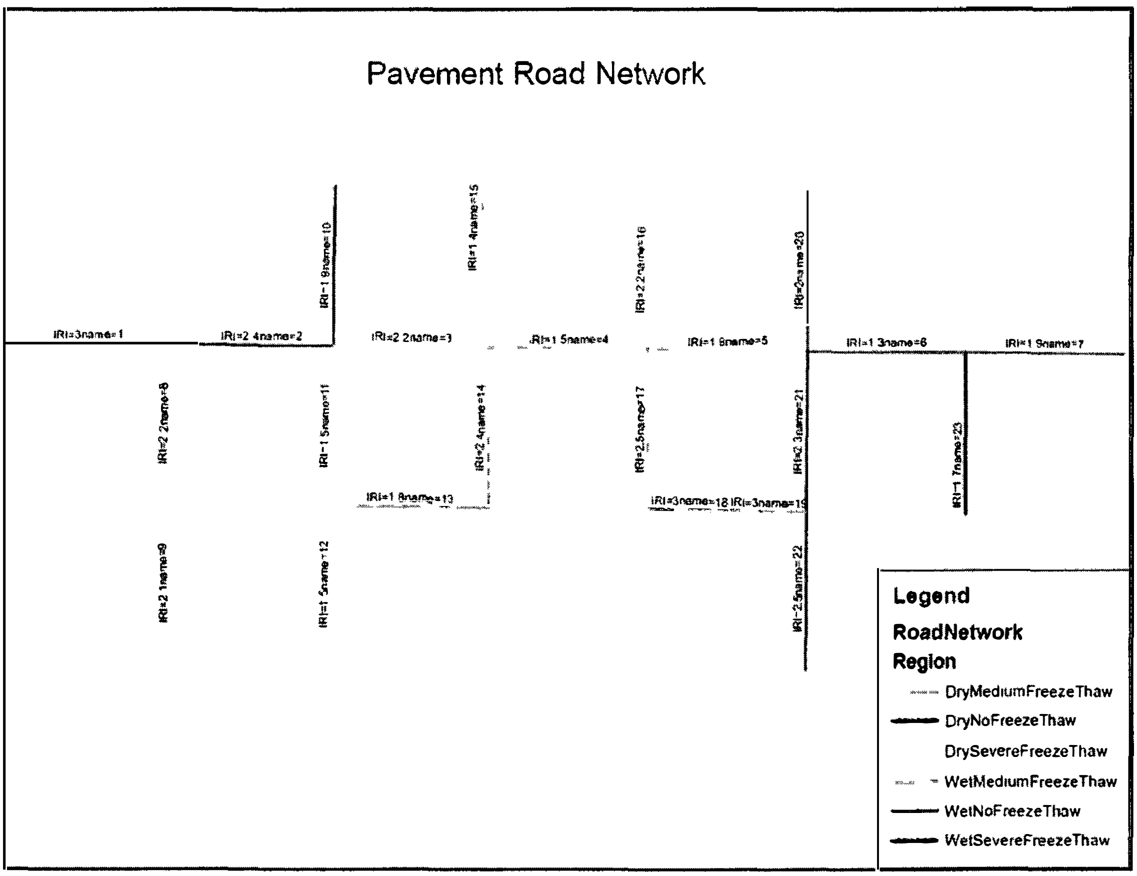

Figure 14. A Hypothetical Road Network.

Table 6 shows the calculated post-treatment IRI results for different treatment scenarios based on the calculated post-treatment performance functions. The forecasted results shown in Table 6 can be used for the pavement management decision making.

4.3. Summary

This chapter outlines separate pre-treatment performance and post-treatment performance models and how the two models are connected by treatment effectiveness models which are developed in Chapter 3.

First, the pre-treatment performance curves for different weather regions and different minor preservation strategies are developed. Next, an explanation was provided for connecting pre-treatment performance and post-treatment performance curves with treatment effectiveness, why the assumptions are used, and how post-treatment performance curves are calculated.

This chapter also explains pre-treatment performance differences of different weather regions and different minor preservation strategy regions. The result shows a clearly weather effects and minor preservation strategy effects on pre-treatment pavement performance

A hypothetical road network is introduced and the corresponding pre-treatment IRI conditions are assumed for segments. Predicted IRI values are derived from the post-treatment performance models with the intent to calculate short term post-treatment IRI values. Once post-treatment performance models are determined, IRI values for one year after treatment are calculated for the twenty-four road segments located among three freeze-thaw cycle level regions, two precipitation level regions, and two minor preservation strategy regions included in this study.

Table 6. Post-treatment IRI Values for Different Treatment Scenarios.

Pre -IRI	Road Name	Zone	Post-IRI Treat1	Post-IRI Treat2	Post-IRI Treat3	Post-IRI Treat4	Post-IRI Treat5	Post-IRI Treat6	Post-IRI Treat7	Post-IRI Treat8	Post-IRI Treat9
2.4	14	D-M	3.03	2.41	2.41	2.251	1.962	1.305	1.009	0.917	0.502
1.8	13	D-M	2.18	1.808	1.746	1.527	1.458	1.022	0.942	0.831	0.502
2.5	17	D-M	3.175	2.511	2.511	2.408	2.07	1.391	1.022	0.935	0.502
3	18	D-M	3.913	3.013	3.013	3.013	2.732	2.009	1.094	1.046	0.502
3	19	D-M	3.913	3.013	3.013	3.013	2.732	2.009	1.094	1.046	0.502
2.5	22	D-N	3.204	2.511	2.511	2.408	2.071	1.391	1.022	0.935	0.502
2.3	21	D-N	2.911	2.311	2.311	2.107	1.862	1.232	0.997	0.9	0.502
1.7	23	D-N	2.056	1.708	1.646	1.438	1.395	1.009	0.933	0.821	0.502
1.7	24	D-N	2.056	1.708	1.646	1.438	1.395	1.009	0.933	0.821	0.502
2.2	8	D-S	3.666	2.211	2.198	1.972	1.768	1.17	0.986	0.884	0.502
2.1	9	D-S	3.444	2.11	2.077	1.847	1.682	1.118	0.974	0.87	0.502
1.5	11	D-S	2.194	1.507	1.461	1.281	1.285	1.006	0.915	0.802	0.502
1.5	12	D-S	2.194	1.507	1.461	1.281	1.285	1.006	0.915	0.802	0.502
2.2	3	W-M	2.721	2.211	2.198	1.972	1.769	1.17	0.986	0.884	0.502
2.2	16	W-M	2.721	2.211	2.198	1.972	1.769	1.17	0.986	0.884	0.502
1.5	4	W-M	1.758	1.507	1.461	1.281	1.285	1.006	0.915	0.802	0.502
1.8	5	W-M	2.165	1.809	1.747	1.528	1.459	1.023	0.943	0.832	0.502
1.4	15	W-M	1.625	1.407	1.374	1.213	1.237	1.016	0.906	0.794	0.502
1.3	6	W-N	1.502	1.306	1.291	1.151	1.193	1.032	0.897	0.786	0.502
1.9	7	W-N	2.32	1.909	1.851	1.625	1.526	1.045	0.953	0.843	0.502
2	20	W-N	2.46	2.009	1.961	1.731	1.601	1.077	0.963	0.856	0.502
2.4	2	W-S	3.478	2.412	2.412	2.253	1.963	1.306	1.01	0.917	0.503
1.9	10	W-S	2.608	1.91	1.852	1.626	1.527	1.045	0.953	0.843	0.503
3	1	W-S	4.579	3.015	3.015	3.015	2.734	2.011	1.095	1.047	0.503

CHAPTER 5. REGRESSION MODEL FORECAST VALIDATION

In this chapter, a review of the regression model forecast validation procedures used in this study is presented and the forecast verification statistical results are calculated for the models developed in the previous chapters. An objective evaluation of the forecasting qualities of the previously developed models is also presented.

5.1. Model Forecast Validation Review

Regression model forecast verification is sometimes called validation, or evaluation. The purpose of this process is to help assess the specific strengths and deficiencies of regression models when they are used to forecast values of the dependent variable using values of the explanatory variables which were not represented in the sample dataset used to estimate the model. Ultimately, this process may provide justifications for uses of the model for forecasting and supporting better decision making (Wilks, 2006). Most of the forecast verification procedures involve measures of the relationship between a forecast and the corresponding observation of the predictand (Wilks, 2006). Subjective evaluation involves engineering judgment while objective evaluation involves statistical comparisons between pairs of forecasts and the observations.

Cook and Kairiukstis (1990) state that reduction of error (RE) "should assume a central role in the verification procedure" (p. 181). RE is an example of forecast skill statistic (Wilks, 2006). Wilks (2006) defined forecast skill as the relative accuracy of a set of forecasts with respect to some set of standard controls, which are usually the average values of the predictand. The equation used to calculate RE can be expressed in the following Equation (12)

$$\mathrm{RE}=1-\frac{SSE_v}{SSE_{ref}} \tag{12}$$

Where SSE_v= sum of squares of validation errors between observed and predicted values over validation period and SSE_{ref}= sum of squares of validation errors between observed and control values or reference values over validation period.

Jackknife is a statistical method that is systematically computing the statistic estimate leaving out one observation at a time from the sample set (Wilks, 2006). One application of Jackknife procedure is to compare difference between the omitted observation's value and predicted value for the omitted observation. The difference is defined as validation error. It can be mathematically expressed as Equation (13)

$$e_{(i)} = y_i - \widehat{y_{(i)}} \tag{13}$$

Where y_i and $\widehat{y_{(i)}}$ are the observed and predicted values of the predictand for validation data set i, and the notation (i) indicates that the validation data set i was not used in fitting the model that generated the prediction $\widehat{y_{(i)}}$.

Sum of the squares of errors for validation, SSE_v, can be expressed as Equation (14) and the sum of squares of errors for reference, SSE_{ref}, can be expressed as Equation (15)

$$SSE_v = \sum_{i=1}^{n_v} e_{(i)}^2 \tag{14}$$

$$SSE_{ref} = \sum_{i=1}^{n_v} (y_i - \bar{y})^2 \tag{15}$$

Where n_v is the validation period or the number of validation tests and $\bar{y}$ is the mean of the predictand, which usually serves as a reference or control value.

Leave-one-out Jackknife procedure will select one validation data point to exclude from the original dataset at one time. The regression calculations are repeated for n times, which should be the number of observations in the original data set. Notation i in Equation (13) can then be explained as the ith observation in the original dataset which is selected as the leave-out validation data. Notation n_v in Equation (14) and (15) then should be n. The Equation (14) will then be identical to PRESS (the predicted residual sum of squares) and RE can be expressed as Equation (16) and used as the objective model verification statistic in this study.

$$RE = 1 - \frac{\sum_{i=1}^{n}(y_i - \widehat{y_{(i)}})^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} = 1 - \frac{PRESS}{SSE_{ref}} \tag{16}$$

Theoretically, the value of RE can range from negative infinity to one, where one indicates perfect prediction for the validation data set. It will only occur when all the residuals for validation data are zero (i.e. PRESS = 0). On the other hand, if PRESS is much greater than SSE_{ref}, RE can be negative and large. As a rule of thumb, a positive RE indicates that the regression model on average has some forecast skill. Contrastingly, if RE$\leq$ 0, the model is deemed to have no skill to predict (Cook & Kairiukstis, 1990; Wilks, 2006). The similarity in form of the equations for RE and regression R^2 expressed as Equation (17) suggests that RE can also be used as validation evidence for R^2. The closer the values of RE and R^2 are to each other, the more the model is accepted as a predictive tool. RE sometimes is referred as Jackknife R^2.

$$R^2 = 1 - \frac{SSE}{SST} = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \tag{17}$$

5.2. Model Forecast Validation Results

Six treatment effectiveness models were developed in this study. The model results were shown earlier in Table 1. The regression R^2 is very low for a seal coat model that meets expectations, since the seal coat treatment failed the significance test for IRI change and should not change pavement surface roughness. The regression R^2 is relatively low for chip seal. The main reason is that the number of observations for chip seal treatment is too small (i.e. 13) and is not a sufficient sample size for regression analysis. Those two models are eliminated for model validation purposes.

Twelve pre-treatment performance models were developed in this study. The model results were shown earlier in Table 5. Altogether, sixteen models were tested for model forecast validation. The results are shown in Table 7.

Hot Mix Resurfacing in Table 7 refers to the treatment effectiveness model for hot mix resurfacing treatment. The rest of treatment effectiveness models follow the same definition pattern. S-D-Nothing in Table 7 refers to the pre-treatment performance model for a severe freeze-thaw and dry region with a do-nothing strategy. S-W-Nothing in Table 7 refers to the pre-treatment performance model for a severe-freeze thaw and wet region with a do-nothing strategy. M-D-Minor in Table 7 refers to the pre-treatment performance model for a medium freeze-thaw and dry region with a minor preservation strategy. N-D-Minor refers to the pre-treatment performance model for a no freeze-thaw and dry region with a minor preservation strategy. The rest of the pre-treatment performance models follow the same definition pattern.

Table 7. Forecast Validation of Regression Models.

Models	R-Square	Jackknife R-Square	Difference
Hot Mix Resurfacing	85.24%	84.66%	0.68%
Hot Mill Overlay	88.01%	72.51%	17.61%
Aggregate Seal	76.80%	25.80%	66.41%
Crack Sealing	83.48%	82.48%	1.20%
S-D-Nothing	91.43%	89.87%	1.71%
S-W-Nothing	88.35%	85.17%	3.60%
M-D-Nothing	81.03%	78.37%	3.28%
M-W-Nothing	84.90%	83.94%	1.13%
N-D-Nothing	77.90%	73.03%	6.25%
N-W-Nothing	79.60%	72.05%	9.48%
S-D-Minor	80.87%	79.84%	1.27%
S-W-Minor	86.49%	86.02%	0.54%
M-D-Minor	77.70%	77.26%	0.57%
M-W-Minor	78.63%	78.58%	0.06%
N-D-Minor	85.02%	84.88%	0.16%
N-W-Minor	69.13%	68.98%	0.22%

Table 7 provides several indications about the models. 1) All the models are accepted with consideration of some forecast skills, since all the Jackknife R-Squares are positive values. 2) Most of the models are accepted as validated models since most of them have Jackknife R-Square values close to R-Square, except for the aggregate seal effectiveness model. 3) Most of the models have Jackknife R-Square values higher than 70%, except for one model. The high Jackknife R-Square values indicate that most of the models can be accepted as exhibiting higher forecasting skills, since 100% means perfect forecast skill. 4) The aggregate seal effectiveness model has the smallest Jackknife R-Square of 25.8%, which means that the aggregate seal effectiveness model will have the lowest forecast skill among all of the models.

CHAPTER 6. MULTI-OBJECTIVE DECISION MAKINGS

In this chapter, a review of pavement management decision making tools, with emphasis on multi-objective optimization tools, is conducted. The first section discusses the previous research and experiences regarding pavement decision making analysis tools. The second section focuses on discussing multi-objective optimization model formulation and application of the method including solvers and results analysis in this research. This section also provides discussions regarding other potential multi-objective optimization model solvers. The last section summarizes the chapter in detail.

