Relative Benefit of Chip Seal Application in Different Climatic Conditions

Based on Initial Pavement Roughness

by

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ABSTRACT

Pavement preservation is the practice of selecting and applying maintenance activities in order to extend pavement life, enhance performance, and ensure cost effectiveness. Pavement preservation methods should be applied before pavements display significant amounts of environmental distress. The long-term effectiveness of different pavement preservation techniques can be measured in terms of life extension, relative benefit, and benefit-cost ratio. Optimal timing of pavement preservation means that the given maintenance treatment is applied so that it will extend the life of the roadway for the longest possible period with the minimum cost. This document examines the effectiveness of chip seal treatment in four climatic zones in the United States. The Long-Term Pavement Performance database was used to extract roughness and traffic data, as well as the maintenance and rehabilitation histories of treated and untreated sections. The sections were categorized into smooth, medium, and rough pavements, based upon initial condition as indicated by the International Roughness Index. Pavement performance of treated and untreated sections was collectively modeled using exponential regression analysis. Effectiveness was evaluated in terms of life extension, relative benefit, and benefit-cost ratio. The results of the study verified the assumption that treated sections performed better than untreated sections. The results also showed that the life extension, relative benefit, and benefit cost ratio are highest for sections whose initial condition is smooth at the time of chip seal treatment. These same measures of effectiveness are lowest for pavements whose condition is rough at the time of treatment. Chip seal treatment effectiveness showed no correlation to climatic conditions or to traffic levels.

DEDICATION

I dedicate this work to my wonderful family – Márti, Sergei, and Viki – for their love, encouragement, and endless support.

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CHAPTER 1. INTRODUCTION

1.1. Background and Problem Statement

Preventive maintenance is the practice of implementing periodic, affordable treatments in an effort to prolong pavement life and sustain pavement condition above an acceptable level. The idea of preventive maintenance has been around for decades; however, few highway agencies today have well-established preventive maintenance programs in place. This, in part, is caused by the lack of sufficient funds that are necessary to implement and sustain effective maintenance programs and by the lack of information on both the optimal timing and long-term benefits of maintenance treatments (Peshkin, Hoerner and Zimmerman 2004). Over the past few decades, it has been observed that highway agencies across the world focused their efforts on building new roadway facilities rather than on maintaining existing ones. However, these assets are now starting to wear out, and highway agencies are entering a “maintenance and preservation mode of operation” (Mamlouk and Zaniewski 2001).

In order to help agencies make better use of their funds, research on treatment timing and its impact on performance in the long-run, is necessary. In the United States, the Strategic Highway Research Program (SHRP) implemented the Long-Term Performance Program (LTPP) in 1986 to create a basis for data collection and research in this regard. Over the past two decades, the program has proved successful and served as a model for many state highway agencies in enhancing their quality control and quality assurance practices. Furthermore, research from the LTPP Program has helped develop better pavement performance models and various indices for measuring ride quality and pavement condition (Simpson, Rada and Lopez 2008).

In fact, ongoing LTPP-based research over the past two decades has been conducted to not only compare various treatment alternatives – such as crack seals, thin overlays, slurry seals, and chip seals – but to also pinpoint the optimal timing of these treatments that would lead to maximized benefits. However, the majority of this research either evaluated the performance of particular treatments or sought to find the most economically appealing option among a number of treatments. Few studies related the condition of the pavement at the time of treatment to the effectiveness of the treatment. The same treatment is known to perform differently when it is applied to pavements in different condition (Morian 2011), and therefore, pavement condition at the time of the treatment must become part of the analysis.

Chip seal is a commonly-used maintenance treatment in the United States and around the world (Gransberg and James 2005). Currently in the United States, most highway agencies use an empirical, experience-based approach in applying chip seal treatment, and no formal guidelines exist that tie chip seal treatment timing to effectiveness (Gransberg and James 2005). Therefore, in order to help highway agencies make better decisions on when and where to apply chip seal treatment, further research on the effectiveness and benefits of chip seal must be conducted.

1.2. Objectives and Scope of Study

The objective of this study was to examine the effectiveness of single-application of chip seal treatment in four different climatic regions in the United States, based upon the existing pavement condition at the time of treatment. The study considered all chip seal sections that were introduced to the Long-Term Pavement Performance (LTPP) Database over the past two decades, but the final analysis relied on a selected set of sections that specify certain selection criteria, as described in the following chapters. Chip seal sections in each climatic region were compared against flexible control sections that did not receive any maintenance or rehabilitation treatment for a number of years. Following a look at the deterioration characteristics of chip seal and control sections individually, sections were combined based upon initial condition, and a collective analysis of the deterioration characteristics of these sets of sections was conducted. This study examined treatment effectiveness from a variety of perspectives, including the life extension, relative benefit, and benefit-cost ratio associated with chip seal application. An attempt was also made to correlate these benefit measures to treatment timing and average traffic levels.

1.3. Organization of Thesis Document

This thesis document is divided into five chapters, including this introductory chapter. Chapter 2 provides a review of current literature on the history, importance, effectiveness, and optimal timing of pavement preservation. Chapter 2 also includes a brief background on chip seal treatment, and it describes different methods and indices used for modeling pavement condition as a function of time. Finally, the end of Chapter 2 summarizes the history and development and organization of the LTPP Database, along with a brief summary of past research that relied on the LTPP Database to predict preventive maintenance performance. Chapter 3 begins with a description of the specific parts of the LTPP Database utilized for this study. Next, Chapter 3 examines the data collection methods, extraction, filtering, and organization of data – for chip seal and control sections – that was utilized in this study. Chapter 4 begins with a comparison of two methods of analyzing treatment effectiveness – treatment timing-based analysis and initial condition-based analysis. Next, Chapter 4 provides a summary of the assessment, modeling, and normalization of the extracted data, along with the benefits of chip seal application in terms of life extension, relative benefit, and benefit-cost ratio. Chapter 4 is concluded by an overview of the results with respect to the four different climatic regions and average traffic levels. Chapter 5 holds a summary of the work performed, conclusions regarding the benefits of chip seal treatment, and recommendations for future research.

CHAPTER 2. LITERATURE REVIEW

2.1. Concept of Pavement Maintenance/Pavement Preservation

With the increasing demand on highway networks and decreasing resources available for maintaining these networks, highway agencies across the world are faced with the problem of maintaining pavement assets in lieu of decreased budgets and reduced staff. The following sections describe in detail the history, definition, importance, and effectiveness of pavement preservation.

2.1.1. A Historical Look at Pavement Maintenance/Pavement Preservation

Historic trends show that highway agencies worldwide typically focus their efforts on construction of new roadways rather than maintaining the already-existing facilities. In 1985, the World Bank implemented a study and discovered that in developing countries, the majority of funds are spent on highway construction (Mamlouk and Zaniewski 2001). With this practice, roadway networks deteriorate into unserviceable condition faster than the rate at which new roads are being constructed (Peshkin, Hoerner and Zimmerman 2004).

Statistics in the United States from the late 1990s showed that federal funding was too scarce to include a significant budget for pavement maintenance and the trend was not predicted to increase (Morian 2011). In 1997, the Federal Highway Administration (FHWA) estimated that over half of all urban and rural roads in the United States were in fair, mediocre, or poor condition. With these observations, it was predicted that the nation’s roadway system will continue to deteriorate because the amount of funding allotted to pavement maintenance is typically less than what is necessary to maintain existing roadway conditions (Kuennen 2003).

According to the proceedings of the Transportation Research Board (TRB) Committee on Pavement Maintenance in 2000 (Moulthrop and Smith 2000), several public- and private- sector groups sponsored a Forum for the Future in 1998 that mapped out pavement maintenance practices in the following few decades. The goal of the Forum was to plan out pavement maintenance strategies that would result in increased safety, convenience, and consumer satisfaction. The Forum determined that the key issues for the coming decades would include a more thorough understanding of pavement preservation and maintenance, pavement performance data, sufficient funding, performance specifications, quality assurance, and research (Moulthrop and Smith 2000).

In its report to Congress for year 2008 (Status of the Nation's Highways, Bridges, and Transit: Conditions and Performance Report 2008), the Federal Highway Administration pointed out that due to increased costs, more public-private partnerships (PPPs) have formed. These partnerships provide conjoined public-private efforts for designing, financing, constructing, and maintaining roadways. In 2006, governments across the United States have spent $161.1 billion on roadways, $40.4 billion of which was allocated for rehabilitating the existing roadway system (Status of the Nation's Highways, Bridges, and Transit: Conditions and Performance Report 2008). Figure 2.1 illustrates the types and percentages of highway expenditures in the United States in 2006.

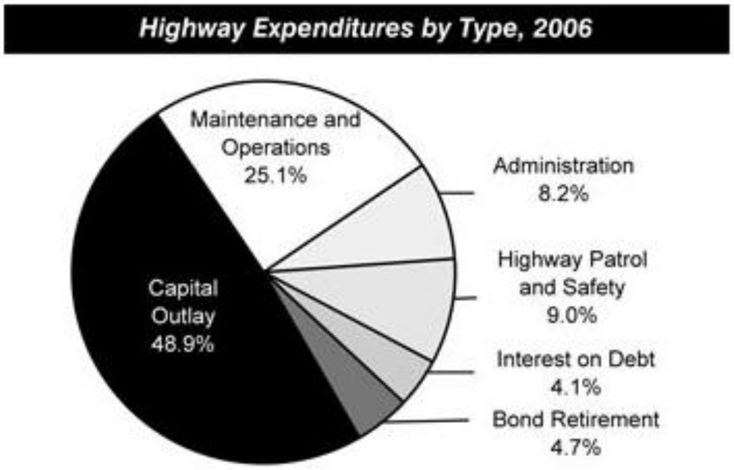


Figure 2.1 Governmental Expenditures for Highways in the United States in 2006 (Status of the Nation's Highways, Bridges and Transit: Conditions and Performance Report 2008)

2.1.2. Definition of Pavement Preservation

Before discussing pavement preservation in detail, it is important to clarify the difference between pavement condition and pavement performance. Pavement condition can be thought of a "snapshot" of how well or poorly a pavement is doing at a particular point in time. Several measures of pavement condition exist, including the Present Serviceability Index (PSI), the Pavement Condition Index (PCI), and the International Roughness Index (IRI). These indices are discussed in more detail in Section 2.3 of this chapter.

Pavement performance is the change of pavement condition measurements over an extended period of time. After several observations of pavement condition, a pavement performance curve can be developed. Depending on the choice of pavement condition measure, the pavement performance curve can show a general upward or downward trend.

Currently, no standard guide exists to help agencies correct a specific distress condition (Mamlouk and Zaniewski 2001; Labi and Sinha 2003; Peshkin, Hoerner and Zimmerman 2004). Consequently, maintenance practices vary greatly across agencies in the United States. While one agency might choose to employ crack seals to fix moderate cracking, another agency may apply micro-surfacing. This variation in treatments is influenced by, for instance, the climatic region, the level of traffic, and the type of subgrade. The dominant pavement maintenance and preservation practices are often the result of a trial-and-error process that has evolved over several decades of experience. Not only are district and state highway agencies using different terminology for the same treatment, but often times, the categorization of maintenance treatments varies from state to state. For instance, while a thin hot-mix asphalt concrete (HMAC) layer may be used as a rehabilitation technique by one agency, the same treatment may fall into the category of preventive maintenance according to another agency. The tight budgets that agencies must adhere to does not help the situation. A preventive maintenance activity may be funded from the maintenance budget in one state, while it may be funded from the capital budget in another state, designating it as a rehabilitation activity (Labi and Sinha 2003).

In order to mitigate the lack of consistent terminology, the FHWA published a memorandum in 2005 that provides guidance and clarification on the definition of pavement preservation (Geiger 2005). As illustrated in Figure 2.2, pavement preservation is a process that involves the following three components: preventive maintenance, minor rehabilitation, and routine maintenance.

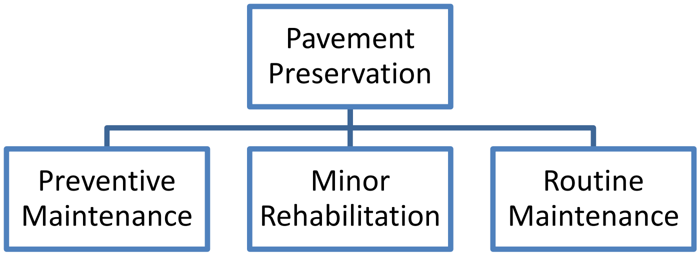


Figure 2.2 Schematic of Pavement Preservation Terminology (Geiger 2005)

Pavement preservation is the “practice of proactively maintaining existing roadways” (Geiger 2005) . It is a “network-level, long-term strategy that enhances pavement performance by using a … cost effective set of practices that extend pavement life” (Geiger 2005). When administered correctly and in a timely fashion, pavement preservation helps state transportation agencies not only save money, but also avoid extensive reconstruction and rehabilitation projects that may disrupt traffic and compromise safety (Geiger 2005).

2.1.2.1 Preventive Maintenance

The American Association of State Highway and Transportation Officials (AASHTO) Standing Committee on Highways, in 1997, defined preventive maintenance as a “planned strategy of cost-effective treatments to an existing roadway system . . . that preserves the system, retards future deterioration, and maintains or improves the functional condition of the system, without significantly increasing the structural capacity” (Geiger 2005).

Preventive maintenance is applied to pavements that are still in "good condition and that have a significant remaining service life" (Geiger 2005). Typically, preventive maintenance involves economical, near-surface repairs on pavements that are in adequate condition at the time of treatment. Several examples of preventive maintenance treatments for asphalt concrete are chip seals, slurry seals, micro-surfacing, thin hot-mix asphalt overlay, crack sealing, and diamond grinding (Geiger 2005). Chip seal treatment is further described in Section 2.3.1 of this chapter.

2.1.2.2 Minor Rehabilitation

The AASHTO Highway Subcommittee on Maintenance defines pavement rehabilitation as "structural enhancements that extend the service life of an existing pavement and/or improve its load capacity. . . [they] include restoration treatments and structural overlays" (Geiger 2005). Rehabilitation can be performed by either removing brittle pavement surface that suffers from "age-related environmental cracking" (Geiger 2005), or by increasing the thickness so that the pavement can accommodate higher traffic loads (Geiger 2005). Depending on the amount of increase in structural capacity, pavement rehabilitation can further be broken down into two sub-categories – minor rehabilitation and major rehabilitation (Geiger 2005).

Minor rehabilitation involves non-structural improvements that mitigate damage, such as top-down surface cracking, due to environmental exposure (Geiger 2005). Minor rehabilitation is considered a form of pavement preservation because such repairs do not improve the structural capacity. Major rehabilitation, on the other hand, involves any type of structural fix that both “increases the service life and/or increases the load-carrying capacity” (Geiger 2005).

2.1.2.3 Routine Maintenance

The AASHTO Highway Subcommittee on Maintenance defines routine maintenance as “. . . 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” (Geiger 2005). The purpose of routine maintenance is to keep the condition of a roadway at a satisfactory level of service, by scheduling frequent maintenance activities, for example, patching potholes, filling minor cracks, maintaining pavement markings, and cleaning ditches near the pavement section (Geiger 2005).

Aside from the aforementioned preventive maintenance measures, corrective maintenance and emergency maintenance also play an important role in state transportation agencies’ construction and maintenance programs. However, these activities fall outside the scope of pavement preservation. The pre-existing condition of the roadway is the key factor that differentiates corrective and emergency maintenance from preventive maintenance (Geiger 2005). Figure 2.3 illustrates the progression of these maintenance techniques.

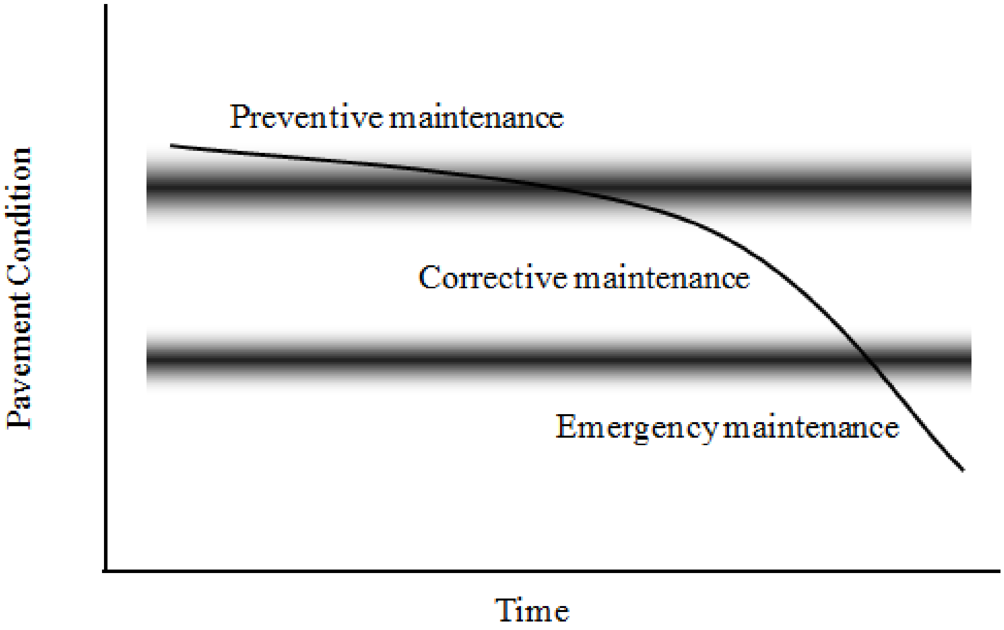


Figure 2.3 Types of Maintenance Measures Based on Pavement Condition (Mamlouk and Zaniewski 2001)

The appropriate type of maintenance measure for a pavement section is governed by the pre-existing condition of the pavement, prior to the maintenance activity. A pavement section whose pre-existing condition falls within the upper and lower threshold values for corrective maintenance will not receive the full benefit of a preventive maintenance measure, because the pavement is too deteriorated and needs more extensive repair. For example, a slurry seal will not “fix” a pavement surface that is cracked and oxidized, and a thin overlay will do nothing to correct a pavement that suffers from alligator cracking. Similarly, a pavement whose pre-existing condition is in the emergency maintenance spectrum cannot be fully recovered by simply using a corrective maintenance measure (Peshkin, Hoerner and Zimmerman 2004).

2.1.2.4 Corrective Maintenance and Emergency Maintenance

Corrective maintenance is typically performed to mitigate deficiencies that compromise the “safe and efficient operation” of a roadway (Geiger 2005). Corrective maintenance activities are generally referred to as “reactive” rather than “proactive” because their primary purpose is to bring pavements back to satisfactory condition (Geiger 2005). Corrective maintenance could consist of pothole repairs, pothole patching, or shoulder patching for AC pavements, and of joint replacement or isolated full depth slab replacement for PCC pavements (Geiger 2005).

Emergency Maintenance involves restoring a pavement to a “minimum level of service” until a permanent fix is designed and scheduled (Geiger 2005). Emergency maintenance is typically implemented following natural disasters such as mudslides, violent flooding, or avalanches (Geiger 2005).

2.1.3. Importance of Pavement Preservation

In order to be effective, pavement preservation needs to be applied to roadways that are still in reasonably “good” condition – while there is no onset of serious damage (Geiger 2005). Mamlouk (1999) considered pavement test sites that received maintenance treatments in four different states. For this study, only pavements whose initial condition was good were selected. The pavement sections were evaluated for short-term performance, based on three years of service. It was concluded that first, sections that received preventive maintenance performed better than sections without treatment after three years, and second, treatments that were applied to pavements in "good" condition performed better than treatments that were applied to pavements in "bad" condition (Mamlouk 1999).