6.1. Pavement Management Decision Makings Literature Review

Decision support analysis tools are used to identify pavement sections in need of treatment, what type of treatment category or treatment is required, and the budget needs over the funding period. The tools vary from ranking approaches to optimization techniques to identify pavement sections (AASHTO, 2001). The tools are summarized in Table 16 after AASHTO Pavement Management Guide (2001).

Clearly, ranking is relatively simple and it is easy to explain the results; however, ranking is a limited method with a restricted capability to account for different constraints and generally will not produce the optimum solution. On the other hand, optimization models are more able to accommodate multiple constraints and solve multiple problems such as section selection, treatment selection, and fund allocation problems simultaneously. In theory, PMSs can benefit from optimization models regarding operation research (OR). In reality, optimization models often receive much criticism. The model itself is too complicated and the results cannot easily be understood by practitioners. The optimum solution often needs to have changes made to it, due to technical, economic, social, environmental, and political issues, which influence decisions on the project selection level (AASHTO, 2001). Some highway agencies have adopted optimization models to make more balanced pavement management decisions. Other agencies have adopted ranking procedures because of the lack of support to apply optimization models in terms of skilled personnel, adequate data, and administrative support.

For network level analysis, optimization models can be categorized as macroscopic and microscopic models, according to different model formulations. Model formulation and solution finding can be simplified by introducing different pavement classes as proportions of pavement for macroscopic optimization models, substantially reducing the number of variables. However, for microscopic optimization models, the decision variables are related to individual pavement sections; in other words, there will be too many decision variables, resulting in an extremely difficult optimization process (Abaza, 2007).

For project level analysis, life-cycle cost analysis (LCCA) and detailed design of individual projects were most commonly applied. LCCA makes decisions based on the comparisons of predefined investment alternatives considering all different cost factors (ARA, 2004): (1) initial cost of building a pavement facility; (2) all upcoming agency costs for preservation activities over the pavement's life; (3) all user costs; and (4) salvage value of the pavement at the end of its life. LCCA requires the extent of detail necessary for competing pavement design alternatives to identify the best solution for investment expenditures; however, the result is typically semi-optimal.

It should be noted that it is difficult to evaluate lower level preservation actions, such as corrective maintenance and routine maintenance. Quantifying the effectiveness of the preservation treatments, in terms of pavement roughness improvement or extended pavement service life, is difficult, so it is also difficult to quantify user costs for these actions. Even though the lower lever preservation actions' direct benefits and costs can be quantified, it is still complicated to integrate the direct and indirect benefits and costs into the optimization model. For example, some researchers try to categorize routine maintenance as a separate preservation action and measure its direct effectiveness and costs in an optimization model (Durango-Cohen, 2004) which still does not account for the fact that lower level preservation actions often occur throughout a pavement's life. Another fact that was often omitted is that lower level preservation actions happen more often and the expenditures increase in relationship to the pavement roughness level (Al-Mansour & Sinha, 1994a; Al-Mansour & Sinha, 1994b). When the pavement surface condition is deteriorating, the lower level preservation actions' direct effectiveness (for instance, performance jump) may not be sufficient; however, the indirect effectiveness (for instance, blocking water into a pavement) still exists. With a rougher road, more cracks and potholes may appear and lower level preservation actions, like patching and cracking filling, may be needed. For an optimization model with the objectives of minimizing its direct agency cost and maximizing its direct treatment benefit, the failure to account for such lower level preservation actions' effectiveness or indirect agency costs may lead to biased or misleading results. Because optimization models are preferred for this dissertation, the literature review is focused on such tools.

6.1.1. Pavement Management Optimization Models Literature Review

A maintenance optimization model is a mathematical model to identify optimal pavement preservation or reconstruction actions and budget allocations. Such optimization models applied in pavement management can be generally categorized as single objective or multi-objective optimization.

Single objective optimization typically addresses different goals (Mbwana, 2000): (1) minimize cost, (2) maximize the treatment benefits or (3) maximize the pavement's condition or life. Pavement related costs are agency costs and user costs. Agency costs are all costs incurred directly by the agency over the life of the projects (Walls & Smith, 1998). Agency cost can be calculated as a function of preservation actions. User costs are travel delay, vehicle operation, and crash costs incurred by the users of a facility associated with both normal operations and work zone operations (Walls & Smith, 1998). User cost can be formulated as a function of pavement condition and preservation actions (ARA, 2004). Some user costs are difficult to quantify, such as crash costs and comfort costs. Minimizing only costs will result in reduced costs but may produce rougher pavement conditions. By only maximizing pavement surface conditions, costs could be higher.

Sometimes the decision makers may be satisfied with optimizing only one objective; however many times an agency will aim to optimize more than one objective in a given analysis time. In this case, there are some common techniques used to compromise conflicting objectives (Mbwana, 2000; Abaza, 2007). The first technique is optimizing one objective and using the other objectives as constraints with a fixed boundary. For example, maximizing the pavement condition improvement associated with applied preservation treatments subjected to budget constraints, or minimizing the total costs associated with applied preservation treatments subjected to certain pavement condition preservation or improvement condition constraints. The second technique is adding all competing single objectives into a single objective. For example, this compromise uses the sum of user costs and agency costs as one objective instead of viewing user costs and agency costs separately (Mbwana, 2000). Instead of using a single objective or the combination of all objectives, the third technique is directly performing a true multi-objective optimization to address competing objectives. For example, agencies can develop solution strategies that consider optimizing both agency cost and pavement roughness (Wu & Flintsch, 2008).

It should be noted that there are limitations and criticisms for each technique. With the first technique, the limitation comes from the assumption that the optimal levels of the objectives being put into the constraints are known. The fixed boundaries limit the objectives' optimal levels. A limitation for the second technique stems from needing to convert all objectives into a single equivalent unit. It is difficult to convert costs into the same units as pavement roughness. Even if one can quantify the same unit for user cost and agency cost, some still criticize the assumption of this technique that marginal user cost equals marginal agency cost, considering non-highway users (Mbwana, 2000). Another criticism regarding this method is that how the greater scale of user costs tends to dominate the decision process over the smaller scale of agency costs (Wu & Flintsch, 2009) and it is unrealistic to simply summarize two costs. The limitation for the third technique comes from the complexity of finding the solution for the model. The more conflicted objectives one includes into the model, the greater difficulty to find the solutions. Thus, it is not a surprise that according to literature reviewed, for those who use a true multi-objective optimization method, none incorporate all objectives into the model. Some models include direct agency costs and pavement condition, while others include direct agency costs and simplified or partial user costs (Worm & Harten, 1996; Labi & Sinha, 2003b; Wu & Flintsch, 2009; Wu & Flintsch, 2008). The reasons vary but can be summarized in two statements (1) objectives are difficult to evaluate precisely and impartially (Wu & Flintsch, 2008), and (2) optimization models are difficult to formulate and solve with all detailed objectives and constraints.

6.1.2. Multi-Objective Optimization Concepts Literature Review

For single-objective optimization problems, the notion of optimality is well defined as minimizing or maximizing the value of one given objective. In multi-objective optimization problems, there are two or more objectives that need to be optimized. When one of the objectives is improving and the other objectives react in the same way, by also improving, then the problem becomes fairly simple. The one unique optimal solution will be found by improving both objectives. But in general, there is no single optimal solution that simultaneously yields a minimum or maximum for all objective functions. For highway maintenance management, agencies need to maintain highways while keeping agency costs as low as possible and at the same time maintaining low surface roughness. These two objectives are in opposition with each other. As costs decrease, the road roughness tends to increase. The theoretically or ideally optimal solution is to have smooth highway pavements with zero cost. Satisfying the two conflicting objectives is not possible. In other words, it is not possible to find an absolute dominant optimal solution which satisfies both conflicting objectives. In this situation, what we want to have is not one unique dominant optimal solution, but a series of solutions where the two boundary solutions are rougher pavements, low cost and smoother pavements, high cost. All the other solutions will be between these two boundary solutions with none of them being a solution that can be improved in one of the objective without sacrificing or degrading at least one other objective. In other words, instead of finding a unique global dominant optimal solution, one would like to obtain series non-dominant, acceptable solutions.

A formal explanation is the family of solutions of a multi-objective optimization problem is composed of all those elements of the search space with which the components of the corresponding objective vectors cannot be all simultaneously improved. The concept is known as Pareto Optimality or Pareto Efficiency, named after Pareto Vilfredo, the Italian economist who first introduced the concept in his studies (Villfredo, 1906).

In general, a multi-objective optimization is defined as finding a vector of decision variables satisfying constraints to give acceptable values to all objective functions. It can be mathematically defined as finding the vector $X^* = [x_1^*, x_2^*, \dots, x_m^*]^T$ of *m* decision variables to optimize *n* objectives.

$$F(X) = [f_1(X), f_2(X), \dots, f_n(X)]^T \quad (18)$$

subject to p inequality constraints

$$g_i(X) \leq 0, \quad i = 1, \dots, p \quad (19)$$

And q equality constraints

$$h_j(X) = 0, \quad j = 1, \dots, q \quad (20)$$

where $X = [x_1, x_2, \dots, x_m]^T$ is the vector of m decision variables, and F(X) = $[f_1(X), f_2(X), \dots, f_n(X)]^T$ is the vector of n objective functions, which must be all minimized.

Then Pareto Optimality can be defined as a decision vector X^*, which satisfies both inequality constraints and equality constraints (the region that defined by all constraints is called feasible solution region Ω) is said to be Pareto Optimal if and only if $\forall i \in \{1,2, \dots, n\}, f_i(X^*) \leq f_i(X) \cup \exists j \in \{1,2, \dots, n\}, f_j(X^*) < f_j(X): X \in \Omega$. It is basically defined as if no other solution can be found to dominate X^* in terms of improving all the objectives simultaneously, X^* is said to be Pareto Optimality. In general, there are several Pareto optimal solutions (often called as non-dominant solutions) for a multi-objective problem. A Pareto set P^* is a set consisting of all the Pareto optimal vectors. A Pareto front PF^* is a set of vector of objective functions which are obtained using the vectors of decision variables in the Pareto set. It can be mathematically expressed as $PF^* = \{F(X) = (f_1(X), f_2(X), \ldots, f_n(X)) : X \in P^*\}$. Finding a Pareto set and corresponding Pareto front is the first step toward the practical solution of a multi-objective problem. In practice a choice must be made for a single final solution from the Pareto set according to some preference information.

6.1.3. Multi-Objective Optimization Solvers Literature Review

None of the feasible solutions allow simultaneous optimal solutions for all conflicting objectives, which is the common difficulty in solving multi-objective optimization. There are many different approaches to solve multi-objective problems, but they can be generally categorized in two classes (Messac, Ismail-Yahaya, & Mattson, 2003): (1) converted single objective approach and (2) Pareto non-dominant solutions approach. The first class tries to formulate one objective function that can represent the decision maker's preference; the resulting solution is pre-assumed to be optimal. The second class obtains a Pareto optimal solutions and then from which select the final optimal solution according to decision maker's preference or other selection criteria.

The most well-known approach used as the first class solvers is goal programming. The basic approach of goal programming is to establish a specific numeric goal for each of the objectives, so it allows negative, positive, or both deviations from each goal. Three types of goals exist: a lower bound goal, an upper bound goal, and a two-sided goal. Goal programing problems can be categorized as non-preemptive goal programing and preemptive goal programming, according to how the goals compare in importance.

Preemptive goal programing needs a hierarchy of priority levels for all goals. Such a case arises when one or more of the goals clearly are far more important than the others. In this case, the goals of primary importance receive first-priority, the secondary goals receive second priority, etc. To solve the problem researchers seek a solution that sequentially minimizes the deviations of the different priority goals.

The non-preemptive goal programing approach assumes that all the goals are of approximately comparable importance to one another. In other words, all the goals are on the same priority level. In this case researchers can formulate the objective function as a sum of the deviations of these objectives from their respective goals or penalty weighted sum of the deviations if desired. Then solving the multi-objective problem becomes seeking a solution that minimizes the weight sum of deviations of these objective functions from their goals.

The conversion of goals from objectives can be mathematically expressed as

$$f_i(X) < G_i \rightarrow f_i(X) + d_i^- - d_i^+ = G_i \rightarrow d_i^- > 0 \text{ and } d_i^+ = 0 \quad (21)$$

$$f_j(X) > G_j \rightarrow f_j(X) + d_j^- - d_j^+ = G_j \rightarrow d_j^- = 0 \text{ and } d_j^+ > 0 \quad (22)$$

$$f_m(X) = G_m \rightarrow f_m(X) + d_m^- - d_m^+ = G_m \rightarrow d_m^- = 0 \text{ and } d_m^+ = 0 \quad (23)$$

Where $f_i(X), f_j(X), and\ f_m(X)$ are three objectives, $G_i, G_j, and\ G_m$ are three goals assigned to the corresponding objectives, $d_i^-, d_j^-, and\ d_m^-$ are three positive deviations from corresponding goals, and $d_i^+, d_j^+, and\ d_m^+$ are three negative deviations from corresponding goals. Then the penalty weighted objective can be expressed as

$$\text{Min}\,(\omega_{i1}d_i^+ + \omega_{j1}d_j^- + \omega_{m1}d_m^+ + \omega_{m2}d_m^-) \tag{24}$$

Goal programming is a practical, flexible, reliable, and easy to implement approach to solve multi-objective decisions with conflicting problems, as shown in Wu's study (Wu & Flintsch, 2008). The technique is also independent of the relative scales of the original objective functions since its objective is minimizing deviations. The drawbacks of goal programing are 1) the method requires decision maker's pre-decision knowledge about assigning and justifying values of relative weights as penalty for different goal's deviations or assigning clear priorities among conflicting objectives. The resulting solution is assumed to be the optimal solution, presenting the decision maker's true preference; 2) the method basically allows violations of objectives' goals; 3) the preemptive goal programing does not allow a trade-off between goals with different priorities; and 4) goal programing cannot consistently yield Pareto optimal solutions. Marler and Arora (2004) pointed out that goal programing provide Pareto optimal solutions if all of the goals are unattainable and Zeleny (1982) discussed that, in general, preemptive and non-preemptive goal programming can result in non-Pareto optimal solutions.

The second type of solver is trying to find Pareto optimal solutions for all conflict objectives. This approach is the most favorable choice because Pareto optimal solutions can offer least objective conflict solutions (Villfredo, 1906) and it does not require pre-decision knowledge to assign weights. One most common method of finding Pareto optimal solution is weighted sum method (Wu & Flintsch, 2009; Das & Dennis, 1996; Srinivas & Deb, 1994; Cohon, 1978). Weighted multiple objective functions are converted into one objective function, Z. It can be expressed as following Equation (25)

$$Z = \sum_{i=1}^{n} \omega_i f_i(x) \tag{25}$$

Where ω_i are fractional weight values that range from 0 to 1.

In this method, the Pareto optimal solutions are found by controlling the weight vector among all potential weights situations with a selected incremental step in ω_i. All weights are summed up to one. This method clearly shows that the preference of an objective is also changed by modifying the corresponding weight. This method is the most popular to generate Pareto optimal solutions found in literature because it is an intuitive and straightforward approach, but it is sufficient enough for finding Pareto optimal solutions and it is simple to implement (Wu & Flintsch, 2009). As noted by Wu and Flintsch (2009), setting relative weight for each individual objective depends highly on the magnitude of each objective function and the weight values assigned to objectives do not necessarily indicate relative quantitative importance placed on the objectives but simply indicate the relative importance relationships. For example $\omega_1 > \omega_2$ only indicate objective $f_1(x)$ is more important than objective $f_2(x)$ but cannot say objective $f_1(x)$ is $\frac{\omega_1}{\omega_2}$ times more important than objective $f_2(x)$. This problem introduces one shortfall of this method: decision makers have difficulty identifying quantitative relationships among the objectives, which leads to difficulty in making final decisions according to their preferences. For example, it is extremely difficult to understand the precise difference between $\omega_1 = 0.6$ & $\omega_1 = 0.4$ and $\omega_1 = 0.7$ & $\omega_1 = 0.3$, since the two sets of weights indicate objective $f_1(x)$ is more important than objective $f_2(x)$ but cannot indicate other differences between the two objectives. If the simulated incremental weight step method (Wu & Flintsch, 2009) is used, the decision maker needs a priori information regarding the decision maker's preference to choose one solution from Pareto optimal solutions.

Combined with the fact that weights lack quantitative meanings, decision maker find it difficult to choose a weight vector and report the meaning of it.

Another concern with this method stems from the way to convert objectives with different scales into one objective. The well-known weighted linear sum method requires that all weighted objective functions are summed into one objective function; then, the user must minimize or maximize one objective to find one Pareto solution. In most cases, the scales and unit of objective functions are different. For instance, decision maker may like to minimize the agency costs while maximizing the pavement surface condition IRI values. Agency costs are measured in dollars; often ranging from $1,000 to over $100,000. However, pavement surface condition IRI values are in measured in m/km. often ranging from 0.5 to 3 m/km. The scale of the two objectives varies from less than one up to hundred thousand and the units of the objectives are different too. To simply sum the weighted two objectives together does not make sense (Messac, Ismail-Yahaya, & Mattson, 2003). Even if a researcher tried to convert the scale of the objective values the same scale (Wu & Flintsch, 2009), the summation of the objectives still will not produce significant information because of the different objective units. Because the units are different and simple summation does not provide adequate information, weights are assigned to the objectives; however, even weigh assignment cannot provide the quantitative importance relationship among objectives.

The last drawback of the weighted sum method may not provide sufficient enough or reliable solutions when the true Pareto frontier is not globally convex or the objective function to be minimized is not globally concave (Das & Dennis, 1997).

There are many other similar methods that can be used to generate Pareto optimal solutions. The methods, including the weighted sum method, can be classified as aggregate objective functions (AOF), which aggregate many objectives into one objective. The normal boundary intersection method (NBI) (Das & Dennis, 1996), the normal constraint method (NC) (Messac, Ismail-Yahaya, & Mattson, 2003), and successive Pareto optimization method (SPO) all solve the multi-objective problem by constructing AOF with weights assigned to original objectives, whereby each set of weights results in a corresponding Pareto solution. All these methods are able to overcome one or two drawbacks related with weighted sum method. According to Mueller-Gritschneder, Craeb, and Schlichtmann (2009), NBI can generate the Pareto front for non-convex Pareto frontier; the NC approach can generate Pareto-optimal solutions near the periphery or true Pareto front; both methods can overcome the problem related to relative scales of the objectives to produce an evenly distributed Pareto frontier. SPO can generate near peripheral Pareto frontier with computational efficiency. Including the weighted sum method, all the methods can be considered AOF methods, since they all need convert multiple objectives into one aggregate objective. The methods require knowledge of weights assigned to different objectives when choosing a final solution among Pareto optimal solutions. According to Wu and Flintsch (2009), in general, no single method is superior to other methods. The selection of a specific method to find Pareto optimal solutions only depends on the users' preferences, the available information, the expected solution requirements, and the software provided (Marler & Arora, 2004).

The methods for multi-objective optimization presented thus far are all solving the multi-objective problem by using single-objective optimization engine. Aforementioned approaches often work with classical search engine with a point-by-point rule and thus are required to be applied many times to find Pareto optimal solutions. Each time they will find only one Pareto optimal solution. However, there exist some approaches that can seek Pareto optimal solutions directly to solve a multi-objective problem. Genetic algorithm (GA) is a kind of evolutionary algorithm. GA was introduced by Holland (1975). However, the method was first implemented emerging in the year 1984 and has become popular in solving multi-objective problems since 1993 (KGAL, 2008). GA is a population-based, non-standard optimization algorithm. It is the most popular algorithm that can handle a multi-objective problem directly. The method has the ability to find multiple optimal solutions in a single run.

GA attempts to replicate natural evolution processes in which those with the fittest characteristics in an environment are more likely to reproduce and survive. In a population, each individual has a set of characteristics that determine suitableness for the environment. The "fittest" individuals are more likely to survive in the environment thus have greater chances of passing their "fittest" characteristics to the next generation. In the next generation, if the best features of each parent are inherited by their offspring, the new individual should have an improved probability to survive in the environment. The favorable characteristics are preserved and unfavorable ones are diminished, leading to a progressive evolution of the populations.

Each individual's characteristics can be thought of as a string of genes or DNA, with each gene representing a particular feature or characteristic. Reproduction process is the "crossover" two parents' DNA strings to generate a new offspring's DNA which has genes from both parents. “Mutation” process can also occur when a particular gene is not an exact copy from either parent.

GA contains the following basic processes or operations:

1. Encoding: define the string of genes including decision variables’ characteristics and define objectives.
2. Initialization: randomly generate an initial population of potential solutions.
3. Evaluation: evaluate the feasibility or “fitness” of each solution according to constraints or/and objectives.
4. Selection: select two solutions biased in favor of “fitness.”
5. Crossover: crossover the offspring solutions at random point or points on the string to generate two new solutions.
6. Mutation: mutate genes of the new solutions based on a mutation probability.
7. Evaluation: evaluate the new solutions according to objectives
8. Begin cycle again at Step 3.

Usually, the process is repeated for a large number of iterations with a significant number of populations to obtain Pareto optimal solutions. The main parameters used in GA are iterations size, population size, crossover rate, and mutation rate.

GA is different from the traditional optimization procedures in several aspects (Liu & Hammad, 1997). First, GAs use random initialization populations, information from previous iterations, and objectives to evaluate and improve a population of potential solutions rather than a single solution at a time. This means that GAs can be adapted relatively easily to Pareto optimal solutions. In contrast, the traditional optimization procedures usually work with only one solution at a time. Second, GAs work with a string of parameters instead of with the parameter themselves, allowing for a variety of parameters as decision variables and complicated objective functions as objectives. This means GAs can be effective regardless of the objectives' and decision variables' nature. In other words, GAs are independent form the structure of the constraints and objective functions (Liu & Hammad, 1997). For problems with complicated objective functions or decision variables, GA approach is an appropriate solver. Third, GAs improve the search process by allowing non-fit characteristics to exist and preserving the best-fit characteristics, instead of searching directly to the best fit string of characteristics. GA also improves the searching process by allowing variations into the population through mutation, meaning GAs can be efficient global searching tools.

How well the GA can evaluate fitness of the solutions becomes the primary questions when developing GA for multi-objective problems (Liu & Hammad, 1997). Fitness is the reason for several different GAs that have different techniques to address evaluation procedures. According to Marler and Arora (2004), such techniques can be categorized as (1) vector evaluated genetic algorithm (VEGA); (2) ranking; (3) Pareto-set filter; (4) tournament selection; (5) niche techniques; (6) fitness sharing; and (7) additional techniques. However, no single technique is, in general, superior to another technique. Rather, the selection depends on the user's preference and available information (Marler & Arora, 2004). Marler and Arora (2004) also pointed out that GAs, especially multi-objective GAs, can produce possible Pareto optimal solutions, for instance goal programming and programming complexity can be marked as the highest level compared to other solvers. Programing complexity refers to the process of programing an algorithm. Moreover, other criticisms of using GA compared to other optimization solvers exist

(Marler & Arora, 2004; Harik, Cantu-Paz, Goldberg, & Miller,1997):the quality of convergence to true Pareto optimal solutions of GA depends on the size of the population and the size of the iterations, and GA requires relatively high computational expense. Parameters' values vary case by case, and there is no generality that one can use to implement GAs. How to handle constraints in GA could be another factor that will affect the quality of the convergence to Pareto optimal solutions.

In conclusion, according to the literature, it is not apparent that one approach or algorithm is superior to another algorithm in terms of solving multi-objective problems. The selection of the solver rather depends on the decision maker's preference, the available information about the problems, software provided, and the expected analysis results. In this study, the author will propose a new simulated constraint boundary model to seek Pareto optimal solutions. The software used to develop solver programing is Statistical Analysis Software (SAS) version 9.2.

6.2. Simulated Constraint Boundary Model

Simulated constraint boundary model (SCBM) originates from the idea of single-objective problems with all other objectives converted as constraints. As mentioned before, the technique is common to solve multi-objective problems (Mbwana, 2000; Abaza, 2007). However, the method often assumes a known optimal level for the bounded or converted objective by providing a fixed boundary (Mbwana, 2000).With advanced computing software, such as SAS, it is not difficult to perform one run to simulate all potential boundaries for the objective with a very fine changing step. With each boundary, the researcher should get one potential Pareto solution. Thus, with simulating fine changed boundary values for the objective, the researchers can get Pareto optimal solutions for the multi-objective problem.

The technique does not require decision maker's a priori knowledge about the optimal level of the converted or bounded objective. In other words, the approach doesn't require decision maker to provide boundaries for the converted objective. Moreover, the approach is absolutely independent from the scales of the objectives. Researchers don't have to transform different units of objectives to dimensionless units or the monetary units. The objectives can be in different units and scales and will be handled directly. Finally, the technique can also provide a decision maker with evenly distributed Pareto optimal solutions if the steps of the boundary change are fine enough. The detailed model formulation is provided in the following sections and a simple case study will also present a comparison of the qualities of the Pareto frontiers generated by simulated constraint boundary method and genetic algorithms.

6.2.1. Model Formulation

This section will elaborate on the mathematical statement of the problem in this study by providing a detailed multi-objective optimization formulation. The most common pavement management multi-objective problem can be assumed to have two performance measures or objectives which are total agency costs and average network roughness. The two objectives are

Objective1: minimize total agency costs
Objective2: minimize pavement network average roughness

In this particular problem, both objectives are in linear forms, so the problem can be considered a linear multi-objective optimization problem. When decision makers consider additional objectives that can be in non-linear form, the problem will be considered a nonlinear, multi-objective optimization problem. For example, the decision maker may want to provide an evenly distributed smoothness highway network, the other objective, which can be a measure of standard deviation of the pavement network roughness index, will be added to the objectives. The objective will be in a nonlinear format of the decision variable. In such a case, the problem will be viewed as a non-linear, multi-objective optimization problem.

To complete the problem, all the objectives should be subject to constraints. The constraints depend on agency policy, and typically include (Bai & Labi, 2009):

(1) Constraints on performance measures. Often the decision maker desires that the levels of certain network performance will achieve specified targets. Sometimes the decision maker desires that the level of certain pavements' individual performances will achieve specified targets. Thus, such constraints should be included, too. For example, each single pavement segment may have a minimum acceptable roughness target according to the pavement segment classes.

(2) Constraints on budget. In practice, an overall budget ceiling for all pavement preservation activities typically exists. Additionally, an overall budget floor for all pavement preservation activities may exist. Thus, an overall budget constraint should be included.

(3) Constraints on policy. In practice, some policies depending on different agencies' preference exist. It will be helpful to include all policy constraints. For example, one treatment at a time for one pavement segment.

One example linear multi-objective 0/1 optimization problem according to the above formulation can be expressed mathematically as following:

$$\text{Min} \sum_{i=1}^{n} \sum_{j=1}^{m} c_{ij} * x_{ij} \quad (26)$$

$$\text{Min} \ (1/\sum_{i=1}^{n} d_i) * \sum_{i=1}^{n} (d_i * \sum_{j=1}^{m} IRI_{ij}^{1} * x_{ij}) \quad (27)$$

Subject to:

$$\sum_{j=1}^{m} IRI_{ij}^{1} * x_{ij} \leq IRI_{ui} \quad \forall i \in \{1, \dots, n\} \quad (28)$$

$$\sum_{i=1}^{n} \sum_{j=1}^{m} c_{ij} * x_{ij} \leq B \quad (29)$$

$$\sum_{j=1}^{m} x_{ij} = 1 \quad \forall i \in \{1, \dots, n\} \quad (30)$$

Where

c_{ij} = cost parameter of treatment j selected to pavement segement i

d_i = distance weight parameter to pavement segement i

IRI_{ij}^{1} =

roughness IRI value one year later for treatment j appliedd to pavement segement i

IRI_{ui} = unacceptable IRI level for each individual pavement segement i

B = budget level for the pavement network preservations

$$x_{ij} = \begin{cases} 1 & \text{if treatment j selected to pavement segement i} \\ 0 & \text{if treatment j not selected to pavement segemnt i} \end{cases}$$

n = total number of pavement segements of the network

m = total number of pavement management treatment options

In the above problem, total agency cost and average IRI roughness of the network are the two considered objectives. The total budget ceiling constraint, the individual pavement roughness unacceptable level constraints, and the one treatment at a time for one pavement constraint are formulated as constraints. To implement SCBM and find the Pareto optimal solutions, there is a need to convert a multi-objective problem into a single objective problem by converting an objective, Equation (27), to a bounded constraint, Equation (31), expressed as

$$(1/\sum_{i=1}^{n} d_i) * \sum_{i=1}^{n}(d_i * \sum_{j=1}^{m} IRI_{ij}^{1} * x_{ij}) \leq average_{IRI} \quad (31)$$

Where

$\text{average}_{\text{IRI}} = \text{predefined pavement network avereage IRI level}$

The simulated constraint boundary model is basically seeking the Pareto optimal solutions by fine changing $\text{average}_{\text{IRI}}$ value. For each fixed $\text{average}_{\text{IRI}}$ value, researchers will obtain one potential Pareto optimal solution. One will obtain even distributed potential Pareto optimal solutions by fine changing $\text{average}_{\text{IRI}}$ value. Then followed by applying Pareto concept, one can obtain a set of Pareto optimal solutions.

6.2.2. Case Study with Simulated Constraint Boundary Model

Consider the aforementioned hypothetical road network shown previously in Figure 14. The current IRI condition map is shown in Figure 15. From Figure 15, one can tell that the current IRI conditions of the road segments vary from 1.3 to 3 m/km with range of 2.7 m/km. The roughest segments are shown in red in Figure 15 which indicates as IRI over 2.5 m/km.

The related information of the road network is summarized in Table 8. Table 8 shows the segments cross over all six weather regions. The current average IRI condition is 2.08 m/km but the individual IRI values vary from 1.3 to 3 m/km.