Ideally, a cost-effective treatment at the right time will restore the pavement to its original condition, as shown in Figure 2.4 below. As seen in Figure 2.4, successive and systematic preventive maintenance treatments not only prolong pavement life, but they also help to keep pavement condition above a certain threshold level. A program of successive treatments may consist of several types of treatment (Mamlouk and Zaniewski 2001). The downward dotted line in Figure 4 shows that if the pavement were left without preventive maintenance treatment, then pavement condition would progressively deteriorate until conventional rehabilitation is required. Conventional rehabilitation can raise the pavement condition to a level equivalent to that of a newly-constructed pavement. However, the costs, traffic delays, and safety concerns associated with conventional rehabilitation make it a less-favorable choice when compared to preventive maintenance treatments.

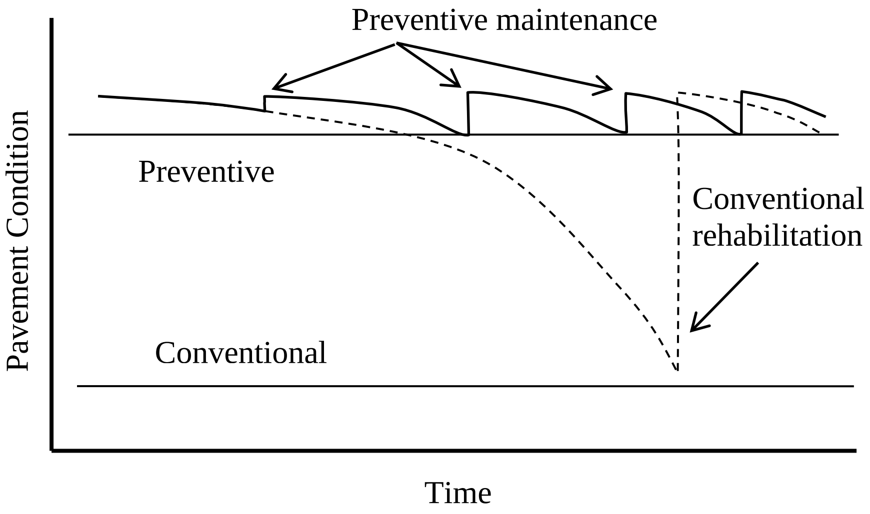


Figure 2.4 Cumulative Effects of Successive Preservation Treatments (Mamlouk and Zaniewski 2001)

Performing preventive maintenance treatments is analogous to regular check-up visits to a dentist, for instance, in order to prevent the onset of cavities, while delaying maintenance until a pavement is failing is analogous to waiting to go to the dentist when the patient requires surgery. From this example, it is easily understood that investing smaller amounts of time and money into routine dentist visits several times is more beneficial than spending a considerable amount of time and money during a single visit to a dentist. The same concept holds true for effectively maintaining roadway networks.

Unfortunately, the current practice of "worst first" pavement maintenance philosophy dedicates already scarce governmental funds to pavements that are on the verge of failing and will soon need serious rehabilitation (Kuennen 2003; Gransberg and James 2005). It may seem that money is best spent on cases where serviceability and safety are compromised; however, spending smaller amounts of money on regular preventive maintenance would help prevent pavements from reaching unserviceable conditions in the first place. It is known that asphalt pavements perform best during roughly the first ten years of their service lives, after which more rapid deterioration sets in. Experts at FHWA agree that pavements should be approached with preventive maintenance treatments before they reach this period of accelerated deterioration (Kuennen 2003).

Few highway agencies today have good pavement maintenance programs, due to the lack of information on the long-term benefits of these treatments and the optimal timing that makes these treatments most cost-effective (Peshkin, Hoerner and Zimmerman 2004). Leaving preventive maintenance until later is especially intriguing to agencies that are on tight budgets because there are no immediate adverse effects of deferring preventive maintenance activities. Furthermore, many agencies claim that they are practicing preventive maintenance simply because they are utilizing preventive maintenance treatments. Unfortunately, preventive maintenance measures are often implemented too late in the life cycle of the pavement, so that the benefits of the particular treatment are never fully realized. The untimely use of preventive maintenance can limit the performance period because the treatment can temporarily mask failure in the underlying pavement structure. Moreover, when implemented too late, the effectiveness of a maintenance treatment may be misinterpreted because the pavement may continue to deteriorate. A fair and adequate assessment of the true value of preventive maintenance requires that the treatment is placed “under favorable conditions” (Mamlouk and Zaniewski 2001).

2.1.4. Effectiveness of Pavement Preservation

The effectiveness of pavement preservation is grouped into two major categories: short-term effectiveness and long-term effectiveness. In both of these scenarios, effectiveness is evaluated based upon observed performance of roadways that received treatment and roadways that did not receive treatment. To be successful, pavement preservation should be an agency program with efficient staff correspondence in the finance, planning and design, materials and construction, and maintenance phases. Pavement preservation cannot be effective unless “long-term commitment from agency leadership” and a sufficient annual budget are available (Gransberg and James 2005).

2.1.4.1 Short-Term Effectiveness and Modeling Approaches

Several attempts have been made in the past to model the short-term effectiveness of preventive maintenance. It has been shown that short-term models are useful because they can, in general, predict the benefits of maintenance, and they are particularly suitable for predicting the effectiveness of individual treatments. If several maintenance treatments are applied during a longer period, it is more difficult to pinpoint the effects of just a single treatment (Labi and Sinha 2003). The incremental change in pavement condition due to maintenance has been studied both in a general sense, by Ramaswamy and Ben-Akiva (1990), and for a particular type of maintenance treatment, by Mouaket and Sinha (1991).

Sihna et al. (1988) has performed a routine maintenance study in Indiana that models the change in Pavement Serviceability Index (PSI) as a function of the type of maintenance and the location of the pavement in either the Northern or the Southern part of the United States. The conclusion of this research was that regardless of the type of maintenance treatment, roughness typically increases after treatment. This finding is not surprising granted that the study did not consider the relative time between treatment application and the time of the condition survey, and this oversight could be costly when estimating maintenance effectiveness. From the research of Sinha et al. (1988), maintenance treatments were shown to be less effective in the Northern part of the United States than in the Southern part of the United States. In addition, pavement maintenance expenditure models that consider pavement characteristics such as age, functional class, and surface type, have shown that pavement expenditure tends to be higher in the Northern region and lower in the Southern region, and typically, expenditures are highest for Interstate roads (Sinha, et al. 1988). It is more costly to maintain flexible pavements than rigid pavements (Labi and Sinha 2003).

Li and Sinha (2000) also developed short-term models that express the change in roughness in terms of the attributes of the pavement. Collucci Rios and Sinha (1985) developed equations that model the instantaneous change in roughness, also known as performance jump (J), due to overlays of varying thicknesses. However, there are currently no extensive studies that address maintenance effectiveness as a function of the change in slope of the deterioration curve, also known as deterioration reduction rate (DRR), due to maintenance (Labi and Sinha

2003). In the past, maintenance effectiveness has been quantified by either addressing the deterioration reduction level (DRL), or by addressing the performance jump, that occurs as a result of maintenance treatments. Past studies did not investigate the relationship between the three measures of deterioration – DRR, DRL, and J (Labi and Sinha 2003).

2.1.4.2 Long-Term Effectiveness and Modeling Approaches

Haider and Dwaikat (2011) state that the long-term effectiveness of pavement preservation is typically quantified by three parameters: (1) treatment service life (TSL), (2) increase in average pavement condition, and (3) the area encompassed by the condition versus time curve and some known threshold value. TSL, also known as life extension, is measured in years and is determined by extrapolating the treatment pavement condition curve until it reaches the predefined threshold value. Average pavement condition is defined as the average condition increase, in percent, between pre- and post- pavement condition. The area bounded by the performance curve is considered the most superior approach to evaluating treatment effectiveness. The area approach not only illustrates the average increase in condition, but it also shows the service life extension that is due to a particular maintenance measure (Haider and Dwaikat 2011).

Depending on the type of condition index that is used, the area below or above the curve may need to be considered. For example, if the index of condition measure is the Pavement Condition Index (PCI), then the performance curve looks similar to that on the right-hand side of Figure 2.5, and the effectiveness of the treatment is the shaded area bounded by the curve and the horizontal axis. However, if the International Roughness Index (IRI) is used to monitor pavement performance, then the performance versus time curve graph exhibits an upward trend, as illustrated by the left-hand side of Figure 2.5. In this case, the effectiveness of the treatment is the area bounded by the condition versus time curve and some upper IRI threshold value, also known as terminal IRI. A more detailed analysis of these pavement condition indicators is available in Section 2.4 of this chapter.

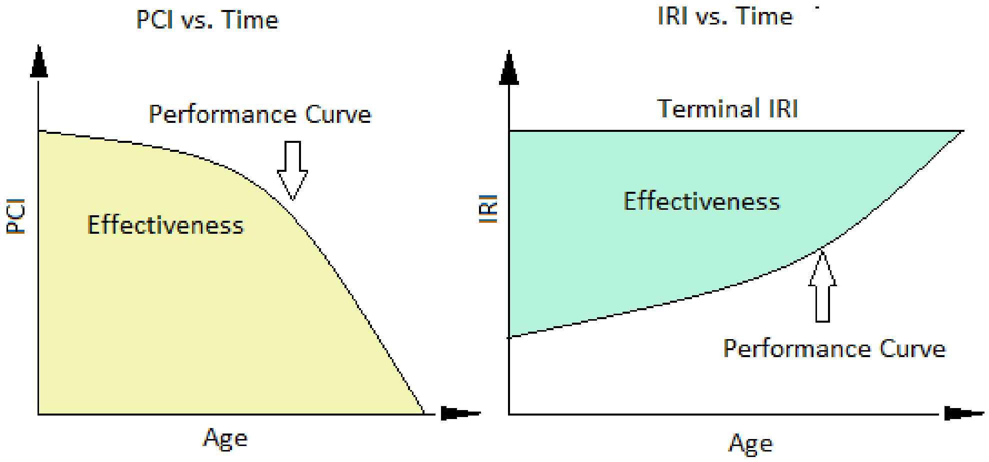


Figure 2.5 Definition of Long-Term Effectiveness

In general, the larger the area bounded by the performance curve and the threshold value, the more effective the treatment. However, when evaluating effectiveness, it is not enough to simply rely on these areas because different types of treatments have different costs (Mamlouk and Zaniewski 2001).

2.2. Optimal Timing of Maintenance Treatments

Optimal timing means selecting and applying the most appropriate treatment, at the correct time, such that benefits can be maximized while costs are minimized (Hajj 2011; Dawson, et al. 2011). The selection of optimal treatment timing is based upon the pre-existing conditions and rates of deterioration. Optimum timing is a function of not only these two parameters, but also of the before-treatment history, type of maintenance treatment, and the cost of the treatment, which is often separated into user costs and agency costs. Benefits, in this context, may be expressed in terms of life extension, treatment life, or total benefit attributed to the treatment (Dawson, et al. 2011).

Dawson, et al. (2011) compared the effectiveness of the same1.8-inch mill and fill on four pavements sections in Washington, in 2003. The treatment was applied to pavements that had similar cross-sections and traffic characteristics but different pre-existing conditions and rates of deterioration. The study demonstrated that knowing the deterioration rate alone is not sufficient for selecting optimal timing; the mill and fill showed the poorest performance and least benefit when it was applied to a badly deteriorated pavement.

Hajj, et al. (2011) investigated the optimal timing of slurry seal treatment in Washoe County, the City of Sparks, and the City of Reno, in Nevada. A total of 2,700 pavement sections were evaluated. The sections were categorized based upon Average Daily Traffic (ADT) values into arterial, collector, and residential roadways. The study analyzed long-term effectiveness and calculated benefit-cost ratios based upon discounted 2009 dollars. The results of the study showed that the benefits of any surface treatment cannot be optimized if the treatment is applied too early. Moreover, the study revealed that the type of construction activity preceding the treatment influences the optimal timing. For newly-constructed pavements, optimal timing was shown to be at 3 years after construction, while for overlays, optimal timing fell anywhere between 3-5 years after overlay.

Morian (2011) examined the performance and cost-effectiveness of thin surface treatments, in Pennsylvania, on pavements with varying pre-treatment conditions. This research showed that an optimal pavement condition, or age, exists where the benefit-cost ratio can be maximized. Even though this study showed that crack sealing had a higher benefit-cost ratio than did Novachip, it must be noted that the chip seal sections analyzed in this study were applied to create surface friction for concrete pavements on Interstate highways.

2.2.1. Selection of Maintenance Treatments

The selection of the appropriate maintenance treatment always begins with visual inspection. Depending on the existing distresses and type of pavement, different maintenance treatments are recommended. It is important to note that in order to be considered "optimal," a treatment needs to address the pavement distress but not necessarily the cause of the distress (Dawson, et al. 2011). Several types of maintenance treatments have been successfully used by various agencies, such as chip seal, slurry seal, micro-surfacing, crack sealing and thin hot-mix asphalt overlay. Out of these treatments, chip seal has been commonly used by many agencies as discussed in the following section.

2.2.2. Chip Seal

2.2.2.1 Definition of Chip Seal

A chip seal, also called an "aggregate seal coat," or "single layer surface treatment," is "a layer of asphalt that is overlaid by a layer of embedded aggregate that furnishes, among other things, protection to the asphalt layer from tire damage and a macro-texture that creates a skid-resistant surface over which vehicles safely pass" (Gransberg and James 2005). The purpose of a chip seal is to seal minor cracks so that the intrusion of water into the base and subgrade can be avoided (Gransberg and James 2005). Chip seals are known to also improve surface friction (Peshkin, Hoerner and Zimmerman 2004).

The Specific Pavement Study 3, (SPS-3) of the Long-Term Pavement Program was implemented to investigate the timing of pavement maintenance actions. From this study, it has been shown that the likelihood of failure of chip seal is up to four times greater when applied to pavements in bad condition as opposed to when applied to pavements in good condition (Gransberg and James 2005). Research by Eltahan, Daleiden and Simpson (1999), found that chip seals "... appear to outperform the other treatments . . . in delaying the reappearance of distress."

2.2.2.2 Typical Uses, Design Methods, and Similar Treatments

Chip seals are used worldwide – in the United States, Canada, New Zealand, Australia, and South Africa. Chip seals are applied to mitigate functional distresses, including longitudinal cracking, transverse cracking, and block cracking, raveling and weathering. They can also be used to maintain pavements that suffer from friction loss and/or exhibit low levels of bleeding and roughness (Peshkin, Hoerner and Zimmerman 2004). The standard practices for choosing chip seal vary depending on location. In North America, chip seals are selected because they prevent water infiltration and remedy minor distress. In international settings, however, chip seals are chosen mainly to provide a wearing surface and to prevent loss of skid resistance (Gransberg and James 2005).

Two basic categories of chip seal design methods exist – empirical design that is based on experience, and design using engineering algorithms. The current practice of chip seal design involves determining the type, grade, and rate of application of asphalt binder for a given aggregate type, size, existing surface condition, traffic volume, and type of chip seal treatment used (Gransberg and James 2005).

Although single-layer chip seals are most common, other derivatives of chip seal exist, including double chip seal, racked-in seal, cape seal, inverted seal, sandwich seal, and geotextile-reinforced seal. Double chip seals involve two consecutive applications of both the binder and the one-sized aggregate that would normally be used for single-layer chip seals. Racked-in seals include an additional protective choke-stone layer on top of a chip seal. The layer facilitates aggregate interlock and prevents the aggregates from loosening before the binder is fully cured. Cape seals involve a single-layer chip seal application, followed immediately by either a slurry seal or micro-surfacing, to provide strong shear resistance. Inverted seals are similar to double chip seals, except that in an inverted seal, small aggregates reside in the bottom of the seal layer, and larger aggregates reside on top. Sandwich seals involve three layers – a dry layer of large aggregates, followed by a layer of asphalt and by a second layer of smaller aggregates. When used on pavements that show signs of oxidization and thermal cracking, chip seals can be enhanced by geotextile reinforcement. This involves the application of a tack coat onto the raveled surface, followed by a geotextile layer. The chip seal is then placed on top of the geotextile layer (Gransberg and James 2005).

2.3. Quantifying Pavement Condition and Modeling of Maintenance Treatments

2.3.1. International Roughness Index (IRI)

2.3.1.1 Definition of IRI

The International Roughness Index (IRI) is "the universal measure of the response of a vehicle to roadway roughness" (Roughness Profile with Speed Profilograph 2003). IRI measures suspension motion over a length of roadway profile at the standard speed of 30-60 miles per hour (50-97 kilometers per hour). The units of IRI are either inches per mile or millimeters per kilometer (Flintsch and McGhee 2009).

2.3.1.2 Modeling IRI as a Function of Time

Several attempts have been made to model IRI as a function of time. Haider and Dwaikat (2010) and Dawson, et al. (2010) state that the most appropriate way to describe roughness is by using Equation 2.1. This formulation is valid for the IRI condition curves for both pre-treatment and post-treatment (Haider and Dwaikat 2011). Once the model parameters are determined, the equation can be used to predict future performance. A minimum of three data points are required to successfully model pavement condition with time (Dawson, et al. 2011).

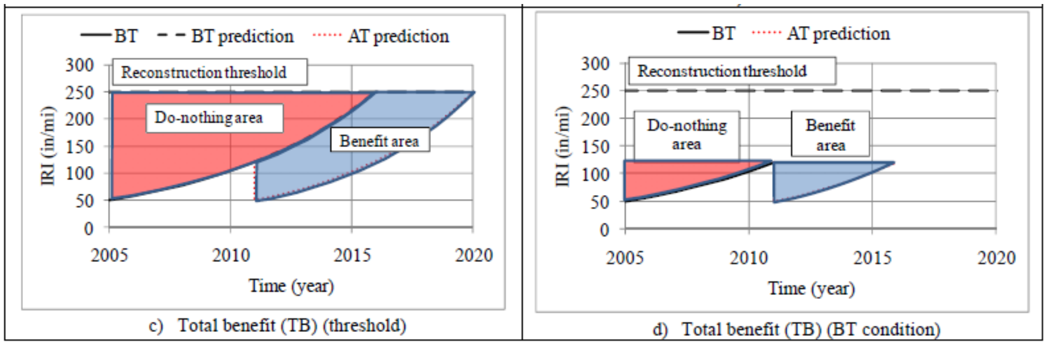
$$IRI = \alpha \cdot e^{\beta \cdot t} \tag{2.1}$$

where:

α = model parameter representing the starting value of the treatment curve
β = model parameter representing the rate of deterioration of IRI over time
t = elapsed time since treatment in years or months (Haider and Dwaikat 2011; Dawson, et al. 2011)

In order to accurately reflect pavement performance, projects in similar geographic locations, with similar pavement types and comparable deterioration rates should be selected. When no such data is available, historical trends need to be used to predict post-treatment performance. When analysis is based on historical trends, however, confidence levels for the accuracy of the model are low (Dawson, et al. 2011).

The long-term modeling approach for roughness suggests that pre-treatment performance is governed by the pre-existing roughness and rate of deterioration before the treatment, and post-treatment performance is defined by the post-treatment roughness and rate of deterioration. It is assumed that immediately after treatment, a downward performance jump can be observed, and the rate of deterioration generally slows down compared to the rate prior to treatment (Haider and Dwaikat 2011). A treatment is most effective when the area bounded the benefit area is maximized (Haider and Dwaikat 2011). The threshold value could either be an arbitrary value set by the agency, or it could be considered as the pavement condition prior to treatment (Haider and Dwaikat 2011; Dawson, et al. 2011). Figure 2.6 depicts the schematic of pre-treatment and post-treatment curves when the condition indicator is IRI.



c) Total benefit (TB) (threshold)

d) Total benefit (TB) (BT condition)

Figure 2.6 Benefits of Pavement Preservation (Dawson, et al. 2011)

2.3.2. Other Measures of Pavement Condition (PCI and PSI)

Pavement condition can also be measured using the Pavement Serviceability Index (PSI) and the Pavement Condition Index (PCI).