Post-treatment IRI values for all potential treatment scenarios are calculated based on the post-treatment performance functions established in Chapter 4. The calculated results for different treatment scenarios are listed in Table 6 of Chapter 4. Where treat1 is "do nothing," treat2 is "minor preservation," treat3 is "seal coat," treat4 is "crack sealing," treat5 is "aggregate seal," treat6 is "chip seal," treat7 is "hot mix resurfacing," treat8 is "hot mill overlay," and treat9 is "reconstruction" option. All the values will be treated as input values as IRI_{ij}^{1} for multi-objective optimization problem.

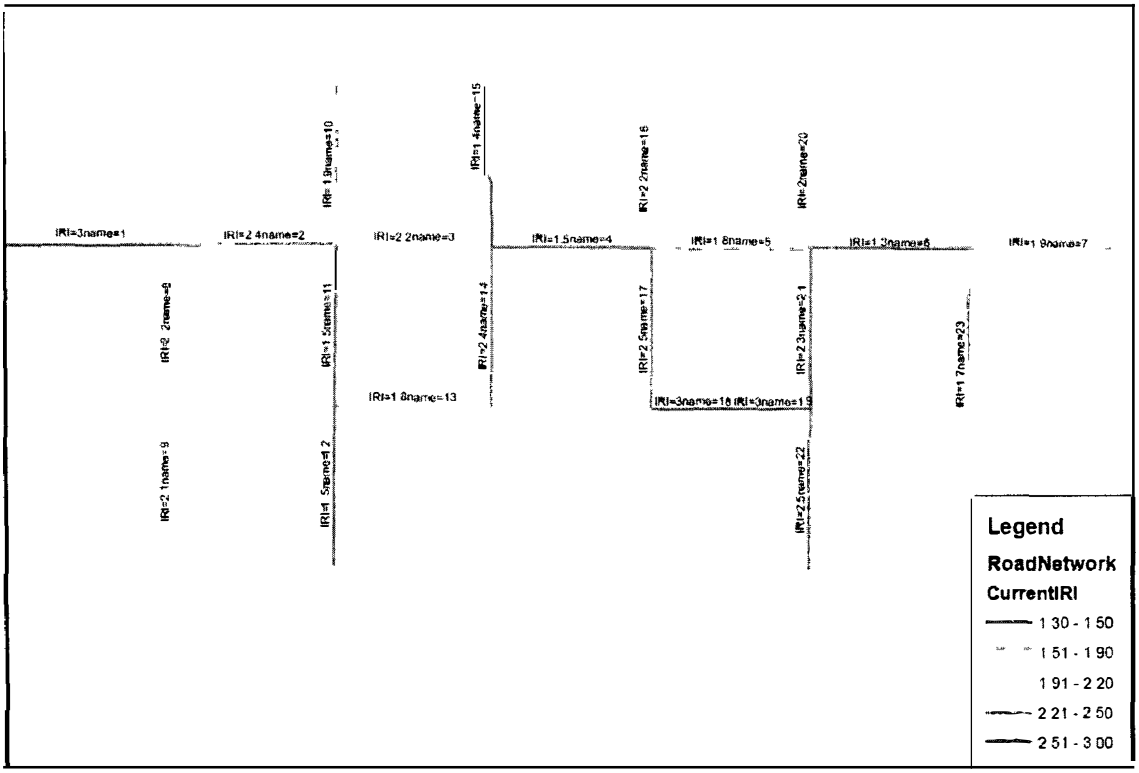

Figure 15. A Hypothetical Road Network IRI Map.

To test the SCBM and make the input parameters simple, the author assumes a set of hypothetical costs values for various treatments. The values are presented in Table 9.

The multi-objective problem formulated with Equation (26), (27), (28), (29), and (30) is solved in this study by using SCBM and GA. The purpose of using the GA is to show the verification and the reliability of the SCBM before applying the SCBM to solve the multi-objective pavement management problem. The reason to choose the GA is simply because the GA is the most popular direct method for solving multi-objective problems (Marler & Arora, 2004).

Table 8. The Road Network Profile.

Segment Name	Freeze-Thaw Level	Precipitation Level	Current IRI
1	Severe	Wet	3
2	Severe	Wet	2.4
3	Medium	Wet	2.2
4	Medium	Wet	1.5
5	Medium	Wet	1.8
6	No	Wet	1.3
7	No	Wet	1.9
8	Severe	Dry	2.2
9	Severe	Dry	2.1
10	Severe	Wet	1.9
11	Severe	Dry	1.5
12	Severe	Dry	1.5
13	Medium	Dry	1.8
14	Medium	Dry	2.4
15	Medium	Wet	1.4
16	Medium	Wet	2.2
17	Medium	Dry	2.5
18	Medium	Dry	3
19	Medium	Dry	3
20	No	Wet	2
21	No	Dry	2.3
22	No	Dry	2.5
23	No	Dry	1.7
24	No	Dry	1.7
Average IRI:	2.08	Standard Deviation:	0.49

To simplify the problem, the budget level is set at 30; each individual pavement segment's unacceptable IRI level is set same at 2.5 m/km; and the distance for each segment is same too.

Table 9. Hypothetical Agency Unit Costs for Various Treatments.

Treatments	Tr1*	Tr2*	Tr3*	Tr4*	Tr5*	Tr6*	Tr7*	Tr8*	Tr9*
Agency Costs	0	1	1.5	2	2.5	3	3.5	4	7

*Tr1= Do Nothing, Tr2= Minor Preservation, Tr3= Seal Coat, Tr4= Crack Sealing, Tr5= Aggregate Seal, Tr6= Chip Seal, Tr7= Hot Mix Resurfacing, Tr8= Hot Mill Overlay, and Tr9= Reconstruction.

For SCBM, the average IRI objective boundary will be simulated from 1.5 to 2.05 m/km with step of 0.01 m/km. Then 56 linear 0/1 integer single-objective optimization programming problems are solved using SAS/PR version 9.2 and PROC OPTMODEL for coding. All 56 problems have one unique feasible solution. Comparing the two objective values of 56 feasible solutions, the author created 37 Pareto solutions, or non-dominated solutions, those are evenly distributed. The Pareto solutions are shown in Figure 16. The software used to the problem is SAS/OR version 9.2 and the coding procedure is PROC OPTMODEL. The computer used to run the code has Intel Core 2 Duo E8400 @ 3.0 GHz and 4 GB RAM. It costs the computer about 5 minutes to get the Pareto solutions.

For the GA, many scenarios with different inputs parameters exist. The input values for the GA and the required time to obtain solutions are shown in Table 10. Eight total scenarios are chosen to compare the results, shown in Table 10. The most common constraints handling approach, the penalty approach, is used to treat constraints (Marler & Arora, 2004). In this study, the magnitudes of the constraints violations are calculated and the weighted constraints violations are directly added to the objectives.

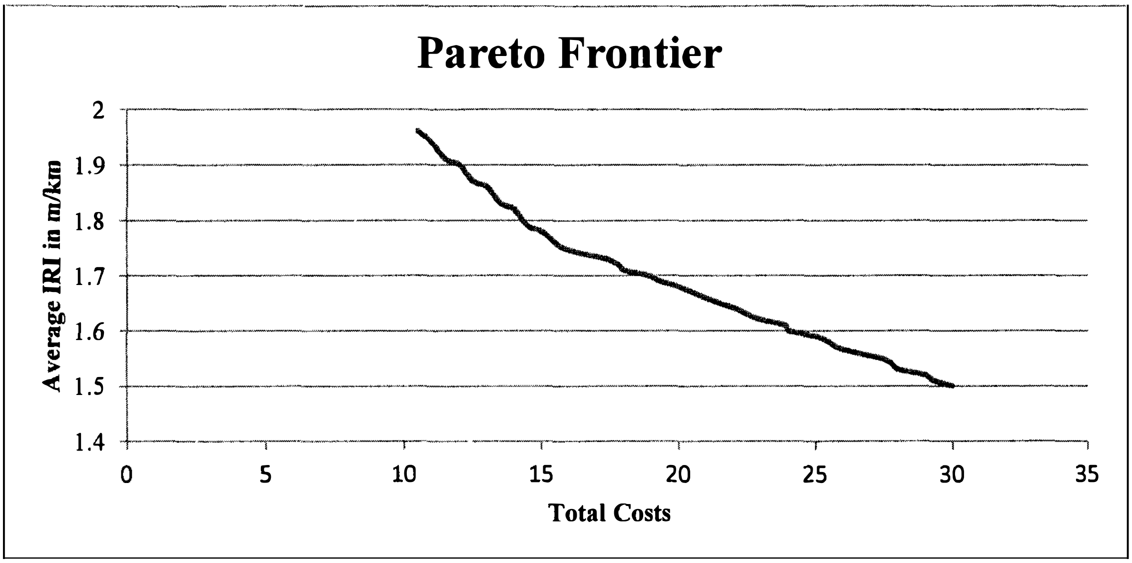

Figure 16. Pareto Solutions for the Case Study by Using SCVM.

The author created eight different sets of Pareto solutions in response to eight different scenarios with different input parameters.

Table 10. Key Parameters for Genetic Algorithm.

Scenario	Population Size	Constraint Violation Penalty Weight	Generation Size	Mutation Rate (percentage)	Running Time (minutes)
1	2000	10	1000	5	17
2	2000	50	1000	5	17
3	2000	100	1000	5	17
4	2000	200	1000	5	17
5	5000	10	1000	5	45
6	5000	50	1000	5	45
7	5000	100	1000	5	45
8	5000	200	1000	5	45

Figure 17 and Figure 18 each show four sets of Pareto solutions obtained by the GA using SAS/OR version 9.2 and coding with PROC GA. The same computer and software are used to solve the problem by GA. The coding procedure is PROC GA which is considered as experimental for SAS/ OR version 9 and 9.1. The SAS software used in this study is version 9.2.

To compare Pareto solutions in Figure 17, one can tell that Scenario 1 produces the nearest Pareto frontier to the true Pareto optimal solutions since both objectives are minimized objectives. However, Scenario 4 produces the near Pareto solutions covered the most potential solutions because its coverage ranges are the highest for both objectives.

To compare Pareto solutions in Figure 18, one can tell that in general, scenario 7 produces the nearest Pareto frontier to the true Pareto optimal and scenario 5 produces the most covered Pareto solutions.

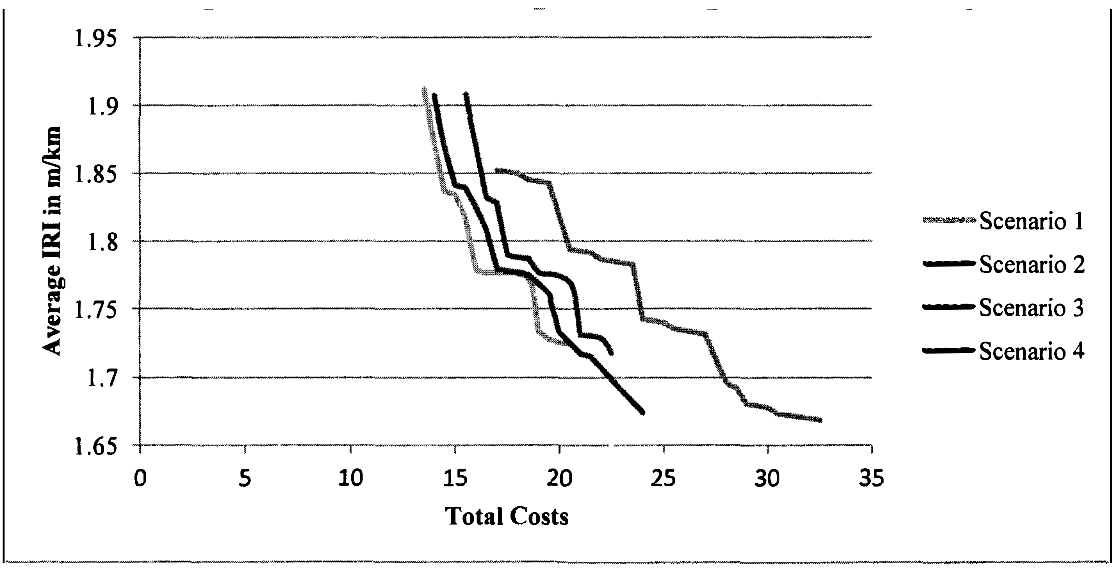

Figure 17. Pareto Solutions for the Case Study by Using GA with Population Size of 2,000.

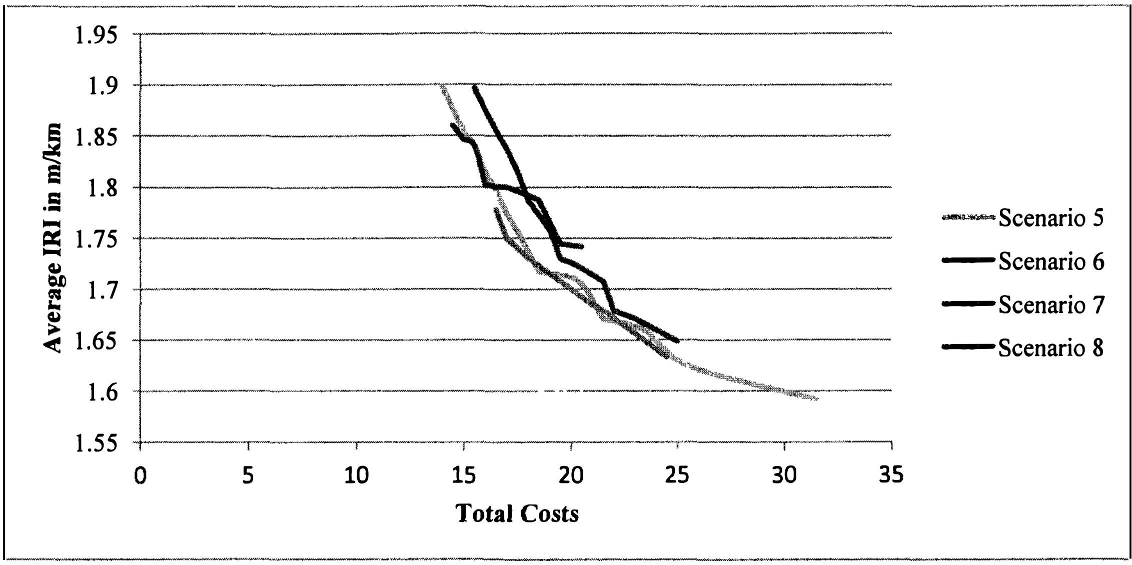

Figure 18. Pareto Solutions for the Case Study by Using GA with Population Size of 5,000.

To compare the best solutions obtained using the GA, Scenario 1, Scenario 4, Scenario 5, and Scenario 7, and the solution obtained by SCBM, all solutions are drawn in Figure 19.

From Figure 19, it is obviously that Pareto solutions obtained by SCBM are better than any set of Pareto solutions obtained by GA for several reasons. (1) SCBM solutions are the nearest solutions to true Pareto solutions since they are the most outer solutions or dominant solutions over the other solutions obtained by the GAs. (2) SCBM solutions cover the most potential solutions in terms of the objectives' ranges. The objective range values are the highest for both objectives compared with the solutions obtained by GAs.