PSI is a refined version of the Present Serviceability Rating (PSR) – the oldest and most subjective measure of ride quality. PSR was originally developed for the AASHO Road Test in the 1950s, and it relied on ratings by a panel of observers who evaluated pavement condition based on ride quality in passenger vehicles. Due to its subjectivity, PSR was transformed to PSI between 1958 and 1960, based on PSR estimates of various roads in Indiana, Minnesota, and Illinois. These PSR estimates, in conjunction with other condition measurements such as cracking and slope variance, were used to develop equations that describe PSI. PSI uses a five-point scale of pavement quality assessment, where the number 5 stands for excellent pavement quality, and 0 stands for extremely deteriorated pavement. A PSI of 2-2.5 is the accepted threshold for unserviceable pavements, depending on the class of the road (Pavement Condition Rating Systems n.d.).

PCI is a unitless quantity that ranges between zero and one hundred, where one hundred means exceptional pavement condition, and zero means fully deteriorated pavement. PCI relies on a point deduction formula that subtracts points from one hundred for every distress type, based on extent and severity (Sotil and Kaloush 2003). PCI is a commonly-used pavement condition index used by agencies across the United States (Flintsch and McGhee 2009).

2.4. Long-Term Pavement Performance Database

2.4.1. History and Development

The development of the Long-Term Pavement Performance (LTPP) Database dates back to 1984, when the need for a comprehensive pavement performance database was announced, based on the poor condition of much of the United States roadway system. America's Highways: Accelerating the Search for Innovation is the first report that recommended the creation of a comprehensive database that could aid with pavement design and management. The American Association of State Highway and Transportation Officials (AASHTO) incorporated LTPP as part of the Strategic Highway Research Program (SHRP) in 1986 (Simpson, Rada and Lopez 2008).

The purpose of LTPP was to collect and store data that can be used to investigate how and why pavements perform the way they do over extended periods of time. Insights from the data could help to improve pavement engineering and maintenance practices. Data collection began in 1987, with seventeen field experiments that covered two main study areas: Specific Pavement Studies (SPS) and General Pavement Studies (GPS). Over the following two decades, the program has flourished and aided the development of pavement design tools such as the Mechanistic Empirical Pavement Design Guide (MEPDG) (Simpson, Rada and Lopez 2008).

2.4.2. Organization of the LTPP Database

The two types of pavement categories in the LTPP database are General Pavement Studies (GPS) and Specific Pavement Studies (SPS). Pavements in the GPS study were already in service at the time of the implementation of the LTPP program (Simpson, Rada and Lopez 2008; Elkins, et al. 2003). GPS studies were known to be designed with good materials and engineering practices that had strategic importance for the future. The GPS study consisted of pavements in varying ages and conditions. The SPS study, on the other hand, included pavements that were specifically designed, constructed, rehabilitated, and maintained to specifically investigate design factors that were not necessarily considered otherwise. For instance, some SPS projects include thin pavements under both light and heavy traffic (Simpson, Rada and Lopez 2008).

The main difference between GPS and SPS pavements is that SPS sections are located next to each other for a given project location. This means that materials, climatic conditions, and traffic levels are relatively similar for SPS sections on a single project. GPS sections are not always co-located. Furthermore, within the LTPP database, similar types of information for SPS and GPS projects are stored in different tables. For instance, construction information for GPS sections is found in the Inventory module, while the same information for SPS sections is stored in special SPS tables (Elkins, et al. 2003).

The LTPP database is divided into modules, or groups of tables that contain similar sets of data. Table 2.1 summarizes the types of modules and the information contained in each module.

Table 2.1 Modules in the LTPP Database (Elkins, et al. 2003)

MODULE NAME	INFORMATION CONTAINED IN MODULE
Administration (ADM)	Tables that describe the database; contains information about data codes, experiment sections, and regions.
Automated Weather Station (AWS)	Data collected by the automated weather stations that were installed on some SPS sites.
Climate (CLIM)	Data collected from offsite weather stations that were used to mimic the climatic conditions near some SPS projects.
Dynamic Load Response (DLR)	Dynamic load response data from SPS sections in Ohio and North Carolina.
Inventory (INV)	Inventory information for GPS and SPS sections, such as location and structure information, as provided by the state or province where the test sections are located.
Maintenance (MNT)	Information about maintenance treatments, such as surface treatments, crack sealing, and joint sealing, as reported by highway agencies.
Monitoring (MON)	Pavement performance monitoring data, such as distress, deflection, rut, profile, and friction.
Rehabilitation (RHB)	Information about rehabilitation treatments and when they occurred.
Seasonal Monitoring Program (SMP)	Precipitation data and frost-related measurements, onsite air temperature, subsurface temperature and moisture content.
Traffic (TRF)	Traffic volume, loads, and classification.
Test (TST)	Materials testing data from field and laboratory settings.

2.4.3. Section Layout and Section Designation in LTPP

2.4.3.1 Section Layout

In the LTPP context, multiple pavement test sections are located adjacent to each other. A test site consists of a test section and a 50-foot (15.2-meter) materials sampling portion on each end. Test sites are divided into sections that are 500 feet (152 meters) long, and a consecutive span of sections makes up a project site. The typical GPS project layout consists of a test section, with a 500-foot (152-meter) and a 250-foot (76-meter) maintenance control zone at the beginning and end of the test site, respectively. The typical SPS project layout is similar to the GPS layout, except that SPS sites contain transition zones between consecutive sections (Elkins, et al. 2003). Figure 2.7 illustrates typical SPS and GPS test section layouts.

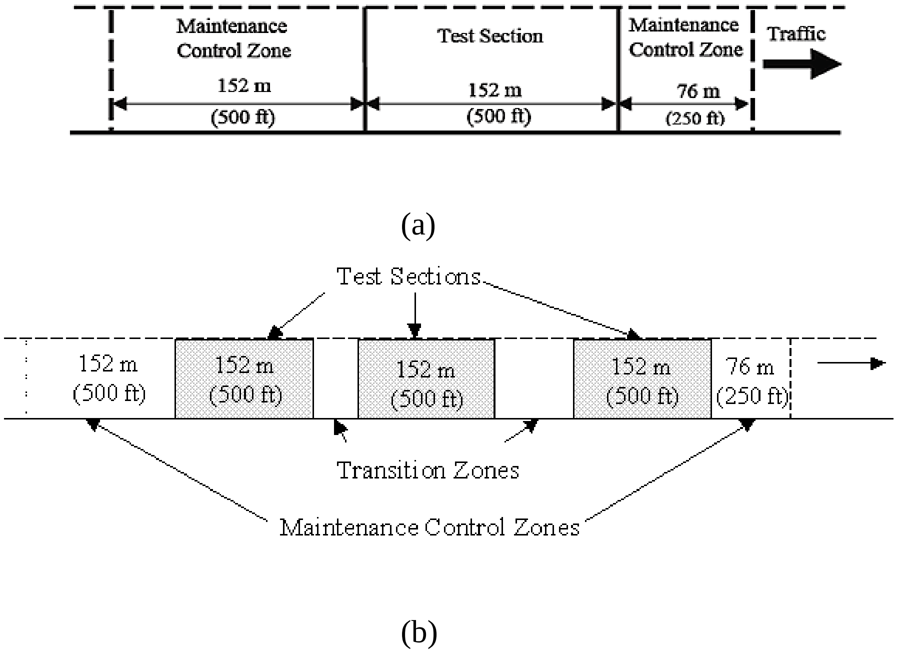


Figure 2.7 Typical Layouts for (a) GPS Test Sites and (b) SPS Test Sites (Elkins, et al. 2003)

Depending on the type of project – SPS or GPS – the project may have gone through different types of maintenance and rehabilitation. For instance, an SPS project site may include five adjacent sections, four of which received a various types of rehabilitation or maintenance at different times, while the remaining section may serve as a control against the others.

2.4.3.2 Section Identification

In order to properly navigate the LTPP database, the user must be familiar the unique designation that describes each pavement section. Each pavement section has a two-part designation – a state code and an SHRP identification number. The state code is a one- or two- digit number that has been uniquely assigned to each participating state (Elkins, et al. 2003). State code appears in essentially every LTPP data table, under the column heading “STATE_CODE.” The section identification number is a 4-digit string; it may be all numerical or a combination of numbers and letters. Section identification numbers are designated as “SHRP_ID” in the LTPP tables. An example of this compound nomenclature is 4A350, where “4” indicates that the section is located in Arizona, and A350 is the unique section identification code (Long-Term Pavement Performance Database 2012).

2.4.4. Past Use of LTPP to Predict Maintenance Performance

The LTPP database has been used in numerous studies to predict and evaluate pavement maintenance measures. Smith, Freeman and Pendleton (1993) used SPS-3 test sites to design a pavement damage model that categorized each pavement distress as a damage index between zero and one, where zero indicates no damage and one indicates extreme damage. This model was used for the remaining life analysis in the AASHTO 1993 Design Guide. Morian, Epps and Gibson (1996) evaluated maintenance treatment performance in the SPS-3 experiment over a 5-year period. This research concluded that chip seal performed best in the Wet Non-Freeze region, although after five years, thin-overlay showed better performance and crack seal proved to be more cost-effective and most resilient in Wet Freeze environments. Chen, Lin and Luo (2003) evaluated the effectiveness of fourteen SPS-3 sites in Texas. The fourteen sites were chosen to represent different climatic and subgrade conditions, and varying traffic levels. The study showed that chip seal performed well when applied to pavements in varying initial conditions, and that crack seal was the most economical choice in terms of initial cost for low-volume roads that otherwise had a sturdy underlying structure. The research of Eltahan, Daleiden and Simpson (1999) assessed survival rates of various SPS-3 sites over eight years and concluded that survival rates for thin overlay, crack seal, and slurry seal were 7, 5, and 5.5 years, respectively. This study also showed that chip seals performed best in delaying the reappearance of distress after eight years. The research of Morian, et al. (2011) investigated the life expectancies of thin overlays, slurry seals, crack sealing, and chip seals in the SPS-3 experiment since 1990. The outcomes of this study were that all treatments, except for crack sealing, add a statistically significant contribution to pavement performance. Also, this research showed that chip seal and thin overlays have similar performance lives, and chip seals are especially suitable for use on lower-classification roadways.

CHAPTER 3. DATA COLLECTION AND ORGANIZATION

3.1. Parts of LTPP Utilized

All data used for analysis was extracted from the DVD version of the Long-Term Pavement Performance Standard Data Release, versions 26.0, January, 2012. The data on the DVD is divided into volumes, and each volume contains a set of modules, as discussed earlier in Chapter 2. In this study, the four main modules used were Administration, Maintenance, Monitoring, and Traffic. The Administration, Maintenance, and Monitoring modules are all found in Volume 1 of the Primary Data Set, while the Traffic module is found in Volume 4 of the Primary Data Set (Long-Term Pavement Performance Database 2012). Table 3.1 summarizes the modules and corresponding tables utilized for data extraction. It is important to note that certain tables may be listed under several modules in order to ease data extraction. For example, the EXPERIMENT_SECTION table is found in both the Maintenance and in the Administration modules (Long-Term Pavement Performance Database 2012).

Since the data from the LTPP DVD comes in a format readable by Microsoft Access, the majority of data extraction, filtering, linking, and elimination took place in Microsoft Access 2010. For instance, custom queries in the program were designed to link information that is common in two data tables that reside in different parts of the LTPP database. Often, the results of such Microsoft Access queries were converted to a Microsoft Excel 2010 file in order to sort, filter, and model the data further.

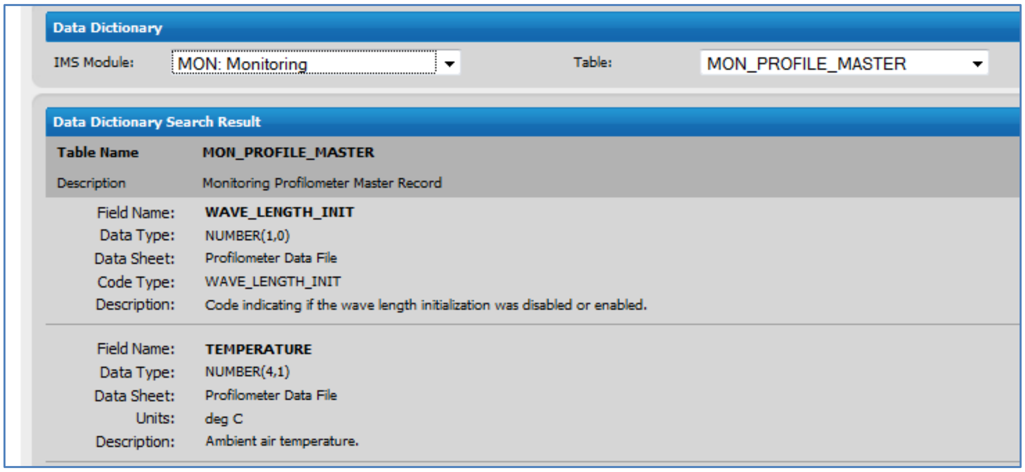
Table 3.1 Summary Modules and Data Tables Used for Data Extraction (Long-Term Pavement Performance Database 2012)

Module	DVD Source	Table Name
Maintenance (MNT)	Volume 1, Primary Data Set	EXPERIMENT_SECTION
		MNT_COST
Administration (ADM)	Volume 1, Primary Data Set	REGIONS
		SECTION_LAYER_STRUCTURE
Monitoring (MON)	Volume 1, Primary Data Set	MON_PROFILE_MASTER
Traffic (TRF)	Volume 4, Traffic Data	TRF_ESAL_COMPUTED
		TRF_MON_EST_ESAL

Because data within the LTPP database is often referenced using numerical codes and combinations of letters and numbers, the LTPP online tool, LTPP DataPave Online, was used for navigating tables and finding the appropriate data for extraction. Three main tools from LTPP DataPave Online include the Table/Field Navigator, the Data Dictionary, and Data Codes (LTPP DataPave Online: Data Extraction Tools 2011).

The Table/Field Navigator is a tool that allows the user to search for a specific string that is used to designate a certain table or a column heading within a table. Column headings in LTPP are referred to as “fields,” and if the unique name of the field is known, the Table/Field Navigator can be used to search for the location of that field within a table and module (LTPP DataPave Online: Data Extraction Tools 2011).

The Data Dictionary is an interactive tool that directs the user to detailed descriptions of fields within a certain table and module. The Data Dictionary includes a drop-down menu that allows the user to first select the module, and then, within that module, the table of interest. The search result yields a list of all fields in that particular table, and a brief description of the information in the field, such as the units used to report values in that field (LTPP DataPave Online: Data Extraction Tools 2011). Figure 3.1 is a snapshot of the Data Dictionary and part of the search results that come up when the user searches for the MON_PROFILE_MASTER table within the Monitoring module. A detailed description of modules and data tables is included in Sections 3.1.1 through 3.1.4 of this chapter.



IMS Module: MON: Monitoring
Table: MON_PROFILE_MASTER

Table Name **MON_PROFILE_MASTER**
Description Monitoring Profilometer Master Record

Field Name: **WAVE_LENGTH_INIT**
Data Type: NUMBER(1,0)
Data Sheet: Profilometer Data File
Code Type: WAVE_LENGTH_INIT
Description: Code indicating if the wave length initialization was disabled or enabled.

Field Name: **TEMPERATURE**
Data Type: NUMBER(4,1)
Data Sheet: Profilometer Data File
Units: deg C
Description: Ambient air temperature.

Figure 3.1 Snapshot of a Data Dictionary Query from LTPP DataPave Online (LTPP DataPave Online: Data Extraction Tools 2011)

Data Codes is another interactive tool that facilitates data extraction by explaining the meaning of the single- and double- digit numerical data codes that are listed under certain fields in a given table. For example, if the user opens the EXPERIMENT_SECTION table under the Maintenance module, numerical codes for the type of maintenance activity will be provided under the field CN_CHANGE_REASON. Data Codes allows the user to search for a detailed explanation of these numerical codes. Figure 3.2 provides a quick glance of the search results when the user searches for the code descriptions under the field MAINT_WORK.

Code Name: MAINT_WORK

● Code
○ Description

Code	Description
1	Crack Sealing (linear ft.)
10	AC Shoulder Restoration (sq. yards)
11	AC Shoulder Replacement (sq. yards)
12	Grinding Surface (sq. yards)
13	Grooving Surface (sq. yards)
14	Pressure Grout Subsealing (no. of holes)
15	Slab Jacking Depressions (no. of depressions)

Figure 3.2 Snapshot of a Data Codes Query from LTPP DataPave Online (LTPP DataPave Online: Data Extraction Tools 2011)

3.1.1. Maintenance

Using the Maintenance module was the first key step in data extraction. Within this module, the table EXPERIMENT_SECTION contains information about all construction activities that took place on all LTPP sections. These construction activities are tallied using the single-digit data code Construction Number (CN). The construction number is indicative of how many times a particular section has been maintained or rehabilitated. When the section is first introduced into the LTPP program, it is assigned a CN of 1, and every time the section undergoes a maintenance or rehabilitation activity, the CN is updated by an increment of one. Each incremental change in CN is accompanied by a date that indicates when the change took place and by another indicator – CN_CHANGE_REASON – that assigns a single- or double- digit numerical code to the type of activity performed (LTPP DataPave Online: Data Extraction Tools 2011).

3.1.2. Administration

The REGIONS table from the Administration module links the state identification numbers, described in Chapter 2, to a specific climatic region. Each climatic region is assigned a one-digit number (LTPP DataPave Online: Data Extraction Tools 2011). The REGIONS table was used to link all sections – control and chip seal – to a specific climatic region. Table 3.2 summarizes the numerical codes LTPP assigned to the four climatic regions.

Table 3.2 Numerical Codes for the Climatic Regions in the LTPP Database (LTPP DataPave Online: Data Extraction Tools 2011)

CLIMATIC REGION	CODE DESIGNATION IN LTPP
Dry Freeze	1
Dry Non-Freeze	2
Wet Freeze	3
Wet Non-Freeze	4

3.1.3. Traffic

As described in Chapter 2, chip seals are typically placed on low-volume roads, although they are occasionally used to maintain roads that experience high traffic volumes. In order to investigate this effect, all available annual KESAL values for both chip seal and control sections were extracted from the Traffic module. This process involved two tables – TRF_ESAL_COMPUTED, and TRF_MON_ANL_KESAL. The first respective table provides a calculated annual KESAL value per LTPP lane-year for a given section, under the field KESAL_YEAR. The second table reports the measured annual KESAL value per LTPP lane-year under the field ANL_KESAL_LTPP_LN_YR (LTPP DataPave Online: Data Extraction Tools 2011). Because computed and/or reported KESAL measurements were not always available for a given section, the KESAL values and corresponding dates were carefully linked to the dates of IRI measurements, as discussed in Section 3.2.3.1 of this Chapter.

3.1.4. Monitoring

The Monitoring module is the largest of all modules within LTPP (Elkins, et al. 2003).Within this module, MON_PROFILE_MASTER is a comprehensive table that contains all information about roughness measurements. The table includes the date and time of the roughness measurement, the lane, length covered and direction of travel, the cloud cover and temperature at the time of measurement, and IRI measurements for the left, -and right wheel paths, as well as the average IRI based on these two wheel paths. For any particular section, the

IRI measurements are grouped by date, and the several daily measurements are listed in order. Monitoring of roughness typically took place yearly, although for some chip seal and control sections, measurements may have been reported for several months during the same year, or no measurements may have been reported for a number of consecutive years (Long-Term Pavement Performance Database 2012).

3.2. Data Collection Methods

In order to collect as much data as possible nationwide, this study did not make a distinction between sections that belong to an SPS or a GPS study. Rather, all sections that fell into the selection criteria, as described in the following sections, were considered, regardless of project affiliation. Since the number of chip seal sections in the United States was limited to only 231 sections (Long-Term Pavement Performance Database 2012), placing further restrictions based on project types would have limited the useable data. In order to stay consistent, the SPS and GPS designation of control sections was also disregarded during the selection process.