Figure 19 illustrates the best solutions obtained by GAs that are closed to Pareto solutions obtained by SCBM. However, the solutions are not identical. The result shows (1) that SCBM is a feasible and reliable method to find Pareto solutions. (2) The GA is a feasible way to solve a multi-objective problem; however, the results' quality is not independent from input parameters, such as population size. Additionally, there is lack of guidance to choose the "right" input parameters, which makes applying the GA into real pavement management system problem is difficult.

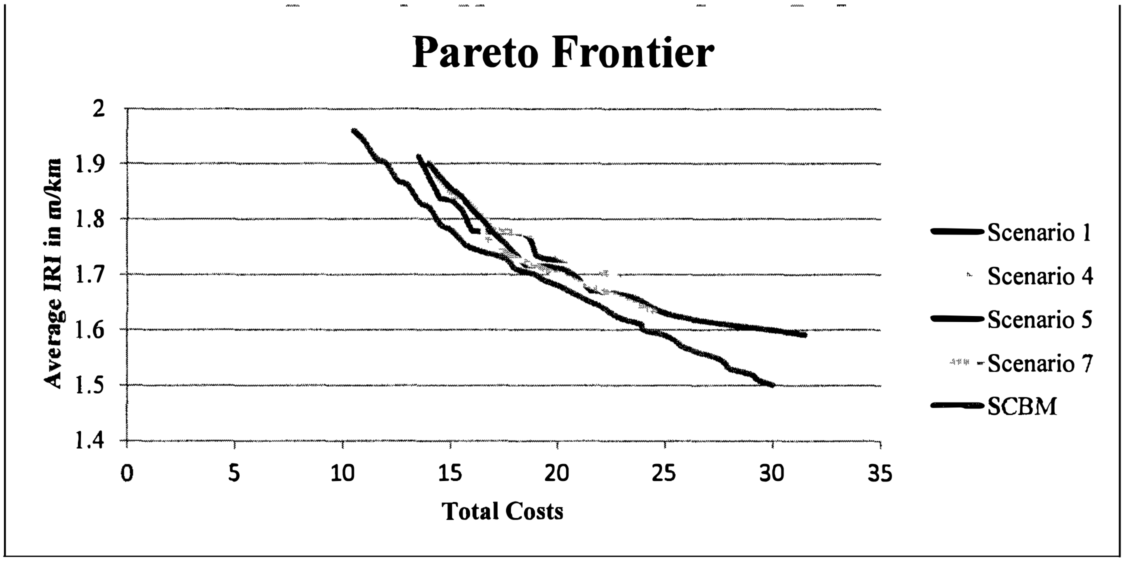

Figure 19. Pareto Solutions for the Case Study by using GA and SCBM.

The quality of GA-produced results is also dependent on how researchers address the constraints. In this case study, the author used another method to address the constraints directly as suggested by SAS (Hutchinson, 2008). The method treats the magnitude of constraints' violations directly as another objective. Based on the original and constraint violation objective functions, a Pareto-optimal set of solutions should evolve in the population and converge toward zero constraint violations by minimizing the constraint violation objective. Unfortunately, with this case study, regardless of the other input parameters the author changed, the set of zero constraint violation Pareto optimal solutions cannot be obtained. The reason why the method does not work is out of the scope of this study, but it could be a result of insufficient the software support. Even though SAS/OR 9.2 is not considered an experimental version of the software, it is still in the transitional phase, especially for solving multi-objective problems.

Moreover, comparing the needed time to obtain the Pareto solutions, one can see that the GA requires more computer resources than SCBM. Considering all aforementioned comparisons, the author concludes that SCBM can be used as a reliable and efficient tool to find Pareto optimal solutions for the multi-objective pavement optimization problem.

6.2.3. Model Application

SCBM can be used to find Pareto solutions for the aforementioned pavement management multi-objective problem. The post-optimization decision making or the methods used to choose the final solution are also illustrated by model application. The same hypothetical road network shown in Figure 15 will be used. To simplify the problem, each individual pavement segment's unacceptable IRI level is set same at 2.5 m/km; and the distance for each segment is same too. The detailed explanations of various treatment agency unit costs are summarized from the literature review. The solutions are obtained using SAS/OR version 9.2 and the coding procedures PROC OPTMODEL and SAS macro.

Annual agency costs related with routine maintenance or minor preservation activities shows a positive relationship with pavement roughness. In general, a pavement in poor condition requires more materials and hours of labor to perform routine maintenance, thus costing the agency more to maintain a pavement with a poor condition. Al-Mansour and Sinha (1994) developed well-known routine pavement cost model based on pavement roughness index, IRI. The equation for roadway maintenance cost is shown in Equation (32) and the equation for shoulder maintenance cost is shown in Equation (33).

$$\text{Log}(AMC_r) = 3.78 - 0.43*\text{PSI} \quad (32)$$

$$\text{Log}(AMC_s) = 3.53 - 0.46*\text{PSI} \quad (33)$$

Where

AMC_r = annual roadway maintenance expenditure ($/lane-mile)

AMC_s = annual shoulder maintenance expenditure ($/lane-mile)

PSI = PSI at time of maintenance

Al-Omari and Darter (1994) developed relationships between IRI and PSI ratings. The equation is

$$PSI=5*e^{(-0.26*IRI)} \quad (34)$$

Where

IRI is measured in millimeters per meter

In this study, Equation (35) will be used to calculate minor preservation activities costs and Equation (35) is developed by combining Equation (32), (33), and (34) shown as

$$AMC = 10^{3.78-2.15*e^{(-0.26*IRI)}} + 10^{3.53-2.3*e^{(-0.26*IRI)}} \quad (35)$$

Where

AMC = annual total road maintenance expenditure ($/lane-mile)

The calculated annual maintenance expenditure will be indexed to 2011 dollars by assuming 5% interest rate. The calculated maintenance costs are shown in Table 11.

Table 11. Maintenance Costs.

Segment Name	1	2	3	4	5	6	7	8
Maintenance Costs*	2157	1463	1268	721	930	602	1008	1268
Segment Name	9	10	11	12	13	14	15	16
Maintenance Costs*	1177	1008	721	721	930	1463	659	1268
Segment Name	17	18	19	20	21	22	23	24
Maintenance Costs*	1568	2157	2157	1090	1363	1568	856	856

*Maintenance Cost in 2011 Dollar per Lane-Mile.

All the other treatments' agency unit costs are summarized in Table 12 by the authors to be appropriately used for various types of treatments. Cost estimates for various types of treatments were summarized from studies performed by Peshkin and Hoener (2004) and Lamptey and Ahamd (2005). The suggested unit costs by those studies are indexed to 2011 dollars by assuming 5% interest rate.

Table 12. Agency Unit Costs for Various Treatments.

Treatments	Tr1*	Tr3*	Tr4*	Tr5*	Tr6*	Tr7*	Tr8*	Tr9*
Agency Costs**	0	4,130	8,127	7,788	9,256	107,751	165,902	1,710,339

*Tr1= Do Nothing, Tr3= Seal Coat, Tr4= Crack Sealing, Tr5= Aggregate Seal, Tr6= Chip Seal, Tr7= Hot Mix Resurfacing, Tr8= Hot Mill Overlay, and Tr9= Reconstruction.
** 2011- dollar per lane-mile.

The budget level is set at 200,000 dollars. For SCBM, the average IRI objective boundary will be simulated from 1.279 to 2.103 m/km with step of 0.001 m/km. Then 825 linear 0/1 integer single objective optimization programming problems are solved. It costs the computer about 30 minutes to get the solutions.

All 825 problems have one unique feasible solution. Comparing two objective-values of 825 feasible solutions, 764 feasible solutions are Pareto solutions, or non-dominated solutions, which are evenly distributed. The Pareto solutions are shown in Figure 20.

Figure 20 shows many non-dominated solutions with average IRI ranging from 1.279 to 2.103 m/km and total agency costs ranging from $53,621 to $199,767. All the corresponding solutions in Figure 20 are non-dominant, which indicates that no one solution is dominant over others in satisfying both average IRI and total agency costs. Figure 20 also shows that the Pareto frontier is convex curve which means that the average pavement network IRI level is decreasing if the total agency cost is increasing. It is expected since the two objectives are conflict with one another.

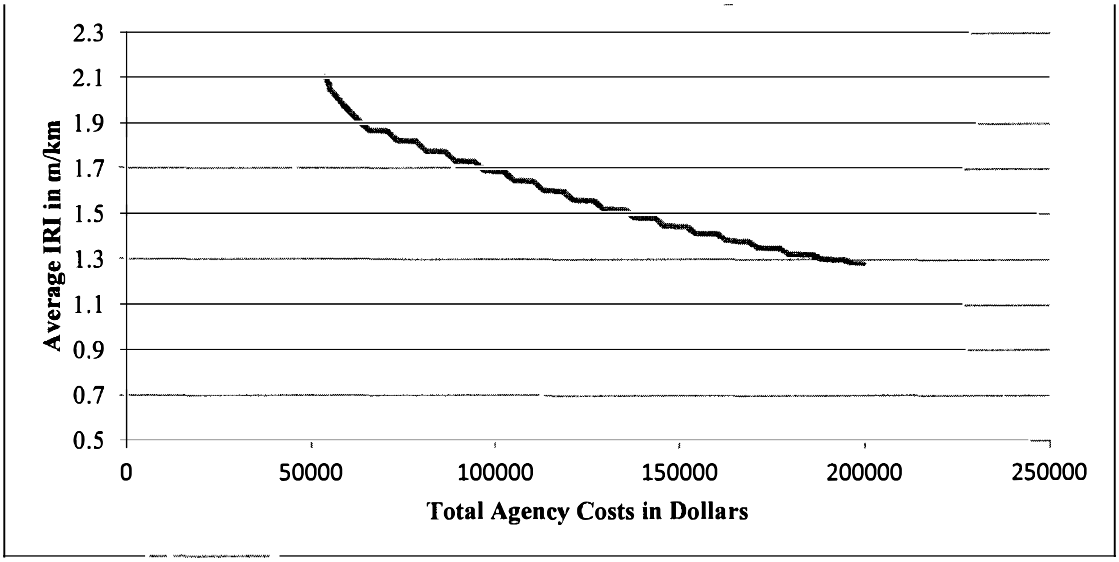

Figure 20. Pareto Solutions by using SCBM.

If the budget level is set at $53,621, which is less than the minimum budget level to maintain no constraint violation, the OPTMODEL will indicate there is no feasible solution. If the budget level is set at $53,622, which is the minimum required budget for no constraint violation, then one unique solution will be generated. The solution generates a total agency cost of $53,621 and average IRI of 2.1 m/km, demonstrating that the SCBM is robust enough to provide various types of solutions. However, with budget level of $200,000, the best average roughness of the road network can be achieved is 1.279 m/km with the highest agency cost of $199,767.

To achieve a complete Pareto frontier that covers all potential total budget levels and IRI levels, the approximate budget of $50,000,000 is set and the average IRI objective boundary will be simulated from 0.5 to 2.103 m/km with step of 0.001 m/km. Total 1,602 sets of solutions are obtained and 1,297 sets of the solutions are Pareto optimal solutions.

The Pareto frontier is shown in Figures 21 to 24. Figure 21 shows the whole Pareto frontier and Figure 22 to Figure 24 shows part of the frontier.

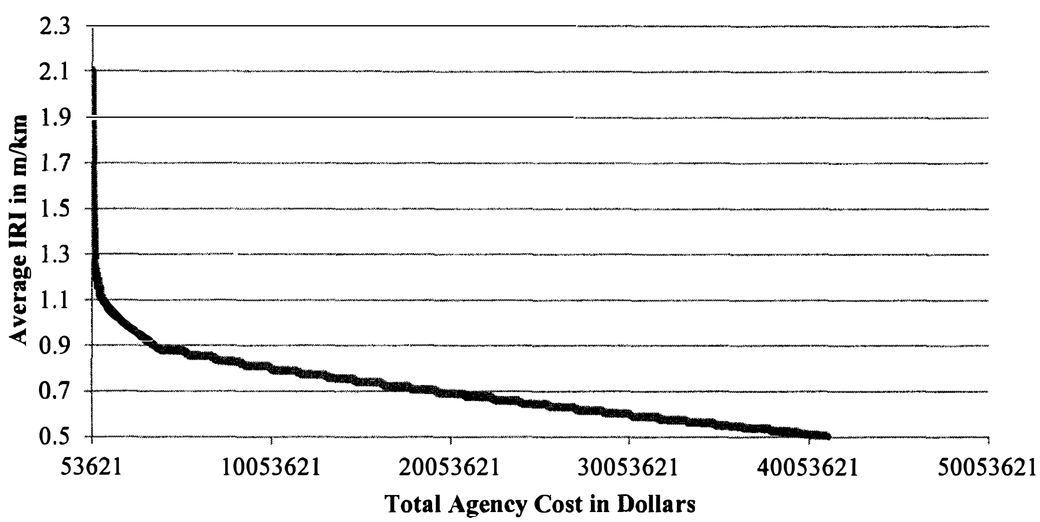

Figure 21. Pareto Frontier for the Pavement Management Problem.

Figure 21 illustrates the Pareto Frontier covering all potential total agency cost and average IRI conditions for the problem. The total agency cost ranges from $53,621 to $41,048,136, and the average IRI ranges from 0.502 m/km to 2.103 m/km.

Moreover, one can see that the slope of the change IRI value per dollar is quite steep and almost constant for IRI ranging from 2.1 to 1.2 m/km. The slope drops and keeping changing for IRI values ranging from 1.2 to 0.9 m/km and then the slope is almost constant for a relative flat level. Figures 22 to 24 provide a clear view for the three above phases.

Figure 22 is the part of Pareto frontier for IRI values ranging from 2.1 to 1.2 m/km. Figure 23 is the part of Pareto frontier for IRI values ranging from 1.2 to 0.9 m/km. Figure 24 is the part of Pareto frontier for IRI values ranging from 0.9 to 0.5 m/km.

The higher the slope of change IRI value per dollar means the better marginal value of the money. More specifically, for each dollar more spent on pavement preservation, the more significant IRI drop that agencies can expect from that dollar.

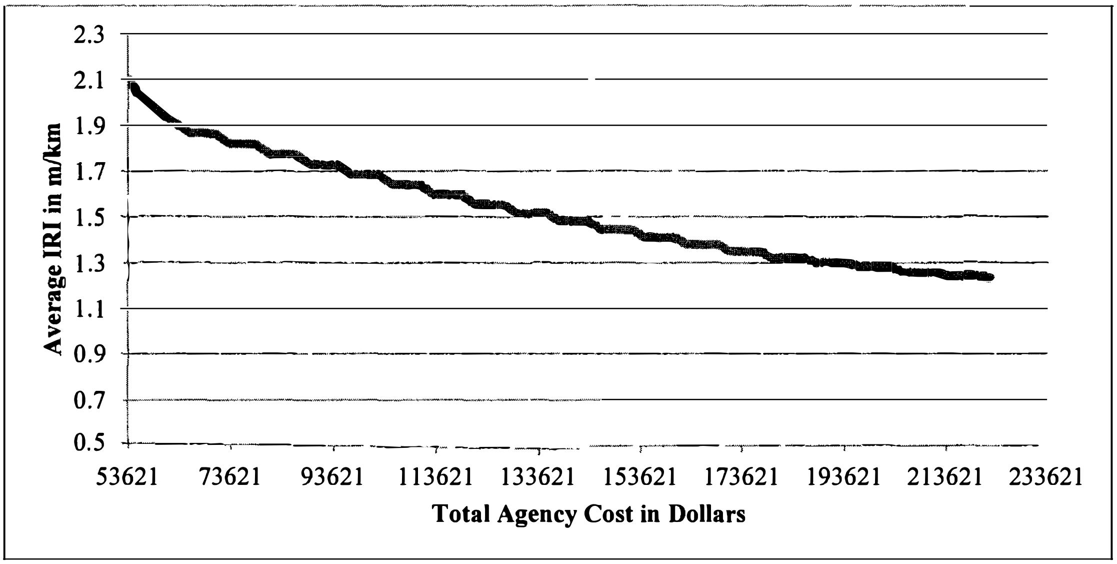

Figure 22. Part I of Pareto Frontier for the Pavement Management Problem.

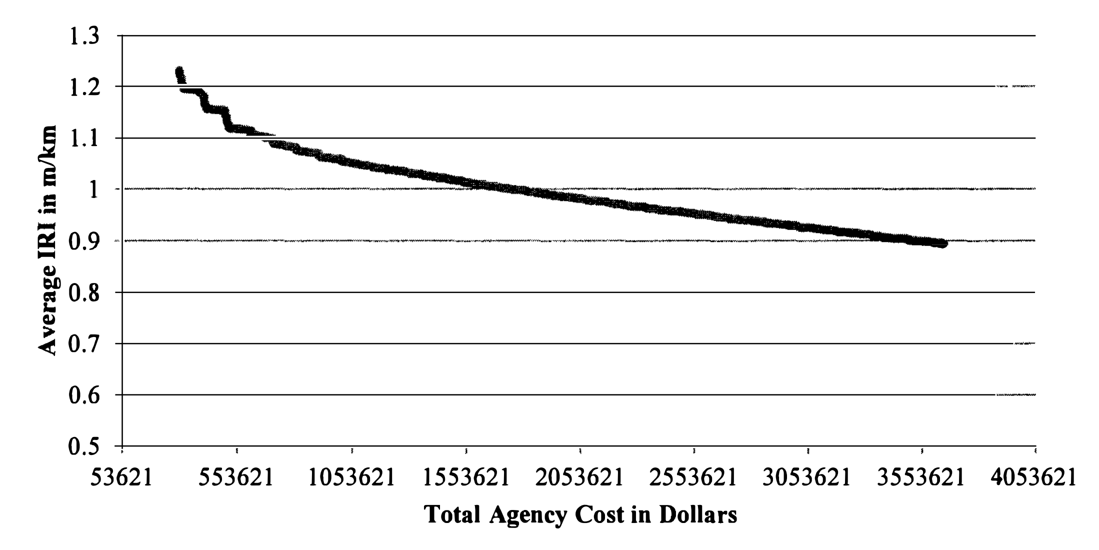

Figure 23. Part II of Pareto Frontier for the Pavement Management Problem.

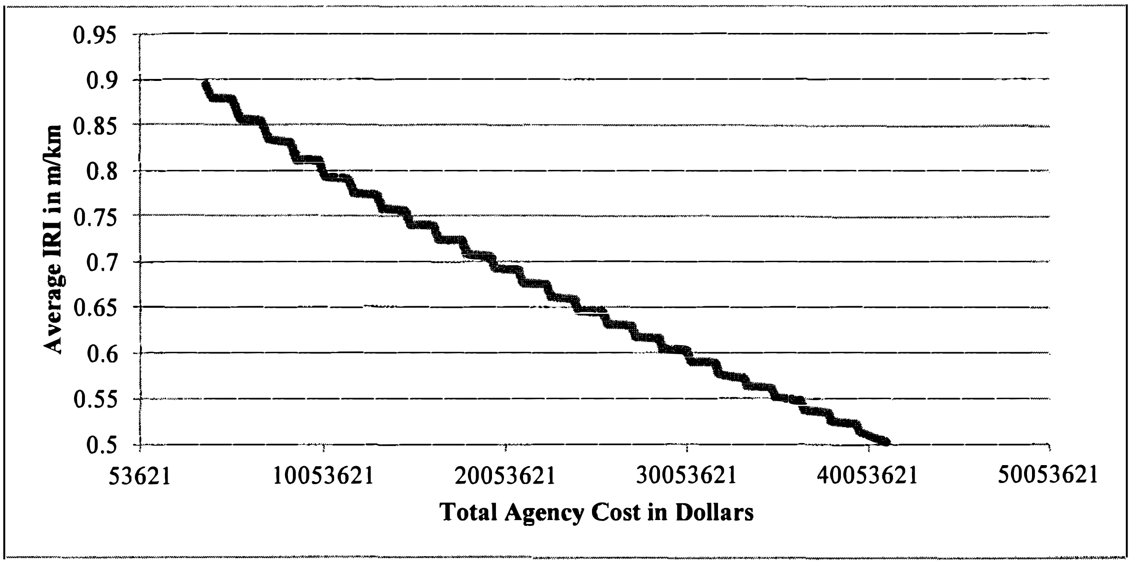

Figure 24. Part III of Pareto Frontier for the Pavement Management Problem.

6.3. Post-Optimization Decision Making

After depicting the complete Pareto optimal set obtained by SCBM, the next step and the most important procedure of decision making is selecting the final solution among many Pareto solutions (Zeleny, 1982). Marler and Arora (2004) pointed out that Pareto optimal sets provide an approach for a posteriori articulation of preferences as well as no articulation of preferences. In contrast with the a priori articulation of preferences method, the posteriori articulation of preferences method allows decision makers to view potential solutions and make final decisions based on their own preferences. The preferences can be assigning relative weights of the objectives or performing detailed individual project implementation comparison. The no articulation of preferences approach allows decision makers to have no personal preference and select the final solutions based on objective methods after obtaining Pareto solutions. This method can provide consistent selection from the Pareto optimal solution set. In this study, the no articulation of preference method is preferred.

Many methods exist and should be addressed. Marler and Arora (2004) summarized a few existing methods with no articulation of preferences for selecting a final solution among Pareto optimal solutions. The authors also pointed out that all the techniques have advantages and drawbacks; no one solution is absolutely superior to another. One method is called the technique for order preference by similarity to ideal solution (TOPSIS). The selected point is as close as possible to the utopia point, the positive ideal solution. The positive ideal solution can be understood as the solution that is composed of the best or most desirable solution for the objective functions. Another straight forward method is the summed objectives. It simply sums the objective functions with equal weights for each solution, then chooses the final solution according to the summation value. In this study TOPSIS is selected to demonstrate the final decision making procedure after obtained the Pareto solutions.

For the specific pavement management multi-objective problem studied in this dissertation, the theoretical utopia point can be (0, 0). The first value in the vector is the average IRI value and the second value is total agency cost value. It basically means that the ideal solution will achieve a zero roughness pavement condition with zero agency cost. However, it is idealistic. The more realistic utopia point should be the best IRI value and the best total agency cost that can be achieved without violate any constraints. In this sense, the utopia point is (0.5, \$5,362).

One direct way to apply TOPSIS is by calculating the distances between the utopia point and points on Pareto frontier. The closest point on Pareto frontier to the utopia point or the point corresponding to the shortest distance should be chosen. The calculation is basically the distance equation between two points. The function of the distance for this specific question is shown in Equation (36)

$$D_i = \sqrt{(f_{i1}(X) - f_1^*)^2 + (f_{i2}(X) - f_2^*)^2} \tag{36}$$

Where

D_i = distance between the i^{th} Preto solution and utopia point

$f_{i1}(X)$ = the first objective value corresponding to the i^{th} Preto solution

$f_{i2}(X)$ = the second objective value corresponding to the i^{th} Preto solution

f_1^* = the first objective ideal utopia point value

f_2^* = the second objective ideal utopia point value

From Equation (36), the scales of the objectives will affect the calculated distances. If the scales of the objectives are very close, then the distances are comparable. If the scales of the objectives are different, then the objective with the greater scale will dominate the other. In other words, the results will favor the greater scale objective. As previously mentioned, the total agency cost ranges from \$53,621 to \$ 41,048,136 and the average IRI values range from 0.502 m/km to 2.103 m/km. The calculated distance will be dominated by the total agency cost and almost independent from the average IRI values. To avoid such bias, the normalized Pareto optimal points will be used. In this study two ways to normalize Pareto optimal solutions will be introduced and implemented.

One way to normalize data is to normalize the data into a common scale (0-1). The method to do so can be expressed as Equation (37)

$$Z_i = \frac{f_i - f_{min}}{f_{max} - f_{min}} \tag{37}$$

The other way to normalize data is to calculate standard value. The method to do so can be expressed as Equation (38)

$$Z_i = \frac{f_i - \mu}{\sigma} \tag{38}$$

The two methods will be used to normalize the Pareto optimal points and utopia point. Then calculate the distances by using Equation (36). The final solution will be chosen according to the minimum distance. According to the calculated results, both methods choose the same solution as shown in Figure 25. Point A ($3,981,648, 0.88) is the selected.

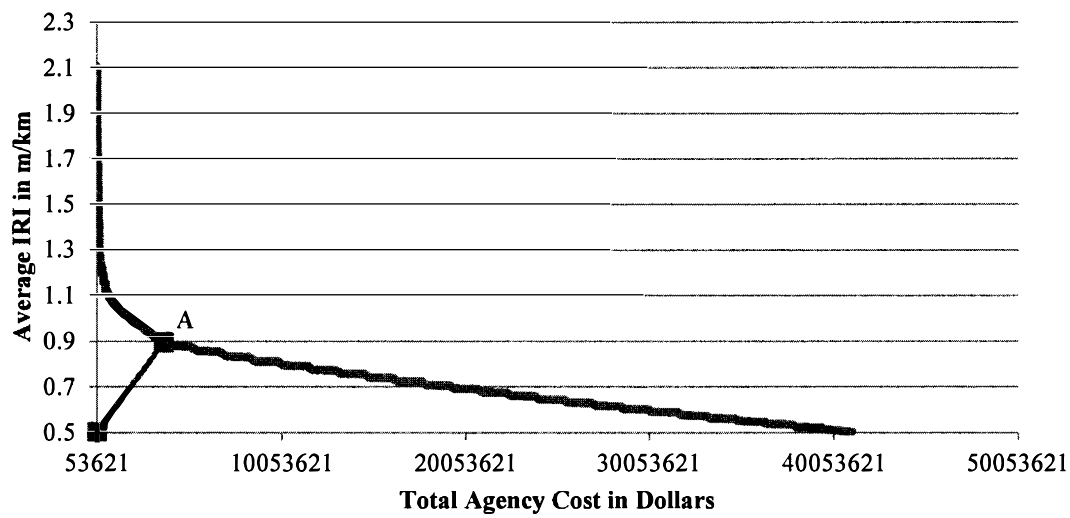

Figure 25. Final Solution from Pareto Frontier for the Pavement Management Problem.

The result shows that the two methods are both reliable for normalizing data sets because the two methods gave the same selection even the normalized data values for the same data are different. The result falls into the second part of the Pareto frontier shown in Figure 22 that matches the expectation since the second part of the Pareto frontier has the steepest slope. The corresponding preservation solutions and the results are shown in Table 13.

Table 13. Pavement Management Strategy and Results.

Segment Name	Selected Treatment	Current IRI	Post-treatment IRI
1	Hot Mill Overlay	3	0.917
2	Hot Mill Overlay	2.4	0.831
3	Hot Mill Overlay	2.2	0.935
4	Hot Mill Overlay	1.5	1.046
5	Hot Mill Overlay	1.8	1.046
6	Hot Mill Overlay	1.3	0.935
7	Hot Mill Overlay	1.9	0.9
8	Hot Mill Overlay	2.2	0.821
9	Hot Mill Overlay	2.1	0.821
10	Hot Mill Overlay	1.9	0.884
11	Hot Mill Overlay	1.5	0.87
12	Hot Mill Overlay	1.5	0.802
13	Hot Mill Overlay	1.8	0.802
14	Hot Mill Overlay	2.4	0.884
15	Hot Mill Overlay	1.4	0.884
16	Hot Mill Overlay	2.2	0.802
17	Hot Mill Overlay	2.5	0.832
18	Hot Mill Overlay	3	0.794
19	Hot Mill Overlay	3	0.786
20	Hot Mill Overlay	2	0.843
21	Hot Mill Overlay	2.3	0.856
22	Hot Mill Overlay	2.5	0.917
23	Hot Mill Overlay	1.7	0.843
24	Hot Mill Overlay	1.7	1.047
Average IRI*:	2.08	Standard Deviation*:	0.49
Average IRI**:	0.88	Standard Deviation**:	0.08

*Pre-treatment Values, & **Post-treatment Values.

Table 13 shows the selected treatment types as being the same for all pavement segments in order to achieve the average IRI condition of 0.88 m/km one year after treatments applied to the pavements. This average IRI condition rating is dropped from the pre-treatment average IRI condition of 2.08 m/km, because the available treatments are limited. Considering the total agency cost objective, the best treatment is hot mill overlay for all the segments.

Moreover, because all segments receive the same treatment, then the standard deviation among post-treatment IRI condition values is relative small, 0.08 m/km, which is not guaranteed since it is not an objective considered in the problem. The model will produce various treatment types for different segments and the standard deviation of the post-treatment IRI can be high. For example if the average post-treatment IRI of 1.88 m/km is chosen, the selected treatments types are range from "do nothing" to "chip seal" and the solution results standard deviation of 0.34.

6.4. Summary

The literature review was conducted with emphasis placed on multi-objective optimization and the methods used to solve such problems. Pareto optimal solutions and non-dominated solutions were reviewed. The genetic algorithm and proposed simulated constraint boundary methods were introduced.

The simulated constraint boundary method was used to seek Pareto optimal solutions for a hypothetical pavement network containing 24 pavement segments across six weather regions. The pavement management optimization problem is a multi-objective problem with the conflicting objectives of total agency cost and average IRI condition. The genetic algorithm was used to solve the problem as well in order to compare the two methods. Both methods were performed using SAS version 9.2 and the codes to solve the problem were developed by the author. The simulated constraint boundary method overwhelmingly showed the greatest results, where the genetic algorithm showed a potential to be a feasible method to solve multi-objective problem.

The simulated constraint boundary method was used to find Pareto optimal solutions for the pavement management multi-objective optimization problem. A complete set of Pareto optimal solutions was found. The post-optimization decision making method is introduced next.

Many methods can inform post-optimization decision making. The methods are categorized as posteriori articulation of preferences and no articulation of preferences. Technique for order preference by similarity to ideal solution was adopted and demonstrated to make post-optimization decisions with no articulation of preferences. The shortest distance criterion was used. Two data normalization methods were used to assist distance calculations. The normalization method was used to avoid objective scale difference bias. One method can generate the same scale unit-less data set and the other one will generate standardized data set. Both methods show the consistent result.