3.2.1. Extraction of Chip Seal Sections

Chip seals are indicated by two maintenance codes – 28 and 31 – in the EXPERIMENT_SECTION table, under CN_CHANGE_REASON. Twenty-eight indicates a single layer surface treatment and thirty-one indicates an aggregate seal coat (LTPP DataPave Online: Data Extraction Tools 2011). These two data codes were the key to extracting all chip seal sections for consideration. It is important to note that under the field CN_CHANGE_REASON, the numbers 28 and 31 may be linked with several other codes for other types of maintenance and rehabilitation. For example, a chip seal section may be listed as “28, 25” where the number 28 indicates the chip seal treatment, and 25 indicates patching of potholes by hand spreading and compacting by truck (LTPP DataPave Online: Data Extraction Tools 2011). In order to solely investigate the effect of chip seal, sections that had other maintenance or rehabilitation activities listed in conjunction with chip seal were not extracted.

3.2.2. Extraction of Control Sections

Control sections were also selected using the CN_CHANGE_REASON indicator. In the case of control sections, this indicator remains blank meaning that no maintenance or rehabilitation activity has been performed on that section, or that no such activity was reported in the database. Because the EXPERIMENT_SECTION table is comprehensive for both flexible and rigid pavements, the control sections selected this way had to go through a crucial filtering process that determined whether the pavement section in question is flexible or rigid. Chip seals did not have to be filtered this way because chip seals are known to be applied to flexible pavements only.

For the control sections, the screening for surface type was done using the table called SECTION_LAYER_STRUCTURE from the Administration module. This table assigns each LTPP section a 2-letter code that indicates the pavement surface type (LTPP DataPave Online: Data Extraction Tools 2011). When filtering out control section candidates, only sections that also had the designation AC – for asphalt concrete – were selected for further consideration. While this may seem like a redundant selection step, oversight of this important information could have led to invalid comparisons of flexible chip seal and rigid control sections. The layer type information is not inherently incorporated into the section identification number, and therefore there is no way to identify a control section candidate as flexible unless this step is incorporated into the filtering process.

3.2.3. Organization of Roughness Data

Once the chip seal and control sections were identified using the extraction criteria described previously in Sections 3.2.1 and 3.2.2, the next step was to extract all available roughness data for those sections. The approach used was to collect all roughness data for all available years for both chip seal and control sections, and then further break down that information based on available traffic data and maintenance and rehabilitation history.

For both chip seal and control sections, roughness data was extracted using two layers of averaging. First, for all roughness measurements on a certain date, the measurements between the left wheel path and the right wheel path were averaged, yielding a single average roughness value. The standard deviation between the measurements from the left and right wheel paths was negligible, and therefore this averaging was deemed acceptable. Since several roughness measurements are reported per monitoring date, the daily IRI measurements for a single date were also averaged, so that a single date was linked to a single roughness value.

Table 3.3 presents an example of averaging roughness data this way for chip seal section 41034, located in Arizona, between years 1990 and 1991.

Table 3.3 Example of Averaging Roughness Data (Long-Term Pavement Performance Database 2012)

State Code	SHRP ID	Profile Date	IRI Left Wheel Path (m/km)	IRI Right Wheel Path (m/km)	IRI Average (m/km)	Average IRI Per Date (m/km)
4	1034	26-Mar-90	0.923	1.484	1.203	1.1464
4	1034	26-Mar-90	0.967	1.307	1.137	
4	1034	26-Mar-90	0.94	1.392	1.166	
4	1034	26-Mar-90	0.929	1.309	1.119	
4	1034	26-Mar-90	0.977	1.238	1.107	
4	1034	13-Mar-91	1.044	1.042	1.043	1.0614
4	1034	13-Mar-91	1.078	1.125	1.101	
4	1034	13-Mar-91	1.083	1.021	1.052	
4	1034	13-Mar-91	1.102	1.026	1.064	
4	1034	13-Mar-91	1.062	1.03	1.047	

3.2.3.1 Linking Roughness Data to Available Traffic Data

After averaging all available roughness data for all control and chip seal sections, the years of roughness measurements were linked to the years that KESAL values – either reported, computed, or both – were available. The typical trend in traffic data was that if measured traffic data was not available for a specific year, then the computed traffic levels were reported, and vice versa. In cases where both computed and measured traffic data was available, measured traffic was taken to override computed traffic. The computed and measured traffic values were not always consistent; it was observed that several sections had a computed annual traffic value of, say, 35 KESALs per LTPP lane-year, while the measured annual traffic value reported may have been, say, 150 KESALs per LTPP lane-year.

All traffic data was averaged across the years that it was available, in order to estimate the traffic levels at each control and chip seal section. While this approach disregards traffic growth or decline rates, it gives a qualitative idea of whether a particular section was experiencing light or heavy traffic during the years that are considered in the analysis. Table 3.4 illustrates the concept of combining and averaging computed and measured traffic data for two control sections in the Dry Non-Freeze climatic zone. All KESAL values in the table are per LTPP lane-year. The blank spaces in the table indicate missing or unreported data.

Table 3.4 Example of Combining and Averaging Traffic Data (Long-Term Pavement Performance Database 2012)

ST_CODE	SHRP_ID	Computed Annual KESALs	Measured Annual KESALs	Combined Annual KESALs	Average of Combined Annual KESALs
6	7454	11		11	15.3
6	7454	4		4	
6	7454		18	18	
6	7454		18	18	
6	7454		19	19	
6	7454		17	17	
6	7454		20	20	
6	8153	18		18	21.8
6	8153	9		9	
6	8153	11		11	
6	8153		37	37	
6	8153		34	34	

Linking roughness data to available traffic data cut down the number of available roughness data points by about 20 percent. For example, if a section, either control or chip seal, had ten years' worth of roughness data available, but it had only eight years' worth of traffic data available, then the two years where traffic data were not reported were excluded from the roughness data. This step entirely eliminated sections without traffic information and created some "holes" in the available roughness data. However, it was observed that whenever traffic data happened to be reported for a given section, the values were typically reported for a number of years. This provided a good link between the available roughness data and traffic data. Figure 3.3 illustrates a schematic of the process of linking roughness data to traffic data.

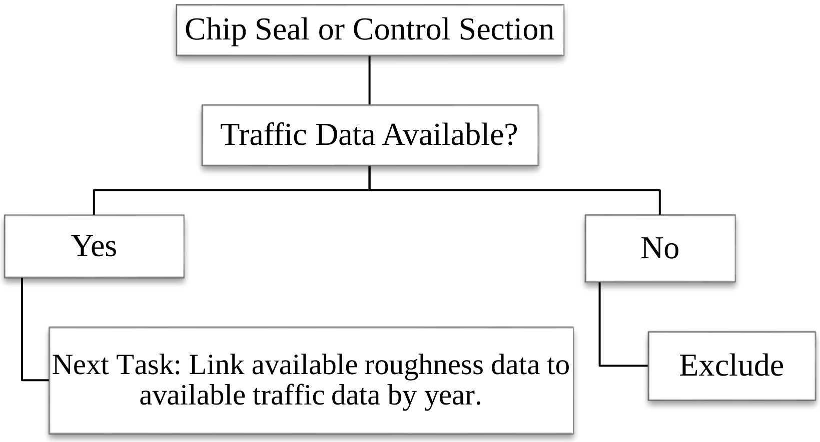


Figure 3.3 Schematic of Refining Roughness Data Based on Available Traffic Data

3.2.3.2 Filtering of Roughness Data for Chip Seal Sections Based on Maintenance and Rehabilitation History

Once all roughness data was linked to traffic data, the selection of control sections was complete. However, all roughness data for chip seals was further refined based on the individual maintenance or rehabilitation history of each section. The objective of this process was to isolate time intervals where the effectiveness of chip seal treatment could be evaluated. This time interval typically involved three dates: the date of construction, the date of chip seal treatment, and the last date of reported roughness measurement after chip seal but prior to the next rehabilitation or maintenance event, if any.

It was noted that regardless of climatic region, about half of the chip seal sections did not undergo rehabilitation or maintenance after the chip seal date. Sections that were chip sealed in the early to middle 1990s were more likely to receive maintenance or rehabilitation after chip seal. However, in all cases, measuring the effectiveness of chip seal treatment was contingent upon the roughness data available on and after the date of chip seal treatment. For chip seal sections that received treatment after, say, year 2000, fewer roughness data points were available, since most chip seal sections in the United States were removed from LTPP monitoring by year 2005 (Long-Term Pavement Performance Database 2012). Table 3.5 summarizes the removal dates of chip seal sections from the LTPP monitoring program.

Table 3.5 Summary of Number of Chip Seal Sections in LTPP Database throughout the Past Two Decades (Long-Term Pavement Performance Database 2012)

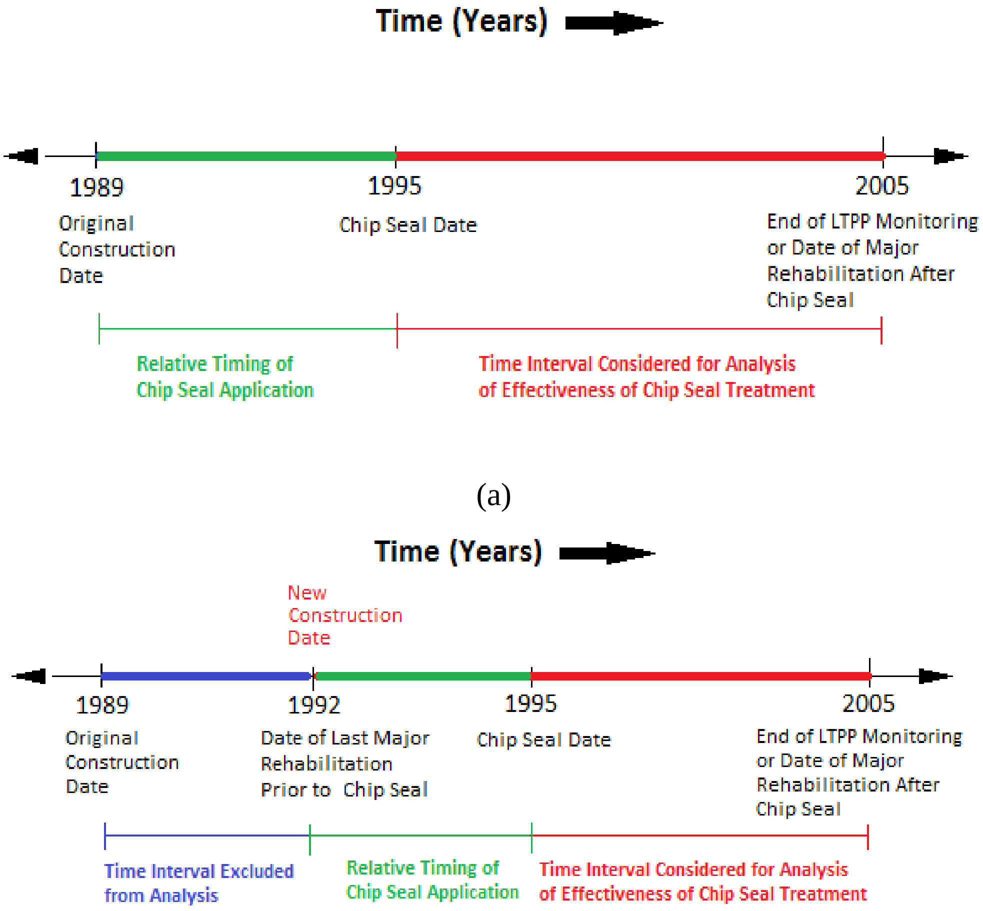
Date Interval	Number of Chip Seal Sections Removed from LTPP Program	Number of Chip Seal Sections Active in LTPP Program
1990-1995	17	214
1996-2000	72	142
2000-2005	37	105
2006-2009	46	59

When selecting the roughness data of chip seal sections for further analysis, the construction and maintenance history had to be examined in detail. Chip seal sections can be divided into two major categories: (1) sections that were originally constructed and then chip sealed sometime later, and (2) sections that were originally constructed, rehabilitated sometime after construction, and then chip sealed sometime after the rehabilitation.

For sections whose maintenance and rehabilitation history follows the first scenario, all available IRI information, ranging between the date of original construction and the end of the LTPP monitoring was kept. If the chip seal section experienced maintenance or rehabilitation *after* the date of chip seal application, roughness data was considered up until the next maintenance or rehabilitation date. That date can be thought of as an “IRI cut-off date” because no roughness data beyond that date was considered for analysis. For chip seal sections that received multiple chip seal treatments, the IRI cutoff date was set as the date of the second chip seal treatment. Such constraints ensured that only one application of chip seal is analyzed.

For sections whose maintenance and rehabilitation history follows the second scenario, the date of latest rehabilitation prior to chip seal was considered as the “new construction date.” For example, if a chip seal section was originally constructed in 1989, an overlay was applied in 1992, followed by chip seal in 1995, then the new construction date was selected to be 1992, and the treatment was considered to be applied after 3 years, as opposed to after 6 years.

Figure 3.4 (a) and (b) illustrate the timing of chip seal application relative to construction activities.



(a)

(b)

Figure 3.4 Maintenance and Rehabilitation Timing Scenarios for Chip Seal Sections with (a) No Major Rehabilitation Prior to Treatment, (b) Rehabilitation Prior to Treatment

3.3. Data Organization

3.3.1. Data Organization of Individual Sections

Once a pool of chip seal and control sections that satisfy the aforementioned criteria was compiled, individual sections were further organized according to state code, SHRP identification number, and the date of roughness measurement, also known as profile date. This sequence put the roughness data and traffic history of individual sections in chronological order and made it easier to view the available number of roughness data points per section, state, and climatic region.

3.3.2. Data Organization of Collections of Sections

The climatic region classification was the largest dividing factor between all sections. Next, all sections within each climatic region were further classified based on initial roughness criteria.

All sections were categorized into groups of pavements whose estimated initial condition was (1) smooth, (2) medium, or (3) rough. The ranges for smooth, medium, and rough condition were introduced based upon the range of estimated initial conditions in the existing data. From an initial assessment, it was determined that the low end of this range is around 40 inches per mile, while the high end of the range is above 160 inches per mile. From these ranges, three even divisions of initial IRI values, as illustrated in Table 3.6, were introduced as follows:

- Sections whose initial condition fell between 40-80 inches per mile were considered smooth.
- Sections whose initial condition fell between 80 and 120 inches per mile were considered medium.
- Sections whose initial condition fell between 120 and 160 inches per mile were considered rough. This category also included a few sections with IRI values above 160 inches per mile.

Table 3.6 Initial Condition Ranges Used in Analysis

Interval of Initial Roughness (in/mile)	Initial Pavement Condition Classification
40-80	Smooth
80-120	Medium
120-160+	Rough

Estimating initial roughness was done by modeling the roughness data for each section individually. Initial roughness in this modeling context is equivalent to the y-intercept of the best-fit exponential regression for a set of consecutive roughness measurements. Equation 2.1 is the built-in function for exponential approximations in Microsoft Excel 2010. This function was used to individually model the roughness data for each section. The alpha and beta parameters, along with the R-squared value, were recorded for each section. The value of the alpha parameter was then used to categorize each section into an initial condition category.

CHAPTER 4. ANALYSIS METHODS AND RESULTS

4.1. Analyzing Treatment Effectiveness

When analyzing the effectiveness of a preventive maintenance treatment, the two key indicators of benefit are (1) life extension and (2) relative benefit.

Life extension is defined as the added pavement life due to a maintenance or rehabilitation treatment. It is essentially the difference between pavement life with treatment and without treatment. Obviously, a larger life extension implies a more beneficial treatment.

As described in Chapter 2, the effectiveness of a treatment can also be measured by the area bound by the performance curve and some arbitrary threshold value. The effectiveness of both treated and untreated sections can be evaluated this way. When the treated and untreated curves are superimposed on the same graph, the difference between the two areas is referred to as Benefit Area (B) (Dawson, et al. 2011). The area bound by the performance curve for untreated pavements and the arbitrary threshold value is called Do-Nothing Area (A) (Dawson, et al. 2011). Relative benefit is simply the ratio of B to A, expressed as a percentage; a higher percentage translates to more beneficial treatment. Equation 4.1 is the expression for relative benefit, and Figure 4.9 graphically illustrates the general concept of relative benefit.

$$Relative\ Benefit = \left(\frac{B}{A}\right) \times 100 \qquad (4.1)$$

where:
B = Benefit Area of Treatment
A= Do-Nothing Area (Hajj, et al. 2011; Loria, et al. 2012)

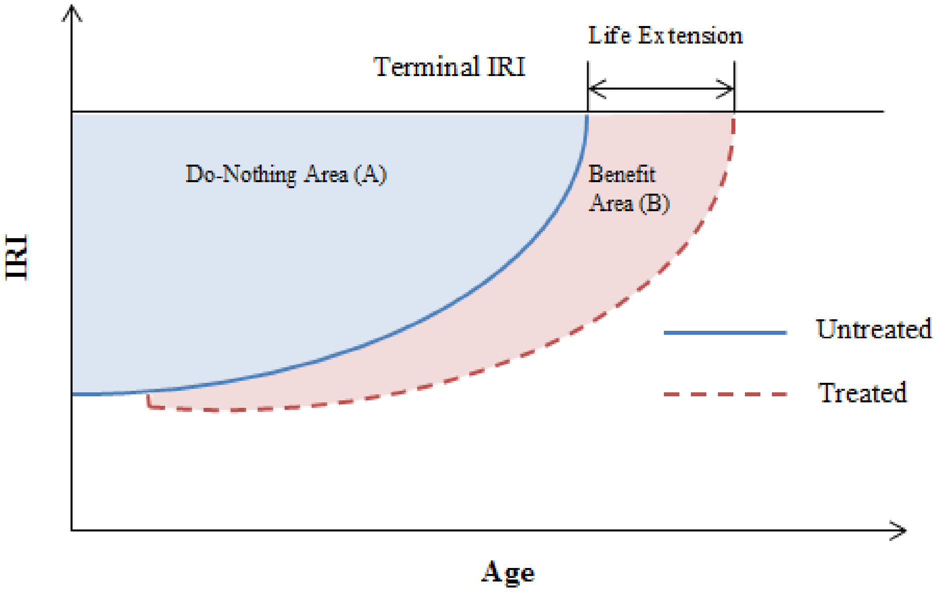


Figure 4.1 General Representation of Relative Benefit and Life Extension

Life extension and relative benefit are a function of both the *condition* of the pavement at the time of treatment and also of the *timing* of the treatment. As emphasized in Chapter 2, the benefit of preventive maintenance is maximized when the treatment is applied early in the life of the pavement, when the condition is still reasonably good. Relative benefit and life extension both *decrease* as the timing of preventive maintenance *increases*. For example, the relative benefit of a chip seal applied seven years after an overlay is not going to be as significant as the relative benefit of the same treatment applied at, say, three years. Using the same example, the life extension of a chip seal applied at three years, is expected to be greater than the life extension due to a chip seal applied at seven years. A larger life extension typically accompanies a greater relative benefit.

4.1.1. Treatment Timing-Based (TT) Analysis

The conventional way of analyzing treatment effectiveness considers a constant do-nothing area (A) and compares the benefit area (B) to this value when the treatment is applied at different times. This way, since A stays constant but B decreases with time, the relative benefit also decreases with treatment timing, as expected. For example, when considering three treatment timings in chronological order, the benefits associated with each are B_1, B_2, and B_3, where B_1 is the benefit associated with the earliest treatment timing. Each of these benefit areas is bound by the treatment curve, the do-nothing curve, and the threshold value, such that $B_1>B_2>B_3$. Consequently, later treatment timing not only affects the benefit but also shortens the life extension attributed to the treatment. Figure 4.2 illustrates the conventional, treatment timing-based method of relative benefit analysis.

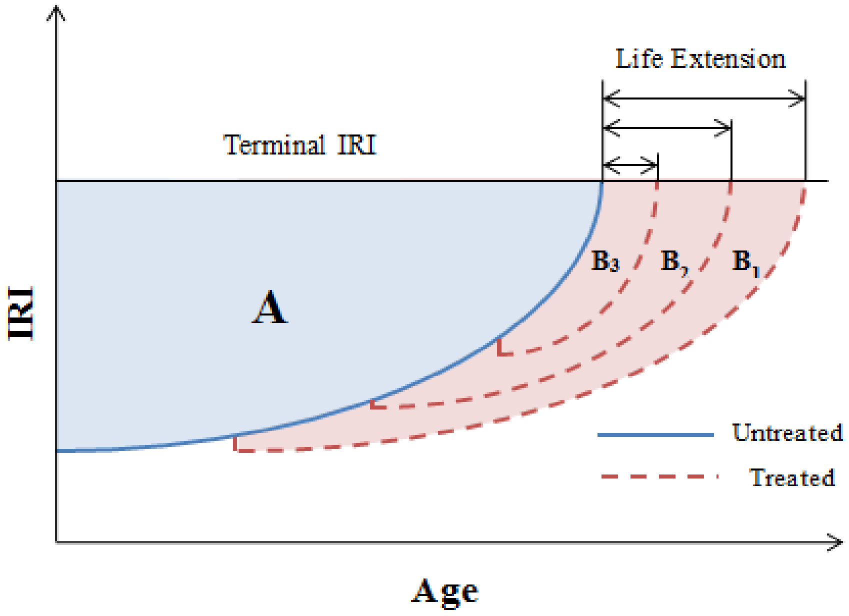


Figure 4.2 Relative Benefit and Life Extension with Respect to Treatment Timing

4.1.2. Initial Condition-Based (IC) Analysis

The initial condition-based (IC) method of analysis, as developed for this study, disregards treatment timing and instead looks at treatment benefits based on initial pavement condition at the time of treatment. The main distinction between the TT and IC analysis methods is rooted in how the two methods look at pavement life. The TT analysis considers pavement life as a whole, from construction until the pavement reaches unserviceable condition. In the TT method, pavement life may be extended by applying treatment at an arbitrary time, as discussed earlier in Section 4.1.1.

The IC method relies on the *remaining pavement life* relative to the condition of the pavement at the time of treatment. For example, if the pavement is smooth at the time of treatment, then the remaining pavement life is essentially equivalent to the total pavement life, say 20 years. When the pavement is already in medium-roughness condition, it is assumed that some time has passed since construction, and the remaining pavement life decreases to, say, 10-15 years. Finally, when the pavement is in rough condition, remaining pavement life is expected to be, say, 3-6 years.

Figure 4.3 illustrates the concepts of relative benefit and life extension for chip seal based on the IC analysis method, with the three initial condition cases superimposed onto the same graph.

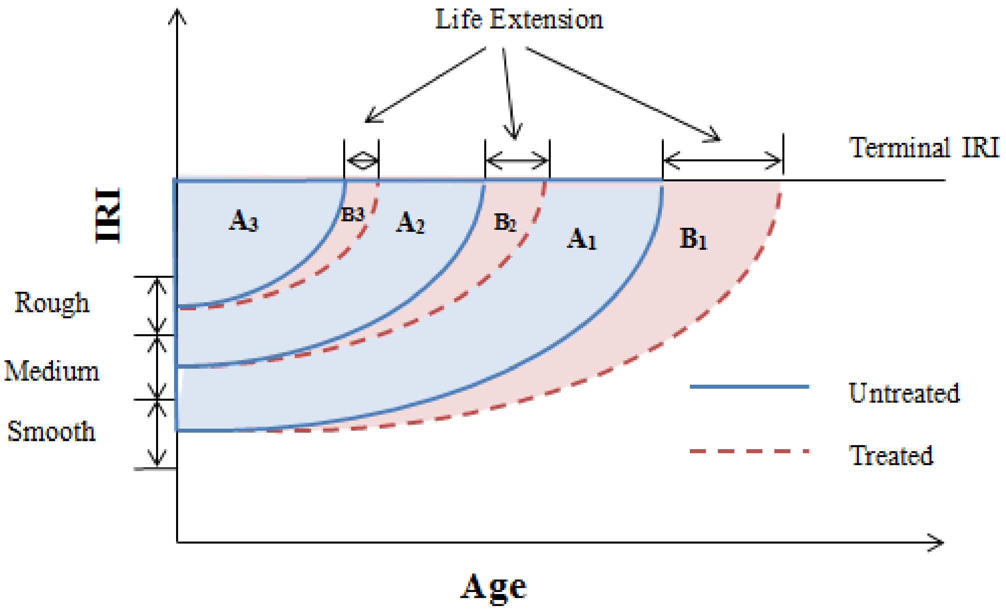


Figure 4.3 Relative Benefit and Life Extension with Respect to Initial Pavement Condition

In the IC analysis, the relative benefit that is calculated simply serves as a comparison between the effectiveness of the treatment against an untreated pavement in that same condition. This methodology compares pavement life and effectiveness with and without treatment, assuming that the treatment curve and the do-nothing curve both start at time=0, regardless of when the treatment was truly applied. This way, treatment timing is taken out of the analysis and the estimated pavement life and benefits – both life extension and benefit area – are simply based upon the initial pavement condition.

Using the IC analysis method, it is expected that *remaining pavement life* for both the treated and untreated sections will be largest for smooth pavements, smallest for rough pavements, and the remaining pavement life of medium pavements will fall somewhere in-between. Moreover, instead of staying constant, the do-nothing area (A) for the control curve will also be significantly smaller as moving from smooth, to medium, then to rough initial condition.

When considering the relative benefit of chip seal on pavements in different conditions, the benefit areas can be labeled as B_1, B_2, and B_3, for smooth, medium, and rough initial conditions, respectively. Similarly, the do-nothing areas can be labeled as A_1, A_2, and A_3, for smooth, medium, and rough pavements, respectively. The benefit areas are always bounded by the treated performance curve, the corresponding untreated performance curve, and the threshold value, such that $B_1>B_2>B_3$. The do-nothing areas are always bounded by the untreated performance curve and the threshold value, such that $A_1>A_2>A_3$. This way, the relative benefit can still be expressed as B_1/A_1, B_2/A_2, and B_3/A_3, for smooth, medium, and rough initial conditions, respectively. It must also be emphasized that because of the decrease in relative benefit from B_1 to B_2 to B_3, the life extension is also expected to decrease in a similar fashion.

4.1.3. Reason for Choosing Initial Condition-Based Method

An attempt was first made to investigate the effect of treatment timing on relative benefit and life extension using the TT method, and to relate these results to traffic levels. This approach required the data within each climatic region to be broken down further into two levels of traffic – high and low – and within those divisions, into five subcategories of treatment timing – 0, 1, 3, 5, and 7+ years. With these restrictions in all four climates, this breakdown of the data required 40 subdivisions, eight of which did not have any chip seal data available and had very limited control data available to begin with.

In addition, large scatter was observed in both the chip seal and control data, especially in terms of starting IRI, and trying to pinpoint the optimal treatment timing did not lead to sound conclusions. The uneven number of sections and data points in all subcategories grouped this way did not allow for fair comparisons. For instance, the results from one subcategory may have been based on one or two sections, while the results for another subcategory may have been based on ten or more sections. Moreover, in some subcategories, the cumulative set of data points did not produce the clearly increasing trend described by Equation 2.1. This initial approach and intricate breakdown led to the hypothesis that if the data were regrouped differently, excluding treatment timing and traffic levels, more sound conclusions would result.

In order to still utilize the extracted data effectively, treatment timing was disregarded from the analysis, and relative benefit and life extension were only investigated based upon initial pavement condition, using the IC method. Since the IC method can still demonstrate a relative comparison between the effectiveness of treated and untreated pavements, it was chosen as the basis for further assessment and final data elimination.

4.2. Assessment of Extracted Data and Final Elimination Process

The assessment of the extracted data was a twofold process. First, the roughness data for all sections individually was modeled and assessed, and eliminations were made as necessary. Second, the remaining data points were graphed collectively to determine whether any more sections need to be eliminated in order to arrive at conclusive results.

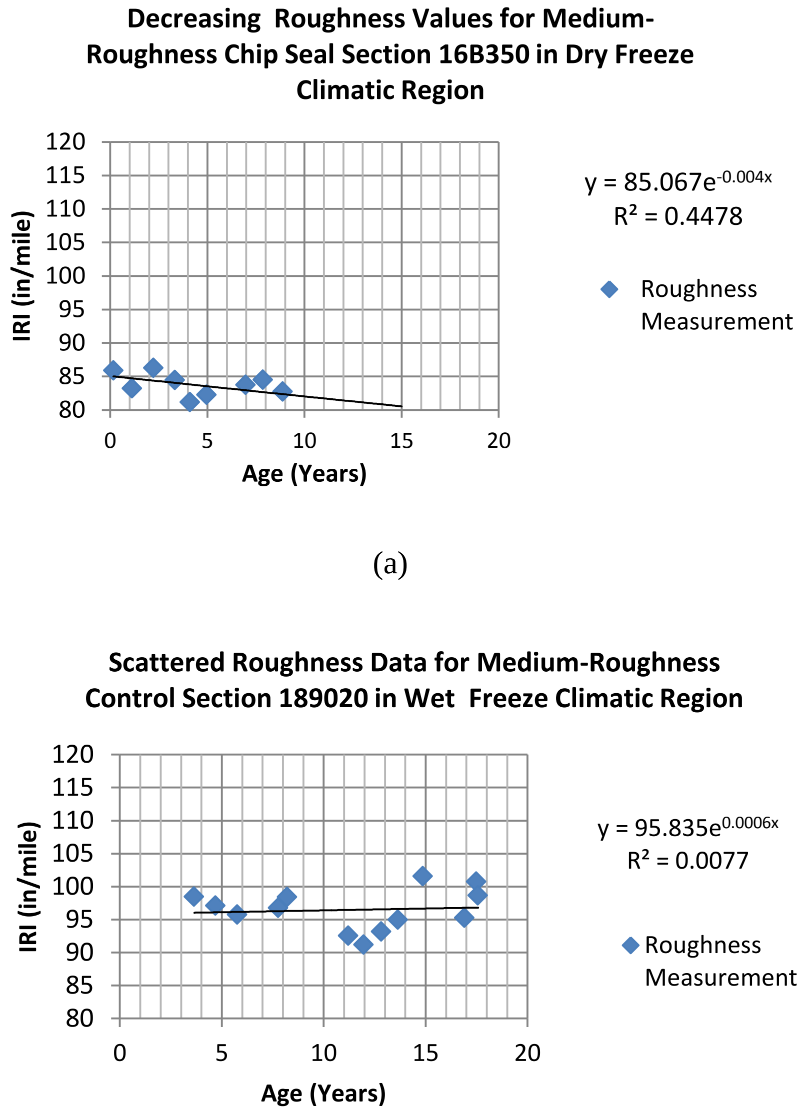
4.2.1. Visual Assessment and Modeling of Individual Sections

In order to be used correctly, the regression Equation 2.1 from Chapter 2 requires that at least three data points be used (Haider and Dwaikat 2011). Therefore, before proceeding to analyze sections individually, all sections that had fewer than three data points were eliminated.

Next, modeling of individual sections showed that several sections had scattered roughness data that was not accounted for in the construction or maintenance history. For example, a few sections exhibited one or more downward performance jumps that did not correspond to any reported rehabilitation or maintenance activity in the Administration module under CN_CHANGE_REASON. This was especially true for control sections; in some cases, unreported decreases in roughness data were observed, even though the Construction Number stayed equal to one.

Furthermore, some sections exhibited an overall “downward” trend in roughness with time. Generally, it is expected that if nothing is done to the pavement, roughness will gradually increase over time; in fact, in order to use the exponential roughness model (Equation 2.1) to represent this *expected* performance, an overall increase in roughness, indicated by a positive beta value, is required.

Visual inspection of every single section was necessary to determine whether it would be appropriate to include the section in the collective analysis. This was done simultaneously as the alpha, beta, and R^2 values for each section were recorded. The visual elimination method coincided with the mathematical model because sections whose roughness data exhibited a downward trend had a negative beta value and, generally, a low R^2 value, indicating a poor goodness of fit between observed and predicted values. Figure 4.4 illustrates an example of two sections whose roughness data was eliminated via visual inspection. The R^2 value in Figure 4.4 represents the goodness of fit between the actual data points and the predicted exponential model.



(a)

(b)

Figure 4.4 Examples of Sections Eliminated by Visual Inspection for (a) Decreasing Trend in Roughness and (b) Scattered Roughness Data

4.2.2. Final Selection Based on Comparable Model Parameters

After data extraction was complete, it was noted that overall, the number of control sections and control roughness data points for far outweighed the number of roughness data points available for chip seal. This is due to the fact that the LTPP database only has records of 231 chip seal sections for the entire United States, a number of which had been eliminated prior to final analysis because of either the absence of traffic information or the scatter of individual roughness data. The abundance of control roughness data points compared to chip seal data points allowed for further elimination of control sections in order to arrive at a more accurate collective comparison between chip seal and control. Of the 231 chip seal sections, only 118 were utilized in this study. Table 4.1 summarizes the number of chip seal and control sections used in this study. Table 4.2 summarizes the number of chip seal and control IRI data points used in this study.

Table 4.1 Summary of Number of Sections Used in this Study

Climatic Region	Section Type	Number of Sections Used		
		Initial Condition		
		Smooth	Medium	Rough
Dry Freeze	Chip Seal	26	7	3
	Control	33	6	3
Dry Non-Freeze	Chip Seal	6	8	3
	Control	45	7	1
Wet Freeze	Chip Seal	20	16	3
	Control	27	7	2
Wet Non-Freeze	Chip Seal	15	6	5
	Control	40	23	2

Table 4.2 Summary of Number of IRI Data Points Used in this Study

Climatic Region	Section Type	Number of Data Points Used		
		Initial Condition		
		Smooth	Medium	Rough
Dry Freeze	Chip Seal	158	36	13
	Control	257	42	19
Dry Non-Freeze	Chip Seal	34	43	10
	Control	262	54	8
Wet Freeze	Chip Seal	124	87	13
	Control	125	53	13
Wet Non-Freeze	Chip Seal	62	20	17
	Control	216	133	6

While the number of sections and data points per initial condition category is comparable for some climatic regions, large differences can be observed in several cases. For example, after elimination, in the Dry Non-Freeze, smooth initial condition category, only 6 chip seal sections were used, against 45 control sections. This leads to a comparison of 34 chip seal data points against 262 control data points. The same trend is evident in the Wet Non-Freeze region, medium-smoothness category, where 6 chip seal sections were evaluated against 23 control sections, resulting in a comparison of 20 chip seal data points against 133 control data points. A more even distribution of sections and number of data points would be desirable, and preferable, in order to draw the fairest comparisons between chip seal and control sections.

The rough initial condition category in each climatic region had the fewest control and chip seal sections and data points, and the numbers of sections and data points were comparable. It is important to note, however, that in the Dry Non-Freeze, rough initial condition category, 3 chip seal sections were evaluated against only 1 control section. In a case like this, the results of the analysis are dominated by the characteristics of the few sections that happen to be available.

The number of sections, and correspondingly, the number of data points generally decrease between the smooth, medium, and rough categories, respectively. This observation supports the fact that chip seal treatment is applied to pavements in either smooth, or medium initial condition, and it is rarely applied on rough pavements.

It is important to note, however, that in many cases, the number of sections and data points is comparable for chip seal and control sections. For example, in the Dry Freeze, medium initial condition category, 7 chip seal sections, with 36 data points, were compared against 6 control sections, with 42 data points. The same is true in the Wet Freeze smooth initial condition category, where 20 chip seal sections and 27 control sections are compared, with 124 chip seal data points, and 125 control data points, respectively. Therefore, in such cases, the comparative analysis between chip seal and control sections is not dominated by the number of available sections or data points.

The mathematical properties of Equation 2.1 were examined to demonstrate how the alpha and beta values in the model translate to the actual performance trends shown by roughness measurements. As discussed earlier in Section 3.3.2, the alpha value is simply equivalent to the y-intercept of the exponential regression. In a practical sense, this translates to the initial roughness value of the pavement at time=0, where the zero could indicate either the date of original construction or the latest rehabilitation prior to chip seal treatment. The regression parameter beta indicates the rate at which the pavement is deteriorating due to increase in roughness with time. The higher the beta value, the more rapidly the slope of the performance curve increases with time, indicating an increasing rate of deterioration with time. Consequently, a higher beta value also corresponds to shorter pavement life. This concept is illustrated in Figure 4.5.

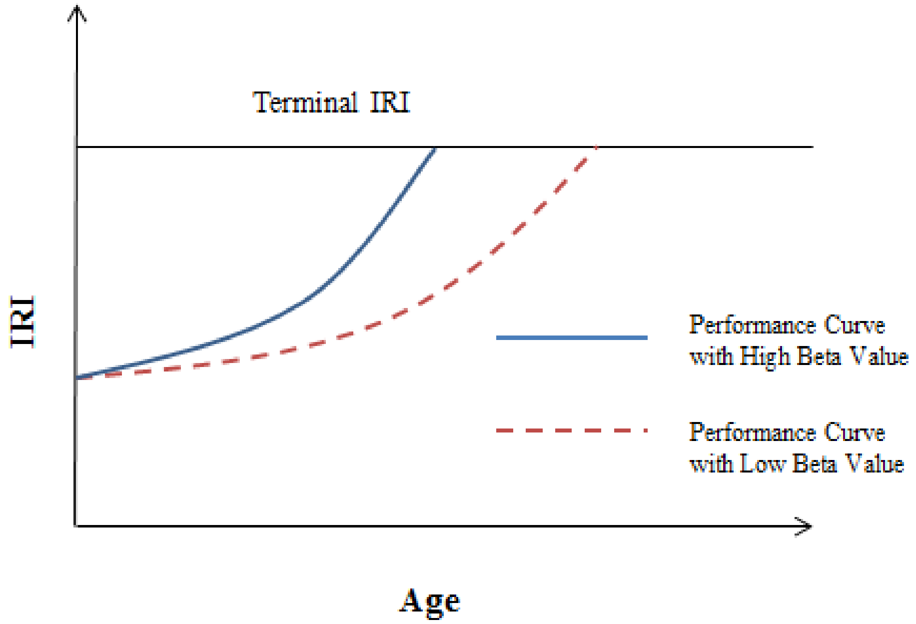


Figure 4.5 Effect of Beta Value on Performance

4.2.3. Collective Modeling

All remaining data points that passed the aforementioned elimination and filtering process were modeled as a whole. Collective modeling involved graphing the roughness data for the pool of sections that fell into the same initial condition category, as described in Table 3.6. The collective set of data points for chip seal were graphed against the collective set of control data points, and final regression models were determined for the data sets as a whole. This step yielded a total of twelve regression models– three per climatic region, for a total of four climatic regions. In each model, remaining pavement life was extrapolated until the performance curve hit an IRI value of 170 inches per mile – a typical terminal roughness value specified by FHWA and adopted by most agencies in the United States (Transportation System Assets: State of the System Report 2002).

Graphing the filtered data as a whole showed expected results overall. The collective regressions for chip seal and control sections in each initial roughness category yielded comparable alpha values, meaning that the initial condition of the selected sections as a whole was approximately the same. Furthermore, in most cases, the regression for the collective set of control data points yielded a slightly higher beta value, indicating that the rate of deterioration of control sections kept increasing with time at a slightly faster rate than chip seal sections. Table 4.3 summarizes the collective performance models for chip seal and control sections.