An interesting observation was found. When average IRI level is set at relative low the available treatments to obtain such level under the consideration of total agency cost are limited. The solution result tends to provide the same treatment to all the pavement segments. Thus, the standard deviation of post-treatment IRI can be low. When the average IRI is set at relatively high level, the generated pavement treatments tend to vary since there are more available treatments. The various treatment types may produce higher post-treatment IRI standard deviations. Higher post-treatment IRI standard deviation means the less consistent network IRI conditions. More specifically, the pavement network average IRI conditions being the same does not mean that the pavement network roughness conditions are consistent. One network can have a low IRI standard deviation while the other network can have a higher standard deviation. Highway users surely will prefer the network with lower IRI standard deviation, even though the two networks have the same average IRI condition. In this study, the author did not include the additional post-treatment IRI standard deviation objective, because adding this objective will turn the optimization problem from a linear 0/1 integer multi-objective problem into a non-linear 0/1 integer multi-objective problem. It requires absolutely different coding and solver to implement SCBM. However, adding additional objective such as post-treatment network IRI standard deviation is technically feasible and will generate a more complete set of Pareto optimal solutions and provide more useful information to decision makers.

CHAPTER 7. CONCLUSION

Pavement is continually deteriorating in response to various influential factors, establishing a need for pavement preservation. Pavement management system preservation decision making is affected by uncertain financial, economic, political and environmental crises that are outside the predictive ability of executives and managers. Furthermore, there is a lack of guidance of pavement management decision making modeling. Moreover, pavement preservation decision making is hindered by limited information provided to decision makers that limit operational and strategic flexibility.

Because of the need for pavement preservation, the lack of guidance for pavement management modeling, the lack of flexibility to operate pavement preservation, and the lack of complete information, it is crucial that agencies have systematic guidance and support available to aid decision making. Guidance and information are critical for making various decisions regarding treatments, such as when to apply a treatment and what treatment type is needed for each pavement segment.

The main objective of this empirical research is to develop systematic approaches to assist pavement preservation resource allocation decision makings. A multi-objective optimization model is intended to enable pavement management decision makers to make strategic network preservation selection and budget resource allocation decisions based on conflicting objectives. Decision makers often face conflicting objectives: maximizing treatment effectiveness, minimizing total cost, and minimizing the variation of network roughness levels or maximizing the consistency of the pavement network quality. The overall objectives and contributions of this research include:

(1) Develop regression models that predict short term treatment effectiveness in terms of IRI performance jumps using data from LTPP.

(2) Develop pre-treatment pavement performance and short-term post-treatment pavement performance models that can be used to predict the short-term post-treatment IRI conditions.

(3) Develop a true multi-objective pavement management decision model pertaining to treatment selection and budget resource allocation.

(4) Demonstrate the implementation of the models developed.

A polynomial function of the before-treatment IRI condition was assumed to fit treatment short-term performance IRI jump. The degree of three polynomial functions fit all different levels of treatment well in accounting for the different performance jump effectiveness behaviors.

The models reveal that there exists a maximum effectiveness of performance jumps for lower preservation level treatments. The maximum effectiveness serves as a "ceiling" beyond which further increase in treatment effectiveness cannot be obtained. The further the pre-treatment pavement condition is from the ceiling, the smaller the treatment effectiveness is. For the higher preservation level treatments, the ceiling is never reached within the life of a pavement. More specifically, within the life of a pavement, the worse the pre-treatment condition is, the better performance jumps will be for the higher preservation level treatments. Models also reveal that for the lower-effective level treatment, the height of ceiling is lower than the one for the higher-effective level treatment. For the lower effective level treatment, the ceiling point is obtained at better pre-treatment condition or younger pavement age. For higher effectiveness level treatments, the ceiling is obtained at a worse pre-treatment condition or older pavement age.

An exponential function of the pavement age was assumed to represent pavement IRI performance curves. The pre-treatment performance curves for six different weather regions and two different minor preservation strategies are developed. A total of 12 pre-treatment performance curves were generated. All 12 pre-treatment performance models show fitness. A method is introduced which is demonstrating how to calculate short-term post-treatment performance functions with treatment short-term effectiveness functions and pre-treatment performance function.

The models demonstrate several findings. The models reveal that pavement IRI deterioration rate is higher with a do-nothing strategy compared to a minor preservation strategy. However, the magnitudes of the difference for different analysis regions are different. Differences in severe weather condition regions tend to be larger than in less severe weather condition regions. Additionally, deterioration rates increase with a freeze-thaw cycle level increase. However, range of the differences among three freeze-thaw regions is smaller for a minor preservation strategy region than for a do nothing strategy region. It shows that minor preservation activities are even more important in severe freeze-thaw regions than in no freeze-thaw regions because such minor preservation activities will lower pavement deterioration rates more significantly in severe freeze-thaw regions than in no freeze-thaw regions. Models demonstrate also that the deterioration rate is higher in wet regions than in dry regions. In most cases, a wet region has higher deterioration rates than a dry region.

There is one counterintuitive result, in severe freeze-thaw regions using do-nothing strategy, wet regions have lower deterioration rates than dry regions. It is expected that the highest deterioration rate would be in severe freeze-thaw and wet regions with do-nothing strategy and lower deterioration rates would exist within severe freeze-thaw and dry regions using do-nothing strategies. The counterintuitive result may be caused by the limited number of observations, 9 and 12 respectively and the other influential factors which were not researched in this study such as traffic factor.

Another finding from the models is that when a treatment is applied to a pavement too early or too late in the pavement's life, it will not reduce deterioration rate. Additionally, the best deterioration rate reduction point for lower level preservation treatment is earlier than it is for the higher level preservation treatment. In other words, it can be obtained at younger age of a pavement. Finally, the models show that the curve of effectiveness is flat, which means the "best" treatment application time is not very sensitive. It is rather a best treatment application time range than a best application time point.

The simulated constraint boundary method was used as the tool to find Pareto optimal solutions for the pavement multi-objective optimization problem. The two objectives are total agency costs and average network IRI value. The genetic algorithm was also tested to solve the problem and compared with SCBM. The SCBM overwhelmingly shows the greatest results, where the genetic algorithm showed a potential to be the feasible method to solve multi-objective problem. The simulated constraint boundary method found a complete set of Pareto optimal solutions.

TOPSIS was adopted and demonstrated to make a post-optimization decision with no articulation of preferences using the shortest distance criterion. Two data normalization methods were used to calculate distance. The normalization method was used to avoid objective scale difference bias. One method can generate the same scale unit-less data set and the other one will generate standardized data set. Both methods show the consistent result. The selected solution obtained by the two normalized TOPSIS shows that point A ($3,981,648, 0.88) is selected. Which means the strategy will result total agency cost of $3,981,648 and average IRI of 0.88 m/km.

This research will provide pavement management officials with a series of models and requisite knowledge from detailed analyses to undertake complex decision making exercises for often conflicting and multi-objective situations with confidence, considering global budget allocations. This research extends the theory behind diversification to available decision making information by introducing multi-objective pavement management optimization formulation and post-optimization decision making with no articulation of preference. This research benefits not only pavement managers or decision makers, but also academics, consultants and government officials by extending the use of multi-objective optimization and post-optimization decision making with no articulation of preferences. Another contribution is distributing knowledge pertaining to pavement preservation treatment short-term effectiveness and a new approach for obtaining short-term, post-treatment performance functions based on pre-treatment performance functions and treatment short-term effectiveness functions.

Limitations of this research open up the possibility of future research in the following areas. Future research should include analysis of the long-term post-treatment pavement performance functions when enough supportive data is available. This would extend the decision making analysis to be long term and to be multi-year strategy analysis. The multi-year pavement preservation decision strategy analysis would provide agencies long-term strategies and allow agencies to perform long-term pavement preservation decision analysis. Moreover, the effect of traffic classes on pavement performance and more other different treatments' short-term effectiveness should be investigated. The extended work will benefit agencies with more useful information about pavement performance and provide more potential treatments information.

The genetic algorithm method should be tested with various constraint-handling techniques. This technique would extend the potential possibility to solve complicated objective function problems and allow more objectives considered. The genetic algorithm shows more handling power than SCBM when handling more than two objectives or when the objective functions are very complicated. The genetic algorithm is independent from the form of the objective functions. For example the objective functions can be mixed linear and non-linear functions, and it will not affect the ability to find solutions with the genetic algorithm. Additionally, future research in this area could include developing a non-linear 0/1 simulated constraint boundary method code. This will include the objective of standard deviation of post-treatment IRI, which is very important information especially for a corridor pavement analysis.

Expanding the models to include user costs as additional objective would enhance the optimization results. Furthermore, adding additional constraints into the models such as upper bounds for labors, upper bounds for percentage of the network in poor condition, upper bounds for percentage of the network assigned with certain levels of treatment could further strengthen the optimization results.

Lastly, the Markov Chain method should be explored as a potential means to solve the pavement bi-objective preservation decision making problem. Markov Chain method requires calculation of transition matrices for different preservation strategies and articulates costs with strategies. The benefits of adopting the Markov Chain method are 1) Markov Chain's stochastic procedure can best represent true pavement stochastic deterioration process; 2) performing multi-year preservation strategy analysis or sequenced events analysis is easily handled using the Markov Chain model; 3) the Markov Chain method is a simplistic modeling approach that can model complex systems such as pavement management systems.

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APPENDIX A. SUMMARY TABLES

Table 14. Summary of Effectiveness of Various Pavement Related Treatments.

Treatment	Agency/Data Resource	Short-term Effectiveness	Methodology	Reference
Overlay	AASHTO road test conducted between October 1958 and November 1960 near Ottawa, Illinois	10.5 mm for rut 59.5 for slope variance 2.3 PSI reduction (forecast value for one section)	Effectiveness model	Chu, & Durango-cohen (2008)
	Indiana DOT	PJ 0-1.7 PSI	Effectiveness model	Labi, & Sinha (2003a)
	LTPP	Mean IRI change: -0.2177 Mean rutting change: -3.1	statistics	Hall, & Correa (2002)
Chip Seal	Indiana DOT	PJ: 0.08-0.63(0.23) PSI DRR: 2.52-4.04 (3.38) PSI	Short term effectiveness models	Labi, Sinha (2004)
	LTPP	Mean IRI change: 0.064(negative effect) Mean rutting change: -1.0 (insignificant)	statistics	Zaniewski, & Mamlouk (1996)
Microsufacing	Indiana DOT	Average 0.442 IRI 4 mm RUT 6.2 unit PCR PJ	Short term and long term effectiveness models	Labi, & Lemptey (2007)
	Indiana DOT	PJ 0.4-1.05 (0.76) PSI	statistics	Labi, & Sinha (2003a)

Table 14. (Continued)

Crack Treatment	Indiana DOT	DRR -0.18-0.7 (0.177) PSI traditional material DRR 0.01-1.39 (0.318)PSI Crumb rubber	Effectiveness models	Labi, & Sinha (2003a)
	LTPP	Mean IRI change: 0.036(negative effect) Mean rutting change: -0.3(insignificant)	statistics	Hall, & Correa (2002)
HMA overlay, functional	Indiana DOT	PJ: 0.8 when initial iri=2m/km	Effectiveness model	Irfan, & Khurshid (2009)
HMA overlay, structural	Indiana DOT	PJ: 1.1 when initial iri=2m/km	Effectiveness model	Irfan, & Khurshid (2009)
Resurfacing	Indiana DOT	PJ: 1 when initial iri=2m/km	Effectiveness model	Irfan, & Khurshid (2009)
Mill full-depth and asphaltic concrete overlay	Indiana DOT	PJ: 1.1 when initial iri=2m/km	Effectiveness model	Irfan, & Khurshid (2009)

Note: Domestic region includes the United States and Canada.

Table 15. Summary of Performance Prediction Models.

Model	Description	Strengths	Weaknesses	Group
Mechanistic	Performance as a function of a number of parameters which is mechanically determined	Predict future changes in mechanistic response of the pavement such as strain, stress, or deflection as a function of some known factors that would cause changes in those responses	Require detailed structural information Each currently used measure of condition is affected by several different factors, some of which cannot be described in purely mechanistic terms	Deterministic

Table 15. (Continued)

Empirical Regression Analysis	Statistical method using historical data to develop relationship between performance indicator and explanatory variables	Better practical value because of the infinite complexity of the underlying phenomena	Limited to the conditions of segments data used to developing the model Unknown factors may affect the precision of the model	deterministic
Empirical Fuzzy sets	Instead of assuming crisp data it use fuzzy set	It handle uncertainties and randomness well	Modeling fuzziness is difficult because of complex interactions among factors The model quality highly depend on the quality of the data	deterministic
Empirical Artificial Neural Network	ANN mimic the actions of human brain to sort out patterns and learn from trial and error, discerning and extracting the relationship that underlie the data	Capability of learning from past examples Produce correct responses when presented with partially incorrect or incomplete data	Demanding a large amount of good quality data and depends on it Difficult to explain the relationship to link the data Difficult to understand how input data influence the output data through learning	deterministic
Mechanistic-Empirical Models	Using mechanistic analysis to predict the pavement response and empirical analysis to relate the responses to observed condition	Reduce the amount of data needed Results based on mechanics are not limited by the range over which the tests were conducted	Still need a relative huge amount of data	deterministic

Table 15. (Continued)

Probabilistic Markov models	Use transition matrices describe the probability that a pavement in a known condition state at a known time will change to some other condition state in the next time period	Stochastic process models represents actual pavement performance process	Demanding large amount of transition matrixes Fixed time interval	probabilistic
Probabilistic survivor curves	A curve representing the number of the sections studied that remain in service at selected age	Can be used to predict the probability that a section will survival at given time in the future	Depending on availability of data	probabilistic
Probabilistic semi-Markov	Markov process with random time intervals	Reducing the size of the problem by using random time intervals	Demanding adequate data to develop the probability distributions of time intervals between consecutive stages	probabilistic
Probabilistic Bayesian	Combining observed data with expert experience by using Bayesian statistical approaches	Using field data or expert opinion to adjust model	Requiring expert opinion and previous experiences.	probabilistic

Table 16. Summary of Decision Support Analysis Tools.