Table 4.3 Collective Performance Models for Chip Seal and Control Sections

Climatic Region	Initial Condition	Section Type	
		Control	Chip Seal
		Performance Model	Performance Model
Dry Freeze	Smooth	$y = 54.741e^{0.0496x}$	$y = 62.136e^{0.0322x}$
	Medium	$y = 91.354e^{0.0461x}$	$y = 103.930e^{0.0342x}$
	Rough	$y = 138.920e^{0.0505x}$	$y = 181.140e^{0.0591x}$
Dry Non-Freeze	Smooth	$y = 34.449e^{0.1005x}$	$y = 65.051e^{0.0533x}$
	Medium	$y = 90.172e^{0.0512x}$	$y = 97.838e^{0.0403x}$
	Rough	$y = 117.370e^{0.0308x}$	$y = 132.060e^{0.0249x}$
Wet Freeze	Smooth	$y =52.854e^{0.0538x}$	$y = 65.845e^{0.0377x}$
	Medium	$y =104.110e^{0.0460x}$	$y = 97.862e^{0.0416x}$
	Rough	$y = 141.990e^{0.0624x}$	$y = 141.280e^{0.0565x}$
Wet Non-Freeze	Smooth	$y = 57.521e^{0.0490x}$	$y = 64.887e^{0.0353x}$
	Medium	$y = 96.004e^{0.0323x}$	$y = 97.263e^{0.0269x}$
	Rough	$y = 120.810e^{0.0333x}$	$y = 113.450e^{0.0356x}$

It was also observed that even though the initial conditions (alpha values) are approximately the same, slight variations of initial roughness values within the defined intervals still exist. For instance, the initial condition for the smooth category in the Wet Freeze climate is approximately 66 inches/mile for chip seal, while it is only about 53 inches/mile for control. While both of these numbers fall within the initial condition range for smooth pavements, the slight variation in initial roughness causes the performance curves to slightly overlap. This trend is especially apparent in cases where the alpha values of the chip seal and control sections are farther apart. Even if the two curves have a comparable beta value, if the exact initial condition of the curves happens to be significantly different, say, by more than 10-15 inches/mile, then the true benefit of chip seal could not be calculated accurately due to overlapping. Ideally, the collective performance curves for chip seal and control sections should not intersect. Such overlaps could lead to under- or over- estimation of life extension and relative benefit. Therefore, normalization was necessary to even out the variations in initial roughness values as predicted by the collective regression models. Figure 4.6 illustrates an example of overlapping performance curves for chip seal and control sections due to varying initial condition values.

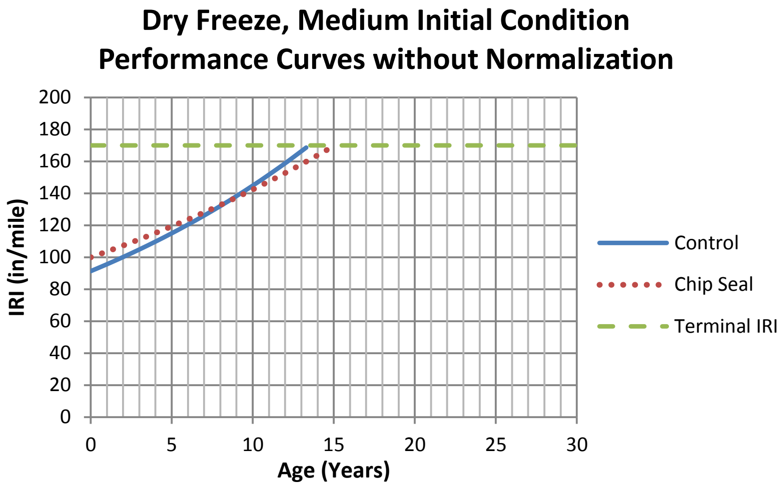


Figure 4.6 Overlapping of Chip Seal and Control Collective Regression Models Due to Variation in Initial Condition

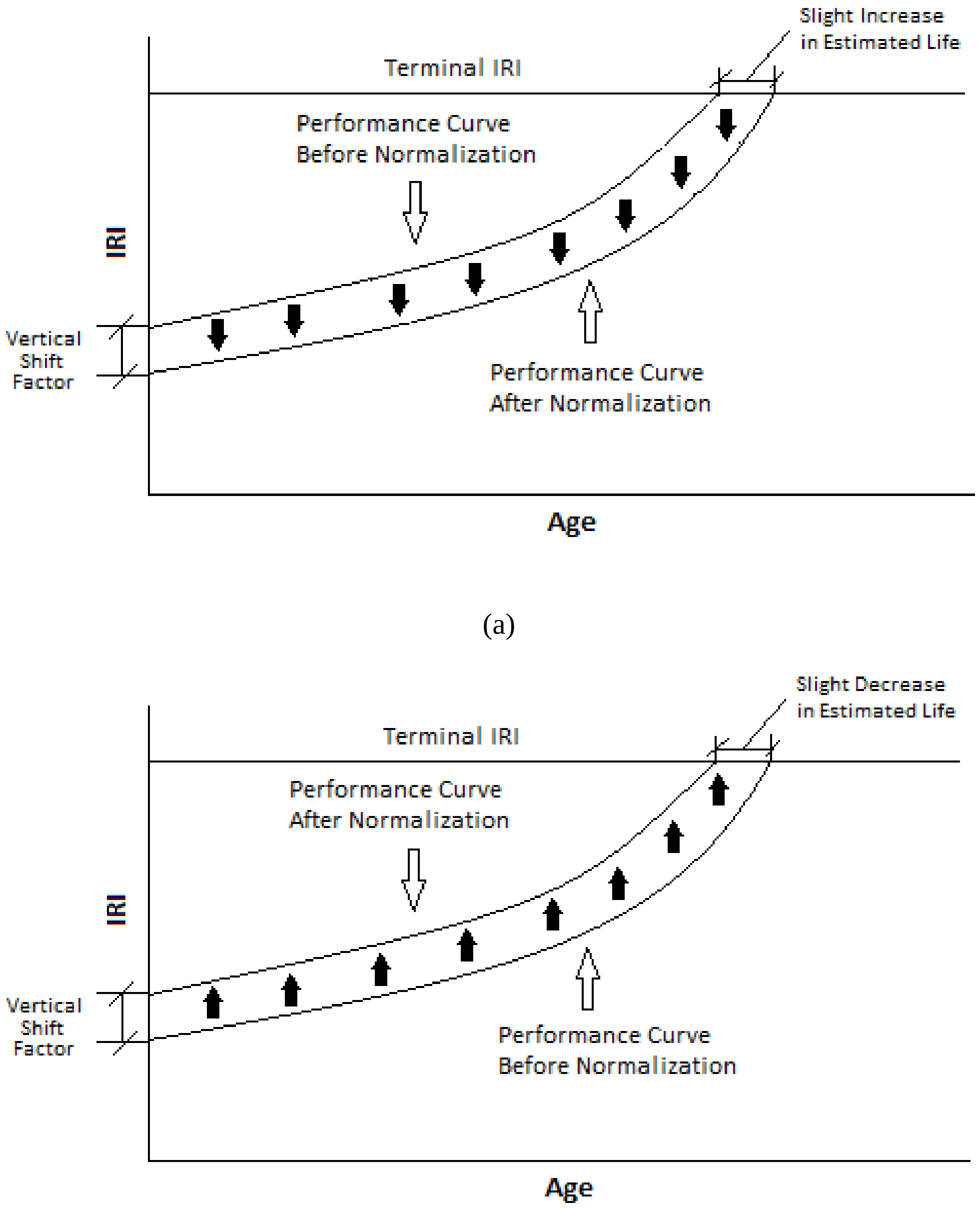
4.3. Normalization and Resulting Performance Curves

Normalization was carried out by vertically shifting the collective performance models either upward or downward, so that the resulting curve has a specified initial roughness value equivalent to the average of the given condition range. The predicted curves, rather than the collective set of data points, were shifted, but this did not have a significant impact on the shape of the curves, as dictated by the beta value. In other words, while the y-intercept of the curves changed significantly in some cases due to normalization, the change in the shape of the curves was negligible, if any. Table 4.4 summarizes the initial condition categories and the corresponding roughness values to which each collective performance curve was vertically shifted.

Table 4.4 Initial Condition Values for Normalization

Initial Pavement Condition Classification	Interval of Initial Roughness (in/mile)	Specified Initial Condition Value for Normalization (in/mile)
Smooth	40-80	60
Medium	80-120	100
Rough	120-160+	140

Two types of vertical shifts were necessary depending on whether the particular collective performance curve started above or below the specified initial condition value for normalization. If the collective performance curve had a y-intercept lower than the specified initial condition value, then the curve was shifted upward so that its intercept matches the specified initial condition value. Conversely, if the collective performance curve had a y-intercept greater than the specified initial condition value, then the curve was shifted downward to reach the same desired effect. Figure 4.7 illustrates these two scenarios for vertical shifting.



(a)

(b)

Figure 4.7 Effect of Vertical Shift on Performance Curves and Estimated Life

The vertical shifts only had a slight effect on the estimated lifetime. For curves that were shifted upward, the estimated lifetime decreased slightly, by 1-2 years at the most, and for curves that were shifted downward, the estimated lifetime increased slightly, by 1-2 years at the most. The effect of this decrease or increase in lifetime was more pronounced for collective performance curves whose initial condition value was far from the specified average condition value. For instance, for the Dry Non-Freeze climate, in the rough category, the original regressions estimated the remaining pavement life to be around 12 years for control and 10 years for chip seal. However, after normalizing both curves to start at the specified roughness value of 140 inches/mile, the estimated remaining life of the control section was cut down to 7 years, and the estimated remaining life of chip seal was cut down to 8 years.

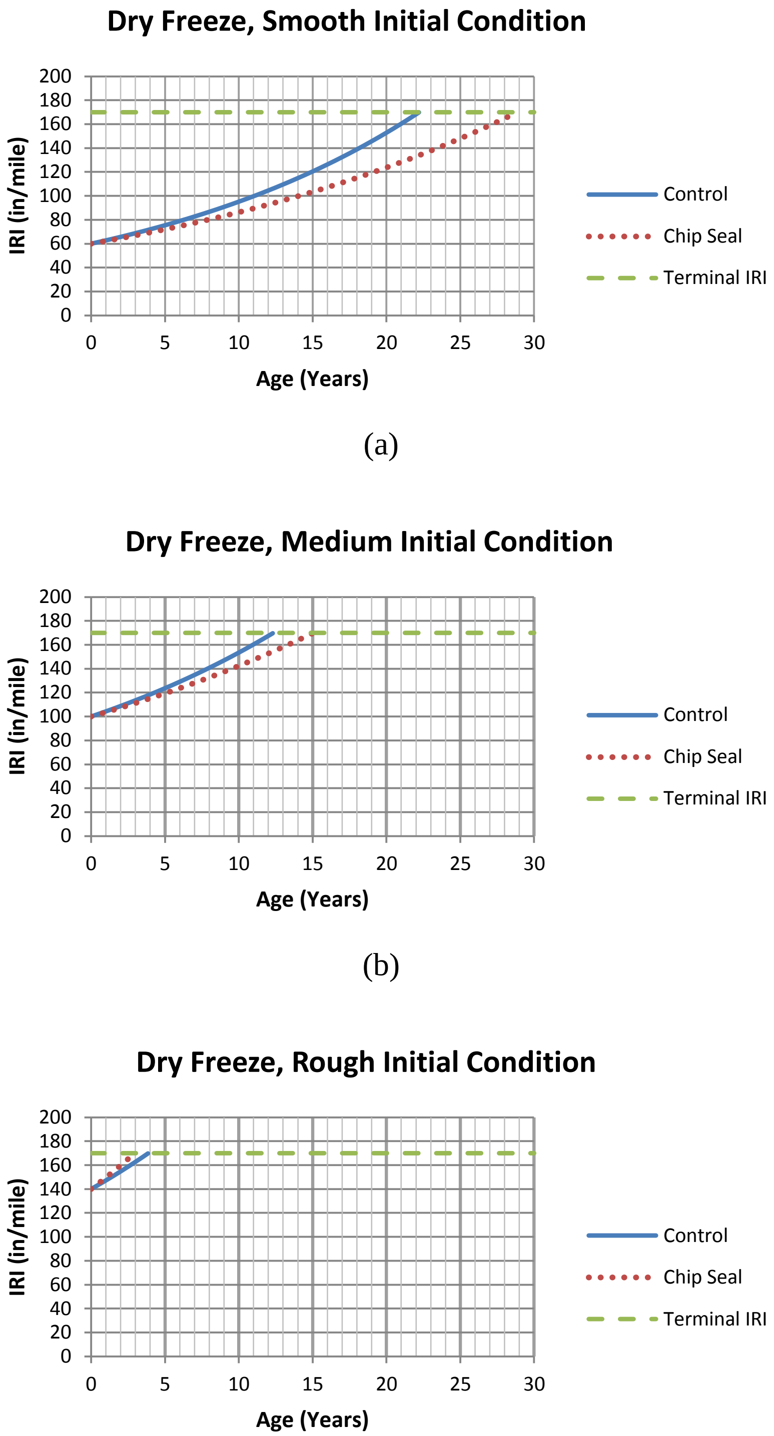
It should also be noted that among all collective performance models, the model for chip seal in the Dry Freeze, rough initial condition category had an estimated initial roughness of 181 inches/mile, and this value is larger than the terminal IRI value of 170 inches/mile that most agencies specify. For consistency, the performance model was still shifted downward by 41units so that its initial condition met the specified criteria. However, due to this large shift, the estimated life for chip seal was slightly lower than the estimated life of the control section.

The performance curves after normalization showed consistent results in terms of life extension and relative benefit. Namely, in eleven of the twelve cases, the estimated remaining life of chip seal was greater than or equal to the estimated remaining life of the control. The only anomaly in this regard was the model for rough initial condition in the Dry Freeze climatic zone, as discussed earlier. Moreover, the increase in rate of deterioration over time was generally larger for control sections in all cases; this observation can be attributed to the careful selection of sections that show similar trends as do chip seals in this regard.

The goodness of fit between the actual roughness data points and the normalized predictive curves was calculated in terms of the adjusted R-squared value, and the ratio of the standard error of estimate to the standard deviation, S_e/S_y. These results are summarized in Table B.1 in Appendix B. The adjusted R-squared values ranged between approximately 0.17 and 0.63 for chip seal performance models, and between approximately 0.22 and 0.93 for control performance models. The S_e/S_y values ranged between 0.61 and 0.92 for chip seal regression models, and between 0.29 and 0.88 for control regression models. In general, a higher adjusted R-squared value is accompanied by a lower Se/Sy value, indicating a better fit. The large ranges in adjusted R-squared and S_e/S_y values can be attributed to the varied number of available data points. Table 4.5 provides a summary of final, normalized performance models. Figures 4.8 through 4.11 illustrate the final, normalized collective performance models for chip seal and control sections in the Dry Freeze, Dry Non-Freeze, Wet Freeze, and Wet Non-Freeze climatic zones, respectively.

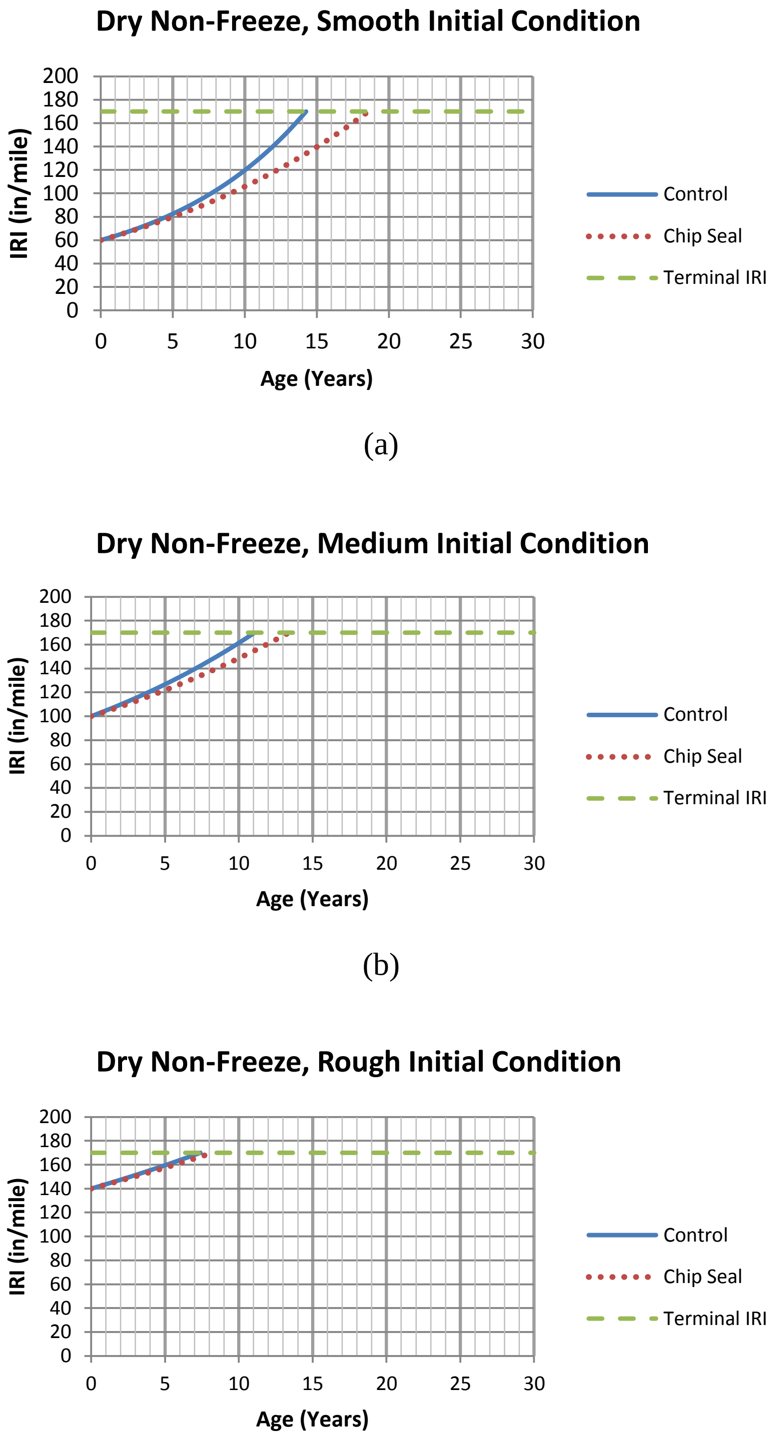
Table 4.5 Normalized Collective Performance Models for Chip Seal and Control Sections

Climatic Region	Initial Condition	Section Type	
		Control	Chip Seal
		Performance Model	Performance Model
Dry Freeze	Smooth	$y = 60e^{0.0470x}$	$y = 60e^{0.0361x}$
	Medium	$y = 100e^{0.0430x}$	$y = 100e^{0.0352x}$
	Rough	$y = 140e^{0.0501x}$	$y = 140e^{0.0657x}$
Dry Non-Freeze	Smooth	$y = 60e^{0.0737x}$	$y = 60e^{0.0560x}$
	Medium	$y = 100e^{0.0479x}$	$y = 100e^{0.0396x}$
	Rough	$y = 140e^{0.0263x}$	$y = 140e^{0.0236x}$
Wet Freeze	Smooth	$y =60e^{0.0499x}$	$y = 60e^{0.0399x}$
	Medium	$y =100e^{0.0474x}$	$y = 100e^{0.0409x}$
	Rough	$y = 140e^{0.0632x}$	$y = 140e^{0.0570x}$
Wet Non-Freeze	Smooth	$y = 60e^{0.0478x}$	$y = 60e^{0.0371x}$
	Medium	$y = 100e^{0.0313x}$	$y = 100e^{0.0263x}$
	Rough	$y = 140e^{0.0292x}$	$y = 140e^{0.0295x}$



(c)

Figure 4.8 Normalized Collective Performance Models for Dry Freeze Climatic Region for (a) Smooth (b) Medium and (c) Rough Initial Conditions



Dry Non-Freeze, Smooth Initial Condition

(a)

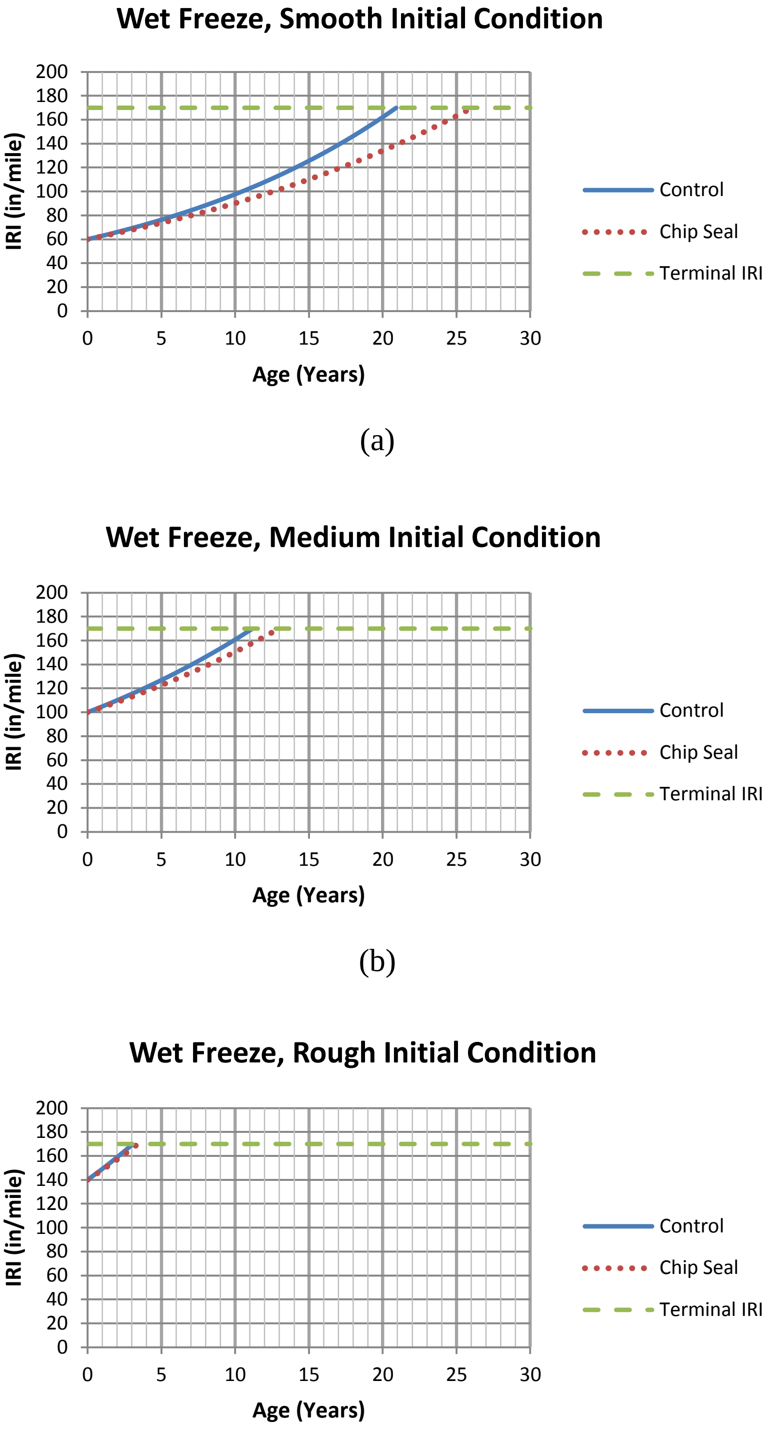
Dry Non-Freeze, Medium Initial Condition

(b)

Dry Non-Freeze, Rough Initial Condition

(c)

Figure 4.9 Normalized Collective Performance Models for Dry Non-Freeze Climatic Region for (a) Smooth (b) Medium and (c) Rough Initial Conditions



(a)

(b)

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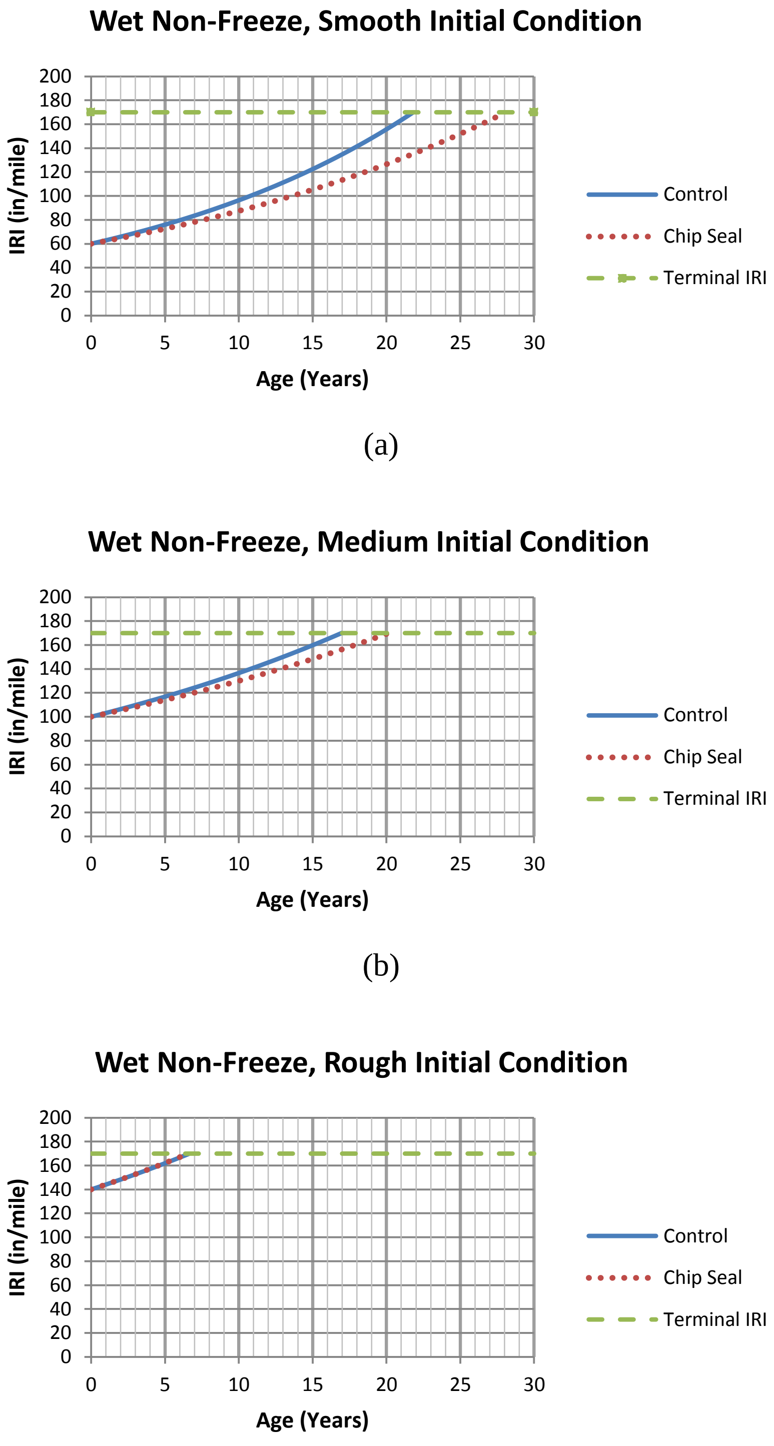
Figure 4.10 Normalized Collective Performance Models for Wet Freeze Climatic Region for (a) Smooth (b) Medium and (c) Rough Initial Conditions



(a)

(b)

(c)

Figure 4.11 Normalized Collective Performance Models for Wet Non-Freeze Climatic Region for (a) Smooth (b) Medium and (c) Rough Initial Conditions

4.4. Evaluation of Life Extension, Relative Benefit, and Benefit-Cost Ratio

4.4.1. Life Extension

Life extension from each collective performance curve was calculated by simply subtracting the estimated remaining life of the control section from the estimated remaining life of the chip seal section. Table 4.6 summarizes remaining pavement life with and without treatment for all initial conditions and climatic zones. Table 4.7 summarizes life extension due to chip seal for smooth, medium, and rough initial pavement condition for all four climatic zones. Figure 4.12 is a graphical representation of life extension due to chip seal.

Table 4.6 Predicted Remaining Pavement Life for Chip Seal and Control Sections*

Climatic Region	Predicted Remaining Pavement Life, Years					
	Smooth		Medium		Rough	
	Control	Chip Seal	Control	Chip Seal	Control	Chip Seal
Dry Freeze	22	29	12	15	4	3
Dry Non-Freeze	14	19	11	13	7	8
Wet Freeze	21	26	11	13	3	3
Wet Non-Freeze	22	28	17	20	7	7

* The values are rounded to the nearest whole year.

Table 4.7 Life Extension Due to Chip Seal Based on Climatic Region and Initial Pavement Condition*

Climatic Region	Life Extension, Years (Percent)		
	Smooth	Medium	Rough
Dry Freeze	7 (32)	3 (25)	0 (0)
Dry Non-Freeze	4 (29)	2 (18)	1 (14)
Wet Freeze	5 (24)	2 (18)	0 (0)
Wet Non-Freeze	6 (27)	3 (18)	0 (0)

*The values are rounded to the nearest whole year.

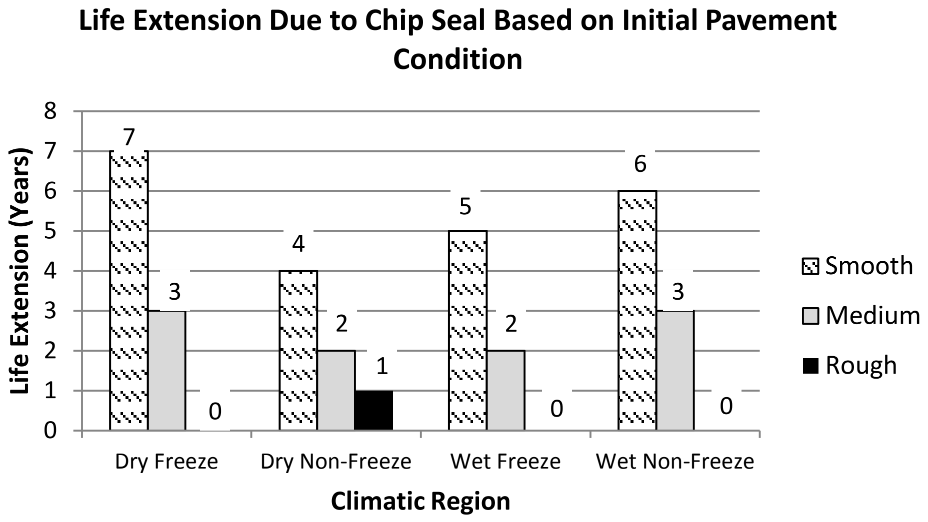


Figure 4.12 Life Extension Due to Chip Seal Based on Initial Pavement Condition in the Four Climatic Regions

The ranges of remaining pavement lives, for all climates overall, were 14-22 years, 12-17 years, and 4-7 years for smooth, medium, and rough control sections. The same ranges were found to be 19-29 years, 13-20 years, and 3-8 years for smooth, medium, and rough chip seal sections. It can be seen from the normalized collective performance curves that regardless of climatic condition, life extension is largest for pavements whose initial condition is smooth at the time of chip seal application. Conversely, life extension is smallest for pavements whose initial condition is rough at the time of chip seal application. Pavements whose initial condition is medium at the time of chip seal application show life extension values that fall within these two extremes.

The ranges of life extension values were found to be 4-7 years, 2-3 years, and 0-1 years for smooth, medium, and rough pavements, respectively. In other words, chip seal treatment increased pavement lives by 24-32 percent, 18-25 percent, and 0-14 percent, for smooth, medium, and rough pavements, respectively. These findings coincide with the expected life extension values reported in literature, as described in Chapter 2. It is expected that the contribution of chip seal to pavement life is maximized when the pavement is still in relatively good condition. The findings regarding life extension in this study precisely illustrate this concept.

It should be noted, however, that when applied to a deteriorated pavement, chip seal may have a negative effect, driving the remaining pavement life lower than it would be without treatment. This concept is illustrated in the Dry Freeze climatic region, for rough initial condition. As mentioned in Chapter 2, chip seal can be used to prevent moisture infiltration. However, when applied to deteriorated pavements, the treatment may seal in moisture underneath the pavement, leading to more rapidly-increasing rate of deterioration over time and shorter remaining pavement life.

4.4.2. Relative Benefit

Table 4.8 summarizes the do-nothing areas, benefit areas, and relative benefit values in all four climatic regions. Figure 4.13 illustrates the relative benefit of chip seal based on initial pavement condition in the four climatic regions.

Table 4.8 Summary of Do-Nothing Area, Benefit Area, and Relative Benefit in the Four Climatic Regions

Climatic Region	Do-Nothing Area (A)			Benefit Area (B)			Relative Benefit (100*B/A) (%)		
	Smooth	Medium	Rough	Smooth	Medium	Rough	Smooth	Medium	Rough
Dry Freeze	1439.6	472.7	64.1	411.4	100.0	None	29	21	None
Dry Non-Freeze	960.5	424.4	114.9	227.6	86.5	12.7	24	20	11
Wet Freeze	1359.9	425.3	47.6	305.0	69.5	5.2	22	16	11
Wet Non-Freeze	1408.3	647.2	103.3	385.4	122.3	None	27	19	None

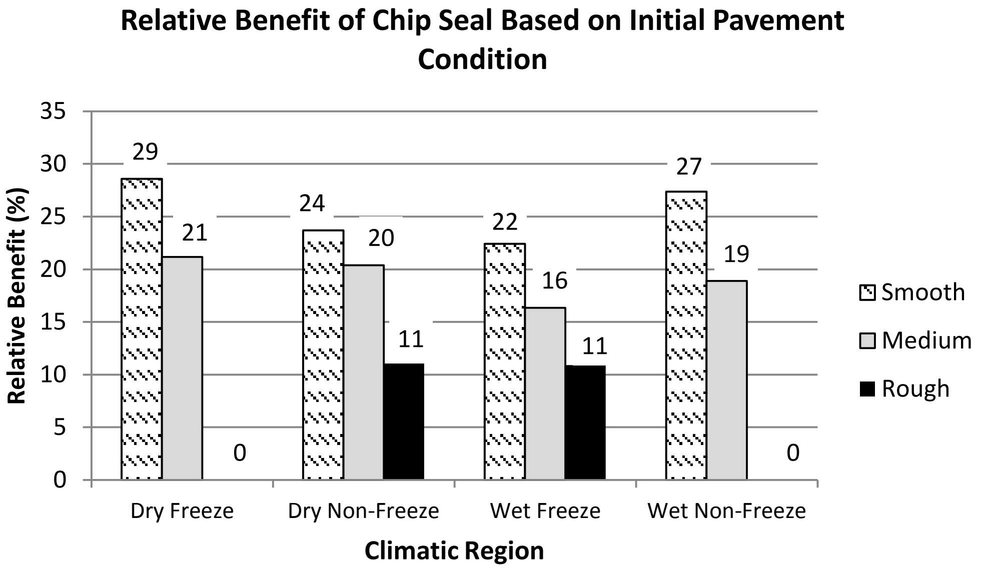


Figure 4.13 Relative Benefit of Chip Seal Based on Initial Pavement Condition in the Four Climatic Regions

The results show that regardless of climatic region and type of sections – chip seal or control – the do-nothing area (A) and benefit area (B) are largest for smooth pavements and smallest for rough pavements. The do-nothing area and benefit area for pavements with medium initial condition fall between these two extremes. For example, the do-nothing areas for the Dry Freeze climatic region are 1439.6, 472.7, and 64.1, for smooth, medium, and rough initial condition, respectively. Similarly, the benefit areas in the same climate are 411.0, 100.0, and 0.0 for smooth, medium and rough initial condition, respectively.

It is also evident that regardless of climatic region, the benefit area for smooth pavements is at least twice as large as the benefit area for rough pavements. This observation implies that it is more beneficial to place chip seal on smooth pavements than on medium-roughness pavements, as expected. Furthermore, for rough pavements in the Dry-Freeze and Wet Non-Freeze climatic regions, there is no significant benefit attributed to chip seal treatment. This result also coincides with the claim that preventive maintenance treatments cannot remedy badly-deteriorated pavements.

Across all four climatic regions, chip seal has the largest relative benefit on smooth pavements, although the relative benefit on medium pavements is comparable. For instance, in the Wet Non-Freeze region, the relative benefit of chip seal is 27 percent for smooth and 19 percent for medium-roughness pavements. Moreover, since no benefit area was shown on rough pavements in the Dry Freeze and Wet Non-Freeze climatic regions, the relative benefit of chip seal is consequently zero in these regions for rough initial condition. This observation can be supported by the fact that pavements in this climate experience freeze-thaw cycles and moist conditions more so than do pavements in the drier, non-freeze climatic regions. It is expected that a preventive maintenance measure on rough pavements in moist and freezing conditions will not deliver significant benefits.

4.4.3. Cost and Benefit-Cost Ratio

An assessment of the economic implications of any preventive maintenance treatment must be considered when evaluating effectiveness. No matter how beneficial a preventive maintenance measure is, it is not useful to any agency unless it is affordable. As discussed earlier in Chapter 2, the tight budgets allocated for maintenance call for a closer look at the costs associated with preventive maintenance measures.

Agencies report that the cost of chip seal ranges anywhere between \$2.50 per square-yard to \$5.00 per square-yard, depending on the price of oil (Chapter 7: Chip Seals n.d.) This represents about one-fifth of the cost of placing a conventional asphalt concrete overlay (Chip Seal Fact Sheet n.d.). About seventy-four percent of the costs associated with chip seal are material costs, fifteen percent are equipment-related costs, and the remaining eleven percent are labor costs (Shannon 2007).

For the purposes of this study, cost was averaged over the past decade to provide an estimated cost figure for the entire United States, regardless of climatic conditions and fluctuations in oil prices. To remain true to the data extracted and presented earlier, the cost figure was derived from the LTPP database. The database reports, in some cases, the cost associated with maintenance treatments, such as crack seals and different types of seal coats, for the year that they were applied. This information resides in the Maintenance module, in the MNT_COST table, under the field SEAL_COAT_AVG_COST (LTPP DataPave Online: Data

Extraction Tools 2011). While this table does not report the cost of each individual chip seal section that was used in this study, it does provide a general idea of how much money, in dollars per square foot, agencies invested in chip seal over the past two decades. Out of the total of 231 chip seal sections, costs are only reported for 32 sections (Long-Term Pavement Performance Database 2012).

To extract the costs, each chip seal section available in the database was linked to the available cost information. The cost of chip seal, according to the reported data in LTPP, has risen from less than $0.10 per square-foot in the early 1990s up to $0.80 per square-foot in the mid-2000s (Long-Term Pavement Performance Database 2012). In order to provide cost figure that is more representative of prices over more recent years, all reported costs prior to year 2000 were ignored. Even so, several reported values seemed unusually large compared to the majority of reported cost figures, and this might be attributed to inconsistent units used for reporting. For instance, the chip seal cost of section 316700 was reported to be 1.43, but since units in the table were not provided and the majority of the numbers in the table lingered between 0.1 and 0.8, anything higher than 0.80 was also ignored. With these filtering techniques, the reported cost figures, ranging between $0.10 per square-foot to $0.85 per square-foot, were averaged, yielding an approximate cost of $0.40 per square-foot, or roughly $3.90 per square-yard, averaged between years 2003 and 2009. This result falls in the middle of the range of approximate chip seal costs mentioned earlier in this section. This cost was scaled up to represent cost per lane-mile, assuming 12-foot lanes.

Once the fixed cost is known, the benefit-cost ratio can easily be calculated. The benefit-cost ratio is equivalent to the benefit area (B) divided by the cost of the treatment (Hajj, et al. 2011). Equation 4.2 below represents the formulation for benefit-cost ratio.

$$Benefit - Cost\ Ratio = \left(\frac{B}{C}\right) \times 1000 \tag{4.2}$$

where:

B = Benefit Area (B) and
C = cost, in $\$/yd^2$ or \$/lane-mile (Hajj, et al. 2011; Loria, et al. 2012)

Benefit-cost ratios for all initial pavement conditions in all climatic regions were calculated. Table 4.9 and Figure 4.14 show this information, where the benefit-cost ratio was calculated using the cost in dollars per lane-mile. Although the benefit-cost ratio is not unitless, no units in Table 4.9 and Figure 4.14 are shown to avoid confusion.