Model	Description	Strengths	Weaknesses	Group
Damage measures, performance indicators, weighted performance indicators, composite criteria	Performance indicators are used for trigger values to initiate treatment for need section Damage measures or performance indicators of usage weighted performance indicators or composite criteria are used for ranking prioritize need sections	Easy to perform and understand Allow condition measure to identify need sections	Difficult to select individual measure to determine the need section Fail to account for the change in benefit for the funds expended Difficult to find a good usage weighting factors	Ranking
First cost	Sections can be repaired by least treatment cost are selected first	Consider unit costs comparison to allocate funding Easy to understand	Need has identified need sections and treatment Ignore the benefit, impact on future condition and the cost of users	Ranking
Life-cycle cost	Least life-cycle cost can be used to identify best treatment and ranking the need sections	The one with least life-cycle cost is the best treatment for the specific section The one with least life-cycle cost section is has the highest rank among all the need sections Consider all types of cost including user costs over the life of the pavement	Salvage value are more difficult to estimate Initial construction costs, future maintenance, and rehabilitation costs are usually estimated User costs are complicated costs	Ranking

Table 16. (Continued)

Benefit cost ratio	Section with the highest b/c ratio in monetary terms has the highest rank	Consider both benefit and cost over the analysis period Both benefits and cost are in the same monetary form b/c ratio value itself has meaningful meaning	It is hard to have monetary benefits values with all types of treatments It is ignore the non-monetary benefits like extended life	Ranking
Cost-Effectiveness	Identify feasible treatment and timing combinations, identify the best cost-effectiveness C/E ratio and rank sections with cost-effectiveness ratio values	Use a surrogate in place of monetary benefits---area under a performance curve Take into account of extended life benefit	Cost-effectiveness value itself has no meaningful meaning	Ranking
Marginal Cost-Effectiveness analysis	Instead of rank sections with C/E values, calculate marginal cost-effectiveness for all sections MCE=(E1-E0)/(C1-C0) and check if MCE is negative or not to eliminate the section ranks	Compare not only ratio but also the incremental values Can be made in any year of the analysis Near optimum results than pure ranking Ability to consider timing of the treatment	More complex than single year optimization Has higher projection uncertainty	Multi-year prioritization
Linear Programming	Solving simultaneous equations with constraints and objective functions expressed as a linear equations	Simultaneous solve many constraints and compare many solution combinations to achieve maximum benefit or minimum cost	Expensive analysis need to insure the true optimum solution	Optimization

Table 16. (Continued)

Non linear Programming	Similar with LP however the constraints and objective function can be non-linear	Simultaneously solves equations to get optimum solution	Need extensive analysis to ensure true optimum solution and it is more difficult to insure	Optimization
Integer Programming	Similar with LP however the decision variables only allows value of 0 or 1	Simultaneously solves equations to get optimum solution More realistic approach with yes-no logic decisions	Require powerful computer resources to process huge information	Optimization
Dynamic Programming	Decisions made in sequence and earlier decisions affect later decisions Find solution by starting at the final condition and working backwards to meet the objective	More realistic approach with considering decisions in a interrelated sequence	Demands powerful computer resources Demands practitioners with a strong background in mathematics statistics and operation research Difficult to explain the results	Optimization
Heuristic method	Trial-error learning process to get the near optimal solution	Promote self-learning and discover to find the solution An alternative to true optimization methods when deal with big size problems	Find near optimal solution not guarantee optimal solution	Optimization
Goal Programming	Considering multiple goals or objective functions	Deal with multiple goals	Require powerful computer resources and good background in GP	Optimization

APPENDIX B. LTPP DATA ADJUSTMENT AND RESULT ANALYSIS

A set of IRI survey values over time is shown in Figure 26.

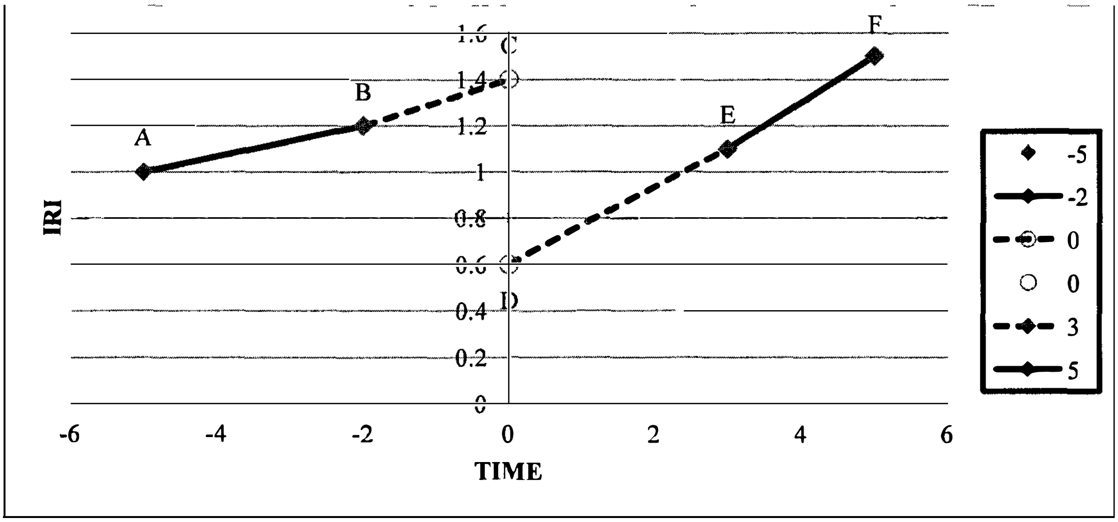

Figure 26. IRI Survey Positions.

If time is defined as zero for a treatment application time, the ideal immediately before and immediately after IRI surveys will happen when Time=0 for most of the treatments. They are shown at position C and D in Figure 26. These relationships will give ideas of what the performance jumps are. There are 11 types of treatments in the LTPP data set used for this dissertation shown in Table 17.

For the purpose of treatment effectiveness analysis, researchers prefer to have IRI survey values of both C-position and D-position shown in Figure 26 for each treatment applied. Unfortunately, the LTPP dataset for this dissertation has no such data available for researchers. Only 111 segments either have C-position or D-position IRI values as shown in Figure 26 for all treatment types combined. As shown in Figure 26, one can determine that if researchers use the B-position IRI and E-position IRI values as right before and after treatment values, treatment effectiveness tends to be underestimated. If the gap

Table 17. Maintenance and Rehabilitation Treatments in LTPP.

Minor Preservation-effect Activities			
Skin Patching	Patching	Full Depth Patching	Drainage
Shoulder Treatment			
Moderate Preservation-effect Activities			
Seal Coat	Crack Sealing	Aggregate Sealing	Chip Sealing
Major Preservation-effect Activities			
Fracture	Hot Mix Resurfacing	Hot Mill Overlay	

period is long enough, counterintuitive treatment effectiveness results will be produced. Thus immediately before and immediately after treatment IRI values must be forecasted before further analysis. Linear interpolation forecasting method will be used to forecast C-position and/or D-position IRI values shown in Figure 26. Additionally, significance test of treatment effectiveness will be checked for both without adjustment and with linear interpolation adjustment.

Another concern is that IRI survey values span 20 years for many test sections, but the survey methods may have changed over time. For example, in one specific test section, the survey profiler software version, or device, or profile manufacture may change year to year. It is important to understand if the survey tools have systematic errors, in order to compare IRI values, one has to adjust IRI values over time with different measurement tools.

The last concern before using the data to perform an analysis is being sure not to analyze the effectiveness of combined treatments. In order to avoid this, sections with only one treatment at a time will be analyzed by eliminating the sections with two or more treatments records at a time. The significance t-test results are shown in Table 18.

Table 18. Treatment Effectiveness Significant Test Results.

Treatment	Do Nothing	Forecast	Adjust	Adjust-Forecast	One-Adjust	One-Adjust-Forecast
Skin Patching	Not Significant	Not Significant	Not Significant	Not Significant	Not Significant	Not Significant
Patching	Not Significant	Not Significant	Not Significant	Not Significant	Not Significant	Not Significant
Full Depth Patching	Not Significant	Not Significant	Not Significant	Not Significant	Not Significant	Not Significant
Drainage	Significant	.	Significant	Significant	Significant	Significant
Shoulder Treatment	Significant	Significant	Significant	Significant	Significant	Not Significant
Crack Sealing	Significant	Significant	Significant	Significant	Significant	Significant
Seal Coat	Not Significant	Significant	Not Significant	Not Significant	Not Significant	Not Significant
Chip Sealing	Significant	Significant	Significant	Significant	Significant	Significant
Aggregate Seal	Significant	Significant	Significant	Significant	Significant	Significant
Hot Mix Resurfacing	Significant	Significant	Significant	Significant	Significant	Significant
Hot Mill Overlay	Significant	Significant	Significant	Significant	Significant	Significant

The "do nothing" method is defined as using direct available records which are measured by using the same IRI survey tools. The forecast method is based on the do nothing method dataset and applying a linear interpolation forecasting method to forecast right before and right after treatment IRI values. The adjusted method is based on the original dataset and applying a systematic tool difference correction. Adjust-forecast method is based on the adjusted method dataset and applying a linear interpolation forecasting method. The one-adjust method accounts for one treatment at a time and IRI measurement tool adjustment concerns. Finally, the one-adjust-forecast accounts for one treatment at a time, tool adjustment, and linear interpolation concerns.

From the results it can be determined that forecasting methods improve data quality for a relatively lower level of treatments, but not as much for rehabilitation. Improving data quality is defined as less counterintuitive results. Both tool adjustment and one treatment a time considerations are necessary since these both will improve data quality.

The reasons for different forecasting improvement results for minor preservation-effect activities, moderate preservation-effect activities, and major preservation-effect activities:

1. Survey frequency tends to be less for segments with better surface condition. In other words, before and after a major rehabilitation treatment on a good pavement, people tend to perform fewer IRI surveys than before and after a major rehabilitation treatment on a pavement in poor condition. Forecasting adjustment method tends to eliminate the segment with better surface condition data because this method requires at least having two before and two after treatment survey IRI values to perform forecasting calculation. Thus, researchers will lose more data which have better performance and better treatment effectiveness when they choose forecasting method. The data lost tends to show better performance and effectiveness, so the forecasting method does not necessarily lead to better results than the non-forecasting method. Table 19 is a sample of data from the LTPP original data set. Table 19 shows that good surface condition road segments have less IRI survey frequency. The sections shown in Table 18 will all be eliminated if the forecasting method is used since the sections only contain one before and one

after treatment values. In that case, the data which contains the better pavement IRI conditions is eliminated.

2. Preventive maintenance treatment is more time sensitive than major rehabilitations in terms of IRI performance measure. In other words, the IRI values change faster before or after preventive maintenance than before or after major rehabilitation, making survey time before or after preventive treatment more critical than major rehabilitation. If the survey time difference is not considered when calculating performance jump for preventive maintenance treatments, the effectiveness will be underestimated more significantly than for major rehabilitation. In other words, a treatment which is more time sensitive in terms of IRI value changes will benefit more by considering the time difference between the time of the IRI survey and the time of treatment. Treatment with less time sensitivity will benefit less.

Table 19. Sample Data with Relationship between Less Frequency IRI and Higher IRI.

Id	State code	Shrp-id	Before-iri	After-iri	Change-iri	Before-time lag	After-time lag
1	4	0603	2.675	0.8866	1.7884	4	13
2	4	0660	3.4094	1.0124	2.397	4	13
3	4	0661	3.3856	0.7148	2.6708	4	13
4	4	0662	2.3312	0.77	1.5612	4	13
5	4	0663	3.3636	1.4428	1.9208	4	13
6	6	0659	4.5412	0.7034	3.8378	4	8

3. For some data which has counterintuitive original IRI survey values, it will lead to less accurate forecasted IRI values using the forecast method. Table 20 shows

another sample of data from the LTPP original data sets to illustrate this type of situation.

In Table 20, a construction number is a sequential assigned number to represent any treatment applied to the pavement section. So one change of construction number means one treatment applied to the pavement section. The IRI survey and treatment application information is also shown in Table 20 for state-code=1 shrp-id=B310 section. The record of change in construction number should be matched with record about treatment application to the same pavement section.

Table 20. Sample Data with Counter Intuitive IRI Survey Results.

State Code	Shrp-ID	Construction Number	IRI Survey Time*	IRI (m/km)	Treatment	Treatment Time*
1	B310	1	1990-06	0.833		
1	B310	2	1991-07	1.798	Hot mix resurfacing	1990-11
1	B310	2	1992-08	1.669		
1	B310	2	1994-08	1.736		
1	B310	3	1997-04	1.769	Chip seal	1996-05
1	B310	3	1998-04	1.751		

* Time in format of year-month

A hot-mix-resurfacing treatment applied in November 1990 is associated with a construction number of two. The next treatment application time is in May 1996 with the construction number changing from two to three. Thus, for the hot-mix-resurfacing treatment applied in November 1990, the first before treatment IRI value is 0.833 (June 1990); the first after treatment IRI value is 1.798 (July 1991); and the second after treatment IRI value is 1.669 (August 1992). The second after treatment IRI value is less than the first after treatment IRI value which is counterintuitive since the surface condition should be deteriorating over time without any pavement treatment. Using the forecast method to forecast right after IRI value, will produce a counterintuitive forecast result which will worsen the significant results.

Lower-level pavement activities, such as corrective maintenance, routine maintenance, and preventive maintenance, can gain greater benefits from using the forecasting method than higher-level pavement activities, such as rehabilitations by considering time sensitivity. Considering IRI survey frequency for different levels of treatments, rehabilitation may gain less benefit than it will lose. Thus, in this dissertation, skin patching, patching, full depth patching, shoulder treatment, crack sealing, seal coat, aggregate seal, and chip sealing treatment activities, one treatment a time, forecasting, and tool adjustment considerations will be take into account. For drainage activity, the same aforementioned considerations should be used, but this will result too small of a sample size. Thus, for drainage, together with hot mill overlay, and hot mix resurfacing treatment activities, one treatment a time and tool adjustment consideration will be used.

APPENDIX C. GLOSSARY

Crack Sealing
Treatments intended to seal cracks and prevent water from entering the pavement structure. The activity often involves pretreat and clean the crack and place a high quality sealant in it. It is categorized as maintenance activity in LTPP.

Shoulder Treatment
Treatments include AC shoulder restoration and AC shoulder replacement. Shoulder treatment is categorized as rehabilitation activity and described as overlays associated pre-treatment.

Chip Sealing
Treatment that apply a thin base of asphalt oil onto an existing pavement followed by embedding a fine aggregate layer into it and then compressed by a roller. Treatments include single layer chip seal, double layers chip seal, and three or more layers chip seal. It is categorized as maintenance activity in LTPP.

Seal Coat
Surface thin layer treatments that include slurry seal, fog seal, tack seal, and prime coat. It is categorized as maintenance activity in LTPP.

Drainage
Treatments include longitudinal subdrains, transverse subdrainage, drainage blankets, and well system. Drainage treatment is categorized as rehabilitation activity and described as overlays associated pre-treatment.

Aggregate Seal
Treatments include aggregate seal and sand seal.

Hot Mix Resurfacing
A treatment that applies a hot and plant pre-mixed mixture of graded aggregates and asphalt to pavement surface. It include asphalt concrete overlay, hot-mix recycled asphalt concrete, and heater scarification, surface recycled asphalt concrete. It is categorized as rehabilitation activity in LTPP.

Hot Mill Overlay
A treatment involve mill pavement surface before apply hot mix overly. It include mill of existing pavement and overly with AC, and mill existing pavement and overlay with hot-mix recycled asphalt concrete. It is categorized as rehabilitation activity in LTPP.

Skin Patching
A skin patching is a light patching treatment. Typically use a fine sand aggregate to improve the appearance of pavement or stop water penetration. Skin patching typically don't remove existing damaged material. It is categorized as maintenance activity in LTPP.

Full Depth Patching
A treatment that requires removing damaged material, repairing supporting material and repairing. It is categorized as maintenance activity in LTPP.

(Source: LTPP data)