Table 4.9 Benefit-Cost Ratio for Chip Seal Based on Initial Pavement Condition in the Four Climatic Regions

Climatic Region	Cost ($\$/yd^2$)	Cost (\$/lane-mile)	Benefit-Cost Ratio		
			Initial Pavement Condition		
			Smooth	Medium	Rough
Dry Freeze	3.90	$27,300	15	4	0
Dry Non-Freeze			8	3	0
Wet Freeze			11	3	0
Wet Non-Freeze			14	4	0

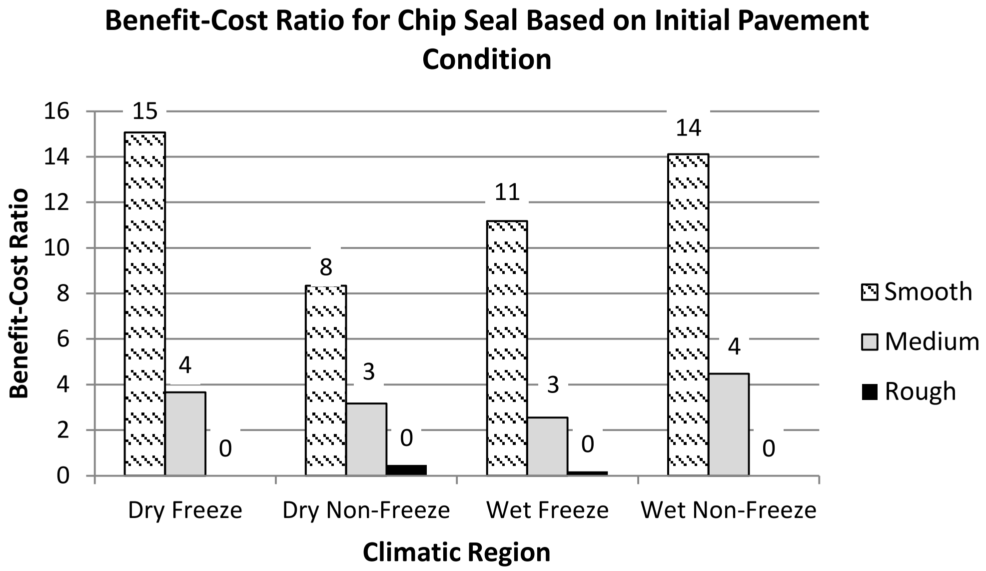


Figure 4.14 Benefit-Cost Ratio for Chip Seal Based on Initial Pavement Condition in the Four Climatic Regions

Based upon the earlier discussion of relative benefits in Section 4.4.2, the same trend was observed as in the case of benefit areas. Namely, regardless of climatic region, smooth pavements were found to have the highest benefit-cost ratio, followed by medium pavements and rough pavements, respectively. It should be noted that even though there was a small benefit area B for rough pavements in both the Dry Non-Freeze and Wet Freeze climatic regions, due to rounding to single digit figures, these small benefits are not reflected in the benefit-cost ratio. The range of benefit-cost ratios is highest in the smooth category, ranging between 8-15, followed by the medium category, ranging between 3-4. The benefit-cost ratio for rough pavements in all four climates is zero. This trend is reasonable because converting the benefit area B to a benefit-cost figure is simply a matter of multiplying by a scalar.

4.5. Relating the Results to Climatic Regions and Traffic Levels

4.5.1. Effectiveness of Chip Seal in Different Climatic Regions

Up until this point, the comparison of results focused on the differences in benefit associated with smooth, medium, and rough pavements, regardless of climatic region. However, the results – life extension, relative benefit, and benefit-cost ratio – can also be assessed from a climatic region standpoint.

For smooth pavements, the highest life extension, at 7 years, is achieved in the Dry Freeze climatic region, followed by 6 years in the Wet Non-Freeze, 5 years in the Wet Freeze, and 4 years in the Dry Non-Freeze regions. It is somewhat unexpected to see that the Dry Non-Freeze region has the smallest life extension for smooth initial condition. Since the Dry Non-Freeze climate does not typically have freezing temperatures or significant rain events, it would be expected that chip seal provides a higher life extension in this region because of the absence of freeze-thaw cycles, which are notorious for damaging pavement. However, the life extension due to chip seal in the other three climatic regions is fairly consistent, ranging between the expected 5-7 years. One reason for this discrepancy is the fact that not many chip seal sections were found in the Dry Non-Freeze climatic region, as shown in Table 4.1. This might have made the chip seal benefit less accurate. Therefore, it can be concluded that overall, climatic conditions have negligible effect on the life extension due to chip seal when the treatment is applied to smooth pavements.

For medium pavements, life extension across all four climates is fairly consistent, with 3 years in the Dry Freeze and Wet Non-Freeze regions, and 2 years in the Dry Non-Freeze and Wet Freeze regions. These results imply that climatic conditions have little to no effect on the added lifetime due to chip seal, even for pavements that have medium initial roughness.

For rough pavements, the life extension is either non-existent or minimal, at one year, for all climatic regions. This result means that climatic region does not have a large impact on the life extension associated with chip seal when the pavement is in rough condition at the time of treatment. Overall, in terms of life extension, climatic regions do not seem to play a significant role in the effectiveness of chip seal treatment, regardless of initial pavement condition. However, this conclusion is contingent upon the number of sections and data points available in each region and may slightly change if more data is to be considered.

The largest relative benefit for smooth pavements is observed in the Dry Freeze climate, followed by the Wet Non-Freeze, Dry Non-Freeze, and Wet Freeze climates. This result is somewhat surprising because it is expected that the largest relative benefit would be realized in the Dry Non-Freeze climatic region. From a pavement standpoint, the weather in this region is most temperate and forgiving. Therefore, preventive maintenance treatments should realize their highest potential in this region because of the absence of damaging climatic factors that are present in the other three climates. However, it makes sense that even for smooth pavements, the smallest relative benefit is observed in the Wet

Freeze climate. Temperature fluctuations and the amount and variety of yearly precipitation are the most unforgiving in the Wet Non-Freeze region.

The relative benefit for medium-roughness pavements stays fairly consistent across the Dry Freeze, Dry Non-Freeze, and Wet Non-Freeze climates, ranging between 19-21 percent. However, the smallest relative benefit, at 16 percent, is once again observed in the Wet Freeze climate. This implies that just like in the case of smooth pavements, medium pavements receive the least added benefit in the Wet Non Freeze climatic region, and this can be attributed to the more demanding weather conditions.

For rough pavements, no relative benefit is shown in the Dry Freeze and Wet Non-Freeze climatic regions, and for the Wet Freeze and Dry Non-Freeze regions, the relative benefit is 11 percent. Since relative benefit is a ratio of areas, relative benefit may be large compared to the life extension, especially when the areas are small, and when both measures are rounded to whole numbers. This explains that even though no significant life extension is observed in the Wet Freeze region, the region still shows a relative benefit of 11 percent. However, across all climatic regions, the smallest relative benefit is still observed on rough pavements, leading to the conclusion that climatic regions do not significantly affect the benefits of chip seal, especially on deteriorated pavements that have little remaining life.

4.5.2. Trends Observed in Average Traffic Levels

As mentioned in Section 3.2.3.1, all roughness data used in this study was also linked to traffic data so that any correlation between the results and traffic levels can be investigated. The assessment of traffic levels in this context is strictly qualitative in nature, because in order to stay consistent, the process involved two processes of averaging. First, the available traffic data for each individual section was averaged for the number of years that it was reported. Second, traffic data was also averaged among the collective set of sections within each initial condition subcategory, for both chip seal and for control sections. Table 4.10 summarizes the average annual traffic levels that only serve as a qualitative comparison.

Table 4.10 Average Annual Traffic for Chip Seal and Control Sections Used in this Study

Climatic Region	Average Annual Traffic (KESAL/LTPP lane-year)					
	Control			Chip Seal		
	Smooth	Medium	Rough	Smooth	Medium	Rough
Dry Freeze	135	81	153	118	69	79
Dry Non-Freeze	272	90	123	764	307	174
Wet Freeze	144	410	357	123	298	62
Wet Non-Freeze	228	223	253	141	57	65

It was observed that even after averaging the traffic data for individual sections within a subcategory, the traffic data still showed significant variation. For instance, the collective set of control sections that qualified for the smooth category in the Wet Non-Freeze region have average annual traffic levels ranging between 20-900 KESALs per LTPP lane-year. This type of variation explains that the initial attempt of grouping sections based upon treatment timing and traffic levels did not yield significant conclusions. The boundaries of the traffic level categories in that original analysis were set to 0-250 KESALs per LTPP lane-year for low traffic, and 250+ KESALs per LTPP lane-year for high traffic. These boundaries were set based upon the available traffic data and in an attempt to provide an approximately even number of sections and data points in the low and high categories.

It should be noted that due to the large range of average annual traffic levels within each subcategory, the collective average over an entire subcategory may not be reflective of typical traffic levels. This effect is especially pronounced in cases where only a few sections make up a subcategory, and traffic levels vary significantly among those few sections. For instance, in the Dry Non-Freeze climate, for smooth pavements, among the five sections used, two have average traffic levels higher than 1,000 KESALs per LTPP lane-year, while the remaining three have average traffic levels below 250 KESALs per LTPP lane-year. With such large variation, the average traffic level for this subcategory is skewed, at 764 KESALs per LTPP lane-year. This value is not necessarily representative of either the low-traffic sections or high-traffic sections found in the subcategory.

In general, the average annual traffic volumes were not correlated to the initial condition of either chip seal or control pavements. For instance, in the Wet Freeze climate, the average traffic level for medium pavements was the highest, while in the Dry Non-Freeze climate, the average traffic level for smooth pavements was the highest. Also, the average annual traffic level was found to be larger for rough control pavements than for medium control pavements for the Dry Freeze, Dry Non-Freeze, and Wet Non-Freeze climates. From these observations, it is safe to conclude that when grouped by initial pavement condition, traffic levels show no clear correlation with treatment benefits or effectiveness. However, the overall assessment of average traffic levels as a whole shows that the range of traffic levels for pavements that receive chip seal treatment is approximately 60-300 KESALs per lane-year. This supports the assertion that chip seal treatments are typically used for low-volume roads.

CHAPTER 5. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1. Summary and Conclusions

5.1.1. Summary of the Work Performed

This study assessed the benefits of chip seal application based on initial pavement condition in four climatic regions in the United States. All data used in the study was extracted from the January 2012, Standard Data Release 26.0, of the LTPP database. Pavement performance was modeled and assessed using the International Roughness Index as a pavement condition indicator.

Chip seal and control sections were selected using an elaborate process that modeled and evaluated individual sections as well as collections of sections with similar deterioration characteristics. Individual sections were grouped into three different categories of initial condition – smooth, medium, and rough. Traffic data for each section used in the study was also extracted and evaluated. Sections whose initial condition and rate of increase in deterioration over time is relatively similar were selected and grouped into the three initial condition categories in each climate. Any sections whose roughness data showed large scatter or unexplained decreasing roughness over time were eliminated.

Exponential modeling of roughness was used to collectively examine the benefits of chip seal against the untreated control sections. Normalization was performed to account for slight variations in initial condition values among collective performance curves within the same initial condition category in order to provide fair comparisons.

The benefits of chip seal treatment were examined using three measures – life extension, relative benefit, and benefit-cost ratio. The benefit-cost ratio involved an approximate cost calculation of chip seal treatment that was based on costs reported in the LTPP database for chip seal sections over the past decade. An assessment of possible correlation between benefit, average traffic levels, and climatic conditions was also included in the study.

5.1.2. Conclusions Regarding the Benefits of Chip Seal Treatment

The results of the study verified the assumption that treated sections performed better than untreated sections. The study also showed that chip seal treatment yields the largest life extension on pavements whose initial condition is smooth at the time of treatment. Life extension for smooth pavements ranged between 4-7 years across the four climatic regions. Life extension for medium pavements ranged between 2-3 years across the four climatic regions. Finally, the least life extension was shown for rough pavements, ranging between 0-1 years across the four climates.

The relative benefit of chip seal across all four climates was shown to be greatest for smooth pavements, ranging between 22-29 percent. Relative benefit for medium pavements ranged between 16-21 percent. Finally, as expected, relative benefit was smallest for rough pavements, ranging from 0-11 percent.

The results of benefit-cost ratio assessment showed the exact same trends as relative benefit. The largest benefit-cost ratios across all climates were observed for smooth pavements, ranging between 8-15. Medium pavements showed benefit-cost ratios of 3-4. Finally, the benefit-cost ratios for rough pavements were negligible to none in all four climatic regions.

No significant variations, in terms of the benefit of chip seal, were observed among the four climates. In other words, the benefit of chip seal was shown to be highest for smooth pavements and lowest for rough pavements, in all four climatic regions with almost the same pattern. The attempt to correlate the benefit measures to average traffic levels also showed no distinct correlation between benefit and traffic level. This implies that chip seal has the same life extension, relative benefit, and benefit-cost ratio regardless of climatic conditions or traffic levels, although it was observed that most chip seal sections analyzed in the study were placed on low-volume roads with less than approximately 300 KESALs per lane-year.

5.2. Recommendations for Future Research

In order to determine the effectiveness of chip seal against other alternative preventive maintenance measures, it is recommended that other similar treatments be examined in a similar manner, assessing effectiveness based on initial pavement condition. This would provide insight into whether certain maintenance treatments have different success rates than chip seal in remedying deteriorated pavements.

Furthermore, since this study was limited to studying the effect of a single application of chip seal, it is recommended that the same analysis be done for pavements that received multiple applications of chip seal treatment, perhaps at varying time intervals. This would quantify whether, and to what extent, the benefit of chip seal can be maximized when the treatment is applied multiple times in a row. An assessment of multiple chip seal applications would also help to pinpoint the optimal frequency of application that would lead to maximized benefits of chip seal treatment.

Because of the large ranges in the goodness of fit between the roughness data points and the collective performance models, it is recommended that other alternative performance models be developed that may reflect the changes in roughness over time more accurately. Such models could be used to predict performance and treatment effectiveness, and to evaluate the validity of the already-existing exponential roughness model used in this study.

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APPENDIX A

LIST OF LTPP SECTIONS UTILIZED IN THIS STUDY

Table A1. LTTP ID Numbers for Chip Seal Sections Used in this Study* (Long-Term Pavement Performance Database 2012)

Climatic Region	Condition at Time of Treatment	ST_CODE and SHRP_ID
Dry Freeze	Smooth	161009, 16A350, 16C350, 300114, 300118, 300119, 300124, 300805, 300806, 307075, 307076, 32B350, 32C350, 491001, 530801, 53C350, 561007, 562019, 562020, 566029, 56A350, 56A363, 56B350, 56B360, 90B350, 90B351
	Medium	8A350, 161005, 169032, 169034, 531007, 567772, 90A352
	Rough	87781, 906400, 90A351
Dry Non-Freeze	Smooth	41034, 4A350, 4D350, 60503, 60559. 60569
	Medium	4C350, 60501, 60502, 60509, 6A350, 6A351, 6A353, 6A363
	Rough	60561, 68535, 6A352
Wet Freeze	Smooth	17A350, 17B350, 18A350, 199116, 26A321, 26B350, 27A350, 27B350, 27D350, 311030, 31A330, 31A350, 31A351, 31A352, 31A353, 36B350, 36B354, 469106, 469187, 47B350
	Medium	26A350, 271018, 29B350, 341033, 36A350, 42A350, 42A351, 460661, 469197, 836454, 83A350, 83A351, 87A350, 87B360, 87B361, 87B362
	Rough	27C350, 382001, 42B351
Wet Non-Freeze	Smooth	12A350, 12A352, 12B350, 12B352, 12C350, 28A350, 481094, 481130, 482133, 483865, 486086, 48D350, 48J350, 48M350, 821005
	Medium	283090, 40B350, 481076, 481092, 486179, 48N350
	Rough	283085, 481096, 483739, 48E350, 48H351

* Some sections were used as control sections before applying the chip seal treatment and as chip seal sections after applying the treatment.

Table A.2 LTPP ID Numbers for Control Sections Used in this Study (Long-Term Pavement Performance Database 2012)

Climatic Region	Condition at Time of Treatment	ST_CODE and SHRP_ID
Dry Freeze	Smooth	87780, 8A340, 161001, 161007, 161010, 300114, 307066, 307075, 308129, 321020, 491007, 531008, 531501, 531801, 536020, 536056, 537322, 561007, 562017, 562020, 566032, 567773, 567775, 81A901, 81A903, 900901, 900902, 900903, 900959, 900960, 900961, 900962, 906400
	Medium	169032, 169034, 306004, 321021, 562015, 906801
	Rough	86002, 491004, 811805
Dry Non-Freeze	Smooth	40113, 40114, 40116, 40119, 40120, 40163, 40260, 40261, 41006, 41036, 41037, 46055, 4A903, 62004, 62038, 62041, 62647, 63030, 66044, 68149, 68150, 68151, 68153, 68535, 69049, 69107, 350101, 350102, 350103, 350104, 350105, 350106, 350107, 350108, 350109, 350110, 350111, 350112, 351003, 351005, 351112, 352118, 356033, 356035, 356401
	Medium	61253, 62053, 67491, 67493, 68156, 68201, 69048
	Rough	68202
Wet Freeze	Smooth	21008, 17B340, 190110, 190112, 190159, 196150, 200902, 200903, 211014, 260115, 260116, 26D340, 27A340, 27B340, 296067, 310114, 36B340, 390110, 412002, 460803, 473101, 479025, 550115, 550117, 550118, 871806, 892011
	Medium	209037, 271016, 271028, 341031, 397021, 891021, 899018
	Rough	891125, 891127
Wet Non-Freeze	Smooth	11019, 11021, 14125, 14126, 16012, 50113, 50114, 50117, 124106, 124107, 129054, 133015, 223056, 280501, 281001, 281802, 283082, 283087, 283089, 283091, 371802, 371814, 372819, 372824, 404164, 406010, 481049, 481050, 481060, 481087, 481168, 481169, 481174, 483569, 483669, 483689, 483749, 486179, 489005, 512004
	Medium	53048, 151008, 281802, 282807, 283085, 370903, 372825, 404165, 407024, 451025, 481048, 481065, 481109, 481111, 481181, 483679, 483729, 483739, 483769, 486160, 511023, 512021, 51A340
	Rough	487165, 721003

APPENDIX B

SUMMARY OF GOODNESS OF FIT FOR NORMALIZED COLLECTIVE PERFORMANCE CURVES

Table B.1 Summary of Goodness of Fit for Normalized Collective Performance Models

Climatic Region	Initial Condition	Figure Number	Section Type			
			Control		Chip Seal	
			S_e/S_y	R^2 adj.	S_e/S_y	R^2 adj.
Dry Freeze	Smooth	4.8 (a)	0.88	0.22	0.61	0.63
	Medium	4.8 (b)	0.44	0.81	0.92	0.17
	Rough	4.8 (c)	0.40	0.85	0.84	0.36
Dry Non-Freeze	Smooth	4.9 (a)	0.79	0.38	0.89	0.24
	Medium	4.9 (b)	0.74	0.44	0.89	0.23
	Rough	4.9 (c)	0.29	0.93	0.78	0.47
Wet Freeze	Smooth	4.10 (a)	0.84	0.29	0.85	0.29
	Medium	4.10 (b)	0.68	0.53	0.82	0.33
	Rough	4.10 (c)	0.53	0.69	0.87	0.24
Wet Non-Freeze	Smooth	4.11 (a)	0.88	0.23	0.83	0.33
	Medium	4.11 (b)	0.85	0.27	0.87	0.25
	Rough	4.11 (c)	0.51	0.65	0.81	0.